Chapter 9

MATERIAL PROPERTIES AND TESTING

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9.1 The Formulation of Membrane Materials

DEFINITION

The materials used for architectural membranes generally consist of a woven fabric coated with a polymeric resin. The strength of coated fabrics are mainly determined by the strength of their constitutive yarns. Weft-inserted fabrics, laminated fabrics and foils are variants of the general concept.

When used externally uncoated fabrics have short service lives. Coating a fabric gives the following benefits:

a) Protecting the yarns against different sources of damage (UV, abrasion, atmosphere)
b) Proofing the membrane against rainwater and atmospheric moisture
c) Stabilising what might otherwise be an unstable fabric geometry
d) Providing material to permit heat-sealed seams

More precisely a membrane consists of different layers combined with the fabric; a prime coat, a top coat and a surface treatment for sealing or printing as shown in the figure 9.1.

The prime coat has the main functions described above and is itself protected by a thin, chemically distinct top coat. The outer layer is specific to the chemical nature of the coatings in order to allow the joining and sealing of pieces of fabrics (and printing where necessary), by chemical compatibility of the components.

MAIN CATEGORIES OF MATERIALS

The two most commonly used materials are:

a) PVC coated polyester fabrics (PVC = polyvinylchloride)
b) PTFE coated glass fabrics (PTFE = polytetrafluoroethylene)

and of these PVC coated polyester is more widely used than PTFE coated glass due in effect to compromises made in the ratios between cost, performance and durability.

Other materials in use are:

c) Silicone coated glass fabrics
d) PTFE coated PTFE fabrics
e) ETFE foils (ETFE = ethylene-tetrafluoroethylene copolymer)
Other yarns can be used such as: aramid (aromatic polyamide) and LCP (liquid crystal polymer based on aromatic polyester).

The top coats are based on polymeric materials such as: acrylic, polyvinylidene fluoride (PVDF) or polyvinyl fluoride (PVF) for PVC coated polyester fabrics, and fluoroethylene propylene (FEP) for PTFE coated glass fabric.

**9.2 Description of Yarns**

**9.2.1 Basic Definition**

The raw material, or as-spun yarn, is based on a given number of infinite length filaments of small diameter (between 3 and 25 microns). Two yarns, or more, can be assembled by twisting in order to obtain a thread of higher strength.

The yarns are obtained by extrusion spinning of melt materials (glass, polyester) or of a solution like aramids.

The basic definition of a yarn consists of:

a) Number of elementary filaments  
b) Linear density or count in tex (g/km), dtex or denier (g/9000m)  
c) Filament diameter  
d) Number of twists/metre, in S or Z direction (S is for a left-hand twist and Z is for a right-hand twist of yarns within a helix)  
e) Finishing treatment.

The general properties of yarns are summarised in table 1:

<table>
<thead>
<tr>
<th></th>
<th>Polyester High Tenacity</th>
<th>Glass</th>
<th>High modulus Aramid</th>
<th>LCP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (g/cm³)</td>
<td>1.38</td>
<td>2.6</td>
<td>1.45</td>
<td>1.40</td>
</tr>
<tr>
<td>Tensile strength (GPa) (N/tex)</td>
<td>0.97 - 1.17</td>
<td>2.4</td>
<td>3.32</td>
<td>3.28</td>
</tr>
<tr>
<td></td>
<td>0.70 - 0.85</td>
<td>0.92</td>
<td>2.35</td>
<td>2.4</td>
</tr>
<tr>
<td>Extension at break (%)</td>
<td>11 - 15</td>
<td>4.5</td>
<td>1.5</td>
<td>2.5</td>
</tr>
<tr>
<td>Tensile modulus (GPa) (N/tex)</td>
<td>12 - 15</td>
<td>73</td>
<td>160</td>
<td>104</td>
</tr>
<tr>
<td></td>
<td>9 - 11</td>
<td>28</td>
<td>109</td>
<td>74</td>
</tr>
<tr>
<td>Water uptake (%)</td>
<td>0.4</td>
<td>≤ 0.1</td>
<td>1.2 - 3</td>
<td>≤ 0.1</td>
</tr>
</tbody>
</table>

Table 1 General properties of yarns
9.2.2 POLYESTER YARNS

Polyester yarns are produced by “melt spinning” a polymer at 265 °C through a spinnerette having a given number of holes defining the number of individual filaments. The process is shown in Fig. 9.2. During the cooling step, crystallisation and orientation of macromolecular chains occur. The drawing of the yarn in one or two steps gives an additional orientation to the macromolecules. In turn this leads to higher values of elastic modulus and tenacity.

High tenacity polyester yarn is characterised by a tensile strength of, at least, 0.7N/tex. The yarn itself is composed of about 200 filaments/yarn. The tenacity, being that high, depends on the degree of crystallisation of the yarn and the orientation of the crystalline and amorphous domains.

The force-extension diagram for polyester yarn exhibits 3 regions correlated to the structure of the polymer chain. This has a zig-zag shape. In zone “I” the angle of this zig-zag chain is initially widened. In zone “II” chains begin to extract themselves from the amorphous area. This makes the yarns more ductile. In zone “III” jamming of the drawn-out chains and growth of crystalline areas occurs and consequently their behaviour becomes stiffer.
It is noticeable that warp and weft yarns have different properties. This is because both the weaving and the coating of the yarns are different. The warp yarns are subjected to different loads to those in the weft, which is where the differences arise. The most important difference is the so-called “weft jump”. The yarns are heated up during the coating of the cloth and the polymer chains in each yarn try to contract again as they exceed the “glass transition” temperature. The warp yarns however are kept under tension and therefore cannot follow this trend. The weft yarns on the other hand are not held and so shrink. They are therefore softer having lower moduli and higher extensions at break (Fig. 9.3). Nevertheless in some cases, by an appropriate processing of the weft during coating, it is possible to reduce significantly these discrepancies between weft and warp yarns (e.g. prestressed process of Ferrari).

These effects on the yarns can be evaluated by measuring their length $l_1$ under tension after extracting them from the coated fabric. The contraction (or crimp index) of the threads is calculated by comparison to the crimped yarn length $l_0$ in the fabrics. The crimp index (%) is equal to $(l_1 - l_0) \cdot 100 / l_0$.

The yarn itself is mostly of the “bright” or “semibright” type. This means that it does not contain pigmentation, or only to a very limited extent, making it sensitive to UV when used in a construction where the PVC would not play the role of a UV absorber. In normal construction the PVC compound absorbs enough UV energy to guarantee a good lifetime of the coated fabric. Pigmentation or UV stabilisation of the polyester is a possibility.

Polyester is an organic material characterised by an ester group, therefore it is sensitive to hydrolysis. Again the PVC barrier plays the role of protecting the yarn from ageing and oxidation. In some cases, where the PVC coating shows pinholing, or did not penetrate into the cloth, “wicking” may appear. Wicking is the migration of water between the filaments that leads to fungi and bacteria growth. The phenomenon results in yellowy, brown lines and specks along the cloth and a reduction in the adhesion properties of the material. This may cause seam problems or delamination of the coating compound. One of the alternatives to overcoming this problem in the short term is the use of hydrophobically treated yarn – commonly referred to as “low wick” yarn.

**9.2.3 GLASS YARNS**

Glass filaments are supplied in various elementary diameters: 3, 6, 9 and 11 micron. The strength of the filaments is strongly dependent on the diameter. The reason for this can be found in the distribution of the inherent tension in the filaments. Glass filaments are drawn from a melt. Thereby the outer layers cool faster than the core which builds up an inherent tension condition. On the outside envelope there are compressive strains in the axial direction and tensile stresses in the centre. In the case of the tensile loads the load tensions are added to the inherent tensions.
Glass filaments demonstrate a linear behaviour up to fracture, as shown in Fig. 9.4.

E-glass is used for coated fabrics; its composition is:

\[ 53 - 54\% \text{ SiO}_2; \; 14 - 15\% \text{ Al}_2\text{O}_3; \; 20 - 24\% \text{ CaO}, \text{ MgO}; \; 6.5 - 9\% \text{ B}_2\text{O}_3. \]

Glass filaments are sensitive to the effects of moisture and to damage to the outer zone which is under tension. For protection they are coated either with PTFE or silicone. Glass is high temperature resistant and can withstand the processing temperatures of PTFE. Glass is UV and weather resistant, has a low creep behaviour and a good dimensional stability. Glass will lose strength if bent or flexed.

### 9.3 Description of Base Fabrics

#### 9.3.1 Definition

Base fabrics are generally woven ones obtained by inserting weft yarns between two layers of warp yarns at 90° to the warp yarns, following a construction designed by the number of yarns per cm and a weave pattern. The main weave patterns used in membrane are plain weave or a 2-2 basket weave (or panama) as shown on Fig. 9.5. The “crimp” of the yarns is less in panama weave.
Woven fabrics are characterized by:

a) Surface weight in g/m²
b) Number of yarns per cm in weft (or fill) and in warp
c) Weave pattern
d) Crimp of the yarns in weft and warp
e) Cover factor (or porosity)
f) Mechanical and physical properties.

Other fabrics like “weft-inserted” fabrics can be obtained by a warp-knitting process which binds warp and weft yarns without crossing the yarns. The web of warp and weft yarns are superimposed over one another and then fixed by a thin knitted yarn⁹. The crimp of yarn is very low, but the shearing property of the fabric is reduced.

The weight of a fabric may be changed by increasing the number or the linear density of the yarns. Depending on the conditions of tension during weaving on a given loom, the crimp of the yarns can change.

As a consequence, the thickness and elongation of woven fabrics are increased with very wavy yarns under low stress, and also with patterns such as plain weave. A more stable fabric is obtained by applying tension to warp and weft of a plain weave fabric, in order to obtain more consistent and more balanced warp and weft stiffnesses throughout the cloth.

### 9.3.2 FINISHING

Generally after weaving a special finish is applied to the fabrics. The purpose of this very thin layer is to increase the chemical and physical compatibilities between the fabric and its first coating. A better compatibility means firstly, a good wettability of the fibres by the liquid resin at the processing stage, and secondly, after wetting a good physical and chemical adhesion between fibre and resin.

For polyester fabrics, the use of low-wick yarns means that a hydrophobic compound has been put onto the fibre in order to have the best fibre resin compatibility so as to avoid moisture diffusion at the fibre/resin interface.

For glass fabrics, a “base coat” is applied to provide a solid anchoring of the PTFE coat. It also determines the flexibility characteristics of the finished coated products. Depending on the expected properties, different formulations can be used.

For low reactive materials, like aramid fabrics, a special chemical modification of the surface of the fibres is necessary to avoid delamination between coating and fabric.
9.4 **Description of Coatings**

9.4.1 **Definition**

Protection of the fabric is generally achieved by applying a resin coating in paste form. Coatings have specific chemical formulations which make the basic resin suitable for processing as well as increasing the levels of performance of particular characteristics such as fire retardance, fungal resistance, and colour pigmentation. The coating process is specific to each chemical resin used. A coating is characterised by its:

a) Weight in g/m²
b) Thickness measured as either the total thickness of the finished product or as the distance between the top of the fabric’s yarn and the outer surface of the coating.

9.4.2 **PVC Coating**

The PVC formulation is a flame-retardant type, as it has to comply with several strict flammability regulations such as the French M2, the German B1 or the US NFPA. These have a distinct impact on the composition of the plasticised PVC.

For the direct coating process, the PVCs used are “paste” PVCs made of either suspension PVC or emulsion types, and containing significant quantities of emulgators. The choice of those polymers in the production process of the coated fabric is critical in the way that the type and concentration of the emulgators have an impact on the processing (rheology), thermal properties and cleaning and surface aspects.

The second major component in the coating is the plasticiser. Plasticisers may be chosen out of a series of phthalates, phosphates, chlorinated products or other esters.

Concerning flame-retardant properties, the phosphates are of the most preferred plasticisers, where in terms of flame-retardant efficiency, the product is more efficient with a higher amount of acyl groups. Upon using phosphates however, one should keep in mind that these molecules have a high tendency to migrate and are susceptible to biological attack. As a matter of fact they act as a feedstock for bacteria and fungi. Phthalates on the other hand are the most widely used plasticisers. Their very good compatibility with PVC however makes them irreplaceable in the formulation of soft PVC. As phosphates, they are also susceptible to migration, and hydrolysis. The latter occurs more strongly with the branched ones rather than with the linear types.

Chlorinated paraffins are the third type of plasticisers. They are extremely efficient in plasticising in combination with an adequate flame-retardant property, but they also have a very strong tendency to migrate to the surface, resulting in a strong dirt pick-up.

To render the fabric its lustre and beauty, the PVC is always pigmented, mostly in white. Also type and concentration of the pigment play an important role in the colour, UV stability and opacity. As with the plasticisers, the pigments may affect the light stability and surface properties as dirt pick-up.
To overcome the weathering problem and dirt pick-up the PVC coating is stabilised with molecules acting as thermal stabilisers, oxidation stabilisers and UV/light stabilisers.

In order to fulfil the flammability criteria, flame retardant additives are added such as antimony oxide, aluminum trihydrate, phosphates, etc. The excellent flame retardant properties of the PVC coated textile itself however is intrinsically given by the chlorine of the PVC. Together with the antimony oxide the chlorine radicals in the gas phase exhibit high recombination efficiencies, killing in this way the flame instantaneously.

The phosphates and aluminum hydroxides on the other hand act as an endothermic surface barrier preventing further pyrolysis of the burning material.

The recycling of PVC coated fabrics is possible using a process (patented by Solvay and applied by Ferrari) which allows the separate recycling of the PVC resin and the polyester fibres by selective chemical dissolving.

The used materials are mechanically cut into small pellets approximately 20 to 60 mm long. In this step all heterogeneous materials, such as metallic parts, can be removed. The plasticised PVC is dissolved in a ketonic solvent at 115 °C while PET fibres remain in suspension in the medium. PET fibres are recovered by filtration and drying. The PVC solution is then precipitated at room temperature using a non-solvent like water. In this step, it is possible to introduce additives in order to restabilise the resin. The precipitate is spin-filtered to give a free flowing powder whose granulometry is about 350 µm. This powder can be used for compounding without any other treatment. Water and solvent are ‘phase separated’ and ‘separated recovered’ for reuse.

The whole process works in a completely closed loop and each of the two components are reused.

**9.4.3 PTFE COATING**

Textile membranes are also manufactured by dip coating glass fabrics with a PTFE dispersion. Drying and sintering at 350 – 380 °C finish the coating process (Fig. 9.6).

PTFE is a unique polymer with outstanding properties, which cannot be achieved by most other polymers. These remarkable properties are closely related to the molecular structure characterised by long chain molecules consisting of recurring tetrafluorothy-
I 228 I

MATERIAL PROPERTIES AND TESTING

I 228 I

Monomer units. The carbon-fluorine compound has a dissociation energy of 460 kJ/Mol and represents one of the strongest bonds in organic chemistry. The PTFE chain adopts a slightly twisting helix with a carbon-based core and an outer sheath of fluorine atoms, which completely shields the chain backbone from chemical attack.

Since PTFE’s upper limit of continuous service temperature is +260 °C it can be used in hot climatic zones. The lower limit of the continuous service temperature is -200 °C. Temperature variations have no influence on the lifespan. Plasticizers are not necessary for flexibility and impact strength at low temperatures. PTFE has a low thermal conductivity (0.25 – 0.50 W/Km) and good insulating properties.

PTFE is under normal conditions inflammable. Only if the environment contains more than 95% oxygen will PTFE fail to resist fire. PTFE membranes pass many international flammability tests with excellent results: ASTM E84, ASTM E108, NFPA 701 (US), BS 476 Part 3, Part 5, Part 6, Part 7 (GB), NF P 92-503 M1 (F), DIN 4102 B1/A2 (D). PTFE has a high melt viscosity (10¹⁰ Pa.s), which prevents the forming of droplets of molten coating during a fire.

PTFE is resistant against the strongest corrosive substances, like hydrochloric acid, hydrofluoric acid, sulphuric acid and nitric acid, hot sodium hydroxide solution, hydrazine or nitrogen oxides. PTFE is not soluble in most common solvents, such as alcohols, esters, ketones and petrol. Therefore the PTFE membranes are inert against all environmental pollutants such as industrial and traffic exhaust gases.

The molecules are macroscopically nonpolar. Its surface energy is one of the lowest known (approx. 18.5 mN/m) and leads to the anti-adhesive nature of PTFE. Therefore the PTFE membranes do exhibit good self-cleaning and water repellent properties.

Because of its hydrophobic properties, PTFE is an excellent protection for the textile reinforcement of the membrane, since glass filaments lose their tensile strength in contact with humidity.

PTFE is totally resistant to UV and IR-radiation. PTFE membranes show no ageing or embrittlement due to UV/IR-radiation. Unlike PVC this performance is achieved without the need of plasticizers, antioxidants, UV-absorbers etc., which could migrate out.

9.4.5 TOP COAT

Top coats are lacquered in order to ensure good cleanability, good slip, and processing, and they offer an efficient barrier for plasticiser migration and weather influences. Most liquid lacquer systems for PVC coated polyester fabrics are made out of acrylcs, PVDF/acrylic mixtures, PVDF (polyvinylidene fluoride).

PVF (polyvinyl fluoride) films can also be used and provide a good resistance and the lowest erosion during ageing9. Fluoropolymers have a better resistance to UV than acrylcs.

Attention should be given to the fact that one always has to make compromises between, for example, optimised weldability, optimised weathering resistance and aesthetic performance.
For PTFE coated glass fabrics the top coat consists of FEP (fluoroethylene-propylene copolymer) to enhance waterproofness, fungal resistance and weldability due to a lower softening point of FEP than PTFE.

9.4.6 SILICONE COATING

Silicone coating is based on silicone rubbers which are obtained by cross-linking during processing, of silicone macromolecules:

\[
\begin{array}{c}
\text{R} \\
\text{Si} \\
\text{O} \\
\text{R}' \\
\end{array}
\]

Different formulations of silicone, combined with different coating processes, allow the production of materials adapted to different uses. Basically, silicone rubbers combine elasticity and mechanical resistance in a wide range of temperature [-50°C to +200°C] even aggressive atmosphere conditions.

Despite a lot of advantages, such as ease of handling, when compared to PTFE coated fabrics the dirt collection and “seamability” of silicone coated fabrics have been limiting factors. However recently developed surface treatments are helping to counterbalance these defects.

9.5 Coated Fabrics

9.5.1 DATA SHEET WITH COMMONLY USED STANDARDS

The producers of coated fabrics have datasheets describing the main characteristics and properties of their products. Typically the datasheet will give:

a) Characteristics of the base fabric and yarn: material, weight, weave construction, yarn count
b) Characteristics of the coating and top coats: material, weight, total thickness and top fabric – coated surface thickness
c) Characteristics of the coated fabric: weight, thickness, available width, colour
d) Mechanical characteristics of the coated fabric: tensile strength in warp and weft direction, trapezoidal tear, coating adhesion
e) Other important properties of coated fabrics: behaviour in fire, light transmission.

All these characteristics are evaluated following International (ISO) or European Standards (EN) if they are existing. If not, national standards are used like NF, DIN, BS, ASTM. The standards are listed in Appendix A3.3.

More detailed properties, such as biaxial stress strain curves, can be obtained from the producers.
9.5.2 CLASSIFICATION OF MATERIALS

A number of manufacturers produce a range of different strength grades for both PVC/PES and PTFE/glass materials. For PVC coated polyester fabrics, the working group for architecture at Messe Frankfurt1 and a French design guide3 have each proposed a classification of five distinct types following the main characteristics as described in Table 2. The main parameters classifying the materials are the tensile strength and the composition of the coated fabrics.

<table>
<thead>
<tr>
<th>Type</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface weight (g/m²)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>French design guide</td>
<td>720</td>
<td>1 000</td>
<td>1 200</td>
<td>1 400</td>
<td>2 000</td>
</tr>
<tr>
<td>WG Messe Frankfurt</td>
<td>800</td>
<td>900</td>
<td>1 050</td>
<td>1 300</td>
<td>1 450</td>
</tr>
<tr>
<td>Yarn linear density (dtex)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>French design guide</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WG Messe Frankfurt</td>
<td>1 100</td>
<td>1 100</td>
<td>1 670</td>
<td>1 670</td>
<td>2 200</td>
</tr>
<tr>
<td>Tensile strength warp/weft (kN/m)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>French design guide</td>
<td>60/60</td>
<td>84/80</td>
<td>110/104</td>
<td>120/130</td>
<td>160/170</td>
</tr>
<tr>
<td>WG Messe Frankfurt</td>
<td>60/60</td>
<td>88/79</td>
<td>115/102</td>
<td>149/128</td>
<td>196/166</td>
</tr>
<tr>
<td>Trapezoidal test warp/weft (N)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>French design guide</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WG Messe Frankfurt</td>
<td>310/350</td>
<td>520/580</td>
<td>800/950</td>
<td>1 100/1 400</td>
<td>1 600/1 800</td>
</tr>
<tr>
<td>Yarn number per cm warp/weft</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>French design guide</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WG Messe Frankfurt</td>
<td>9/9</td>
<td>12/12</td>
<td>10.5/10.5</td>
<td>14/14</td>
<td>14/14</td>
</tr>
</tbody>
</table>

Table 2 Classification of membranes: PVC coated polyester fabrics

For PTFE coated glass fabrics, the situation is different. By analogy with Table 2 a classification for PTFE coated glass fabrics into seven different types is shown in Table 3. A comparison is therefore possible between type 1 to 5 and type G3 to G7 referring to these two classifications.

<table>
<thead>
<tr>
<th>Type</th>
<th>G1</th>
<th>G2</th>
<th>G3</th>
<th>G4</th>
<th>G5</th>
<th>G6</th>
<th>G7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile strenght warp/weft (kN/m)</td>
<td>262/22</td>
<td>43/28</td>
<td>70/70</td>
<td>90/72</td>
<td>124/100</td>
<td>140/120</td>
<td>170/158</td>
</tr>
<tr>
<td>Filament diameter (micrometer)</td>
<td>9</td>
<td>6</td>
<td>6</td>
<td>3</td>
<td>3 or 6</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Surface weight (g/m²)</td>
<td>500</td>
<td>420</td>
<td>800</td>
<td>1 000</td>
<td>1 200</td>
<td>1 500</td>
<td>1 600</td>
</tr>
<tr>
<td>Trapezoidal tear warp/weft (N)</td>
<td>300/300</td>
<td>300/300</td>
<td>400/400</td>
<td>450/450</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3 Classification of membranes PTFE coated glass fabrics

General comparative properties of materials for tensile membranes are given in Table 4. Between the two main materials used up to now, PVC coated polyester tends to be used more often than PTFE coated glass fabric. Nevertheless each material has its advantages and disadvantages which need to be considered with respect to the cost and functional parameters of each project.
These differences are related to the nature of the materials: glass filaments have greater strength than polyester ones but lower flexibility due to their lower extension. Thus the folding of glass materials introduces greater difficulty in the handling of fabricated panels. On the other hand the creep/relaxation of polyester is typical of a polymeric material requiring different procedures for tensioning to those of glass.

The nature of the polymers of the coatings accounts for the differences. PTFE and silicone have good chemical durability regarding environmental parameters due to their chemical inertia. PVC has to be formulated with plasticizers to be as soft as needed by the mechanical requirements; that is why the durability has to be controlled by top coats.

“Self cleaning” is better when fluoride components are on the surface of the membranes.

Reaction to fire is also a distinctive parameter between the materials where flame propagation, or smoke toxicity are to be taken into account. The European directive for building construction products 89/106/CEE of 21/12/1988 defines new rules for fire safety requirement (Cf. Appendix A3.4). Euroclasses are not, as yet, mandatory for the materials of tensile membranes, but they could be adopted by the producer and fabricator. New tests of fire reaction have been designated (Cf. Appendix A3.4)

Due to improvements in quality the lifespan of all the materials have increased. Nevertheless glass fabrics offer an advantage over polyester fabrics. The durability of polyester fabrics can now be evaluated by taking into account the level of prestress and the level of pollution where the membrane is sited. More generally the ageing of fabric in service conditions results in a loss of strength by comparison with new fabric.

Beside the two main materials, for some specific applications silicone coated glass fabrics have some opportunities to be developed. Also PTFE coated PTFE fabric has, for instance, a tear resistance superior to the others.

<table>
<thead>
<tr>
<th></th>
<th>PVC coated polyester fabrics</th>
<th>PTFE coated glass fabrics</th>
<th>Silicone coated glass fabrics</th>
<th>PTFE coated PTFE fabrics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile strength warp/weft (kN/m)</td>
<td>115/102</td>
<td>124/100</td>
<td>107/105</td>
<td>84/80</td>
</tr>
<tr>
<td>Fabric weight (g/m²)</td>
<td>1200 (type 3)</td>
<td>1200 (type G5)</td>
<td>1100</td>
<td>930</td>
</tr>
<tr>
<td>Trapezoidal tear warp/weft (N)</td>
<td>800/950</td>
<td>400/400</td>
<td>960/700</td>
<td>925/925</td>
</tr>
<tr>
<td>Visible light transmission (%)</td>
<td>10-15</td>
<td>10-20</td>
<td>&lt; 80</td>
<td>19-38</td>
</tr>
<tr>
<td>Flexibility/crease recovery</td>
<td>high</td>
<td>low</td>
<td>high</td>
<td>high</td>
</tr>
<tr>
<td>Cleaning</td>
<td>easier with top coats</td>
<td>self cleaning</td>
<td>self cleaning</td>
<td>self cleaning</td>
</tr>
<tr>
<td>How to make the seams</td>
<td>by high frequency</td>
<td>thermally</td>
<td>vulcanisation</td>
<td>stitching</td>
</tr>
<tr>
<td>Life span (years)</td>
<td>&gt; 15-20</td>
<td>&gt; 25</td>
<td>&gt; 25</td>
<td></td>
</tr>
<tr>
<td>Cost</td>
<td>low</td>
<td>high</td>
<td>high</td>
<td></td>
</tr>
</tbody>
</table>

Table 4 General comparative properties of materials for tensile membrane
9.6 ETFE Foils

ETFE is a copolymer of ethylene and tetrafluoroethylene, having a melting temperature range of 250-270 °C, a density between 1.73-1.77g/cm³, a LOI (Limit Oxygen Index) of 30% and very good chemical resistance.

ETFE foils have specific advantages such as translucency up to 90%, high absorption of radiation, low absorption of UV and visible light giving associated advantages for use in horticultural green houses.

ETFE membrane has a bilinear elastic isotropic behaviour and its general properties are summarised in Table 5.

<table>
<thead>
<tr>
<th>Thickness (microns)</th>
<th>Weight (g/m²)</th>
<th>Tensile strength L/T (N/mm²) (DIN 53455)</th>
<th>Tensile strain L/T (%)</th>
<th>Tear strength L/T (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>87.5</td>
<td>64/56</td>
<td>450/500</td>
<td>450/450</td>
</tr>
<tr>
<td>80</td>
<td>140</td>
<td>58/54</td>
<td>500/600</td>
<td>450/550</td>
</tr>
<tr>
<td>100</td>
<td>175</td>
<td>58/57</td>
<td>550/600</td>
<td>430/440</td>
</tr>
<tr>
<td>150</td>
<td>262.5</td>
<td>58/57</td>
<td>600/650</td>
<td>450/430</td>
</tr>
<tr>
<td>200</td>
<td>350</td>
<td>52/52</td>
<td>600/600</td>
<td>430/430</td>
</tr>
<tr>
<td>250</td>
<td>437.5</td>
<td>46/40</td>
<td>700/700</td>
<td>730/730</td>
</tr>
</tbody>
</table>

Table 5 ETFE foils properties
L/T (Longitudinal/Transversal direction)

9.7 Mechanical Characteristics of Coated Fabrics

9.7.1 Introduction

How can a curved surface be created from a flat one, and what are the material properties required for this to happen?

A material’s shear stiffness plays an important role in the manufacture of a curved surface, and so this parameter needs to be as low as possible. Whilst uncoated fabrics have a negligible shear stiffness they lack in durability, whereas coated ones have a relatively low shear stiffness in contrast to their stiffness in the yarn direction. It is therefore reasonable to say that a coated fabric is suitable for manufacturing a curved surface.

The first task therefore is to determine the shear stiffness of the coated fabric. For this purpose a mathematical-physical interpolation is needed to be able to define “shear stiffness” in a meaningful way.
9.7.2 DEFINITION OF MODULI

Stiffness depend on the relationship between the stress tensor and the strain tensor. Starting with the simplest case, a linear relationship between the two variables can be postulated. The stresses can be mathematically described as a second stage tensor \( \sigma_{ab} \), and the extensions can be described in the same way as \( \varepsilon_{ab} \). A linear relationship between two second stage tensors is given by means of a fourth stage tensor \( E_{abcd} \):

\[
\sigma_{ab} = E_{abcd} \varepsilon_{cd}
\]

This relationship however must be subject to certain invariancy conditions for the relationship to be physically meaningful. Because of the two primary directions – warp and weft – coated fabrics have a symmetrical structure. Fig. 9.7 shows a circular element cut out of the material. The two primary directions are identified by two lines crossing one another. Now by applying tension along the horizontal axis the deformation figure is in the form of the ellipse (a) as shown in Fig. 9.7. By rotating the original circle through an arbitrary angle, and again applying the same state of tension parallel with the principal axis, the resulting ellipse (b) differs from the first since the position of the warp and weft has specified a structure. (In the case of an isotropic material the deformation figures will be identical).

Assume now that the material is anisotropic. Anisotropy is described by the symmetry group of the material. The rotations of the starting circle, under which were obtained the same deformation figure, are called the symmetry group. The symmetry group can be stated very simply: it consists of all rotations of 180 degrees. Other rotations do not give the same deformation figure. The situation is shown in Fig. 9.8. The cross at the top shows the original system, the lower one shows the rotated systems which cannot be differentiated from it. When the coordinate system is parallel with the axis in the upper circle, the figures in the lower system can be described in the following way: together with the unit figure these movements form an orthogonal anisotropic group. In the transformation matrices of the orthogonal anisotropic group only +1 and -1 appear as components which deviate from zero.

The components of the stress tensor transform themselves according to the following rule, where \( T_{ab} \) are the components of the transformation matrix:

\[
\sigma_{ab} = T_{am} T_{bn} \sigma_{mn}
\]

Those of the strain tensor follow a similar rule.
At most they change their prefix and always in the same way. The corresponding 4th stage elasticity tensor must thereby not change under the movements of the group. It transforms according to the rule that all components having an unequal number of ones and twos in their indices, change their prefixes. However because they must not change for reasons of symmetry they must have the value of zero. The components which thus differ from zero are only:

\[ E_{1111}, \quad E_{2222}, \quad E_{1122} = E_{2211}, \quad E_{1212} = E_{2121} = E_{1221} = E_{2112}. \]

The equal signs given originate from the fact that both stress tensor \( \sigma_{ab} \) as well as strain tensor \( \varepsilon_{ab} \) are symmetrical. One can also write:

\[
\begin{align*}
\sigma_{11} &= E_{1111} \varepsilon_{11} + E_{1122} \varepsilon_{22}, \\
\sigma_{22} &= E_{1122} \varepsilon_{11} + E_{2222} \varepsilon_{22}, \\
\sigma_{12} &= 2 E_{1212} \varepsilon_{12},
\end{align*}
\]

\( E_{1111} \) is the stiffness in the warp direction, \( E_{2222} \) is the stiffness in the weft direction, \( E_{1122} \) describes the transverse extension, \( E_{1212} \) is the shear module.

If the behaviour of the fabric is non-linear, then these considerations are valid for the tangential stiffness tensor.

### 9.7.3 Comments on the Calculating of Stress Distribution in Membranes

In connection with the formulation of the elastic modulus it is useful to return to a widespread assumption, namely that the transverse extension modulus \( E_{1122} \) and the shear modulus don’t have a significant influence on the stress distribution in prestressed membranes made of coated fabrics. Whilst this is true in many cases there are exceptional cases where neglecting the corresponding variables can have serious consequences. To explain this, the stress distribution is shown with and without the corresponding values in a hyperboloid having fixed straight edges. See Figs. 9.9, 9.10.

In Fig. 9.10.a the stress distribution is shown in the hyperboloid under a snow load without taking account of \( E_{1122} \) and \( E_{1212} \). The crossings of the main stresses are shown and a uniform distribution can be seen.
In Fig. 9.10.b the same snow load is applied and the stress distribution is shown taking account of $E_{1122}$ and $E_{2212}$. In the main field it is difficult to see any difference from the top picture. However in two of the corners an increase in the stress can be seen transverse to the direction of the principal stress. It should be noted here that most of the cases of failure known to the author have started in such gussets. Thus if a minor inaccuracy is made in the cutting out process, and if it is then insensitively assembled, it is easy to exceed the fracture stress.

9.7.4 Biaxial Test to Determine the Shear Stiffness $E_{1212}$

Biaxial tests cause a deformation as shown in Fig. 9.11. This deformation cannot however be reproduced simply since it is difficult to apply shearing forces.

It is necessary therefore to approach the problem differently if the twin axis testing device shown below is to be used: A sample is cut, in which the warp or the weft is orientated at, for example, 45 degrees to the boundary. The tensions are $n_{11}$ in the direction along one boundary and $n_{22}$ in the direction perpendicular to this. This gives stresses in warp and weft of:

$$n_{11} = E_{1111} \varepsilon_{11} + E_{1122} \varepsilon_{22} \quad n_{22} = E_{1122} \varepsilon_{11} + E_{2222} \varepsilon_{22}$$

Thus there are shear stresses in the coordinate system of the main anisotropic direction if the stresses parallel with the boundaries are not the same. The corresponding shear deformations must also be measured. To do this the deformations parallel with the warp direction are first measured and then those parallel with the weft direction and those at 45 degrees to the warp and weft. Thus the components of the strain tensor are given as:

$$\varepsilon_\beta = \begin{bmatrix} \varepsilon_{11} & \frac{1}{2} \varepsilon_{11} - \frac{1}{2} \varepsilon_{22} \\ \frac{1}{2} \varepsilon_{11} - \frac{1}{2} \varepsilon_{22} & \varepsilon_{22} \end{bmatrix}$$
When this test is performed the following can be observed. Initially the resistance to shear deformation is low. It is possible to push the material virtually at random. If the shear stress is increased however the shear deformation no longer increases, the resistance is greater. This behaviour is shown in Fig. 9.12.

The reason for this is that as long as the warp and weft yarns do not obstruct each other the resistance to lateral displacement is only provided by the coating. This goes on until the warp and weft yarns mutually jam together. At this point the resistance to further pushing increases dramatically. This is called a “jamming condition”. The critical angle, where the resistance starts, limits the spacing of the yarns for a prescribed curvature.

9.7.5 STRENGTH

The strength of the coated fabric is exclusively determined by the strength of the yarns. What is of prime importance here is not the strength of an individual yarn but that of a unit width of the fabric. During the processes of weaving and coating the yarns experience a reduction in strength which interests the manufacturer and coater of the material. The reason for this is that he can find out how protective for the individual yarn are his weaving and coating processes. The end user however is only interested in the strength which the end product demonstrates.
However the strength of the coated fabric is less than that of the individual yarn strength multiplied by the number of yarns per unit width. The explanation for this is that each yarn is deflected at each crossover point by a force applied to it by the yarn crossing it. Such deflection reduces the yarn's strength, since in addition to the axial force a bending moment has also been applied which combined together reduce the strength of the yarns in both directions. This effect does not exist with the weft-inserted fabrics.

Here it should also be noted that warp and weft threads can have different properties.

9.7.6 BIAXIAL STRESS-STRAIN BEHAVIOUR IN A SHORT-TERM TEST

The next item of interest is how the material stretches when it is loaded. This property is described by:

a) stiffness in the warp direction
b) stiffness in the weft direction
c) transverse extension
d) shear stiffness

These properties are of interest to the structural engineer since their values have a significant input into the calculation of membrane stresses. As will be shown later the biaxial behaviour can be described well in a numerical model using experimental measurement of the free parameters. The solution to the description of the short-term behaviour can be found by such means. For this purpose knowledge of the stiffness of the warp and weft yarns is needed. It is also essential to understand clearly that the numerical values of the moduli produced by this approach are not constant but depend on the force applied and the loading history.
9.7.7 TEAR PROPAGATION

A further task is the determination of the tear propagation behaviour of a coated fabric. The method forming the basis of most European "norms" and shown in Fig. 9.14, uses a trapezium shaped sample containing an initial slit running out the shorter of the two free edges.

Figure 9.15 shows clearly the fixing of the sample in the jaws of the testing machine as well as the change in shape of the sample under uniaxial loading.

A more representative test for tear propagation within membrane structures is shown in Fig. 9.16 where a test piece containing an initial "slit" is put under biaxial load. The resulting deformations have been made more visible by means of the Moiré fringe technique. It can be seen that the initial "slit" has extended into the shape of an ellipse.
The force which originally passed directly through this zone before the tear existed, has now been “led around the tear”, and the deformations that have occurred for this purpose are clearly visible. This is in contrast with the behaviour of the trapezoidal sample where the force could not be “led around the tear”. Therefore the trapezoidal sample only measures how individual threads each take up force at the root of the tear as a result of their deformation.

It can also be seen from Fig. 9.16 that the force diverted around the tear only influences a narrow strip. This provides the opportunity to design a corresponding sample strip displaying the characteristics of tear propagation in a uniaxial test. The corresponding deformation shown in Fig. 9.17, shows a progression which can be compared with a corresponding strip cut out of the biaxial sample in Fig. 9.16.

After consideration of such samples the question arises as to what actually should be measured in a tear propagation test.

A tear propagates according to the laws of thermodynamics if the energy used for the creation of a new surface is smaller than the deformation energy which was released in the tear propagation. Therefore it is reasonable to assume that in the case of the extension of an initial tear the energy stored in the distortion field is smaller, but for the creation of a new surface energy is consumed. The latter can be referred to as energy of the free surface.

At first sight it’s not clear how a material’s propensity for tearing can be included in an engineering specification. The question can be most simply answered by assuming that there is already a tear of known length in the membrane. The question now is whether this tear would extend further if field stresses increase as a result of an increase in externally applied load or whether it remains stable. However the length of the starting tear (also referred to as “the critical tear” length) needs to be specified.
9.7.8 LONG TERM BEHAVIOUR, RESIDUAL STRENGTHS AND BEHAVIOUR UNDER TEMPERATURE CHANGES

Following on from the above it is clear that the long term properties of the fabric are determined by the long term behaviour of the yarns and their geometry within the fabric. The exception to this is a starting phase in which the contact geometry between warp and weft is established. For the long-term behaviour it is necessary to take note that creep, relaxation, and temperature play a significant role. In the case of polyester yarns it is possible to save time by means of increased temperature within certain limits.

It should also be noted that strength reduces following long term loading. The so-called "residual strength" is therefore lower than the "short-term strength". This depends on the duration and size of the load. The residual strengths at the end of the planned service life limit the permitted operating tension in prestressed membranes. Durability of PVC coated polyester fabric could be estimated by taking into account the level of pollution and the initial pretensioning (see the Baegert expression²).

9.7.9 CREEP BEHAVIOUR AND RESIDUAL STRENGTHS

The creep behaviour and residual strengths of yarns or the fabric need to be determined.

9.7.10 RELAXATION BEHAVIOUR

With certain boundary conditions it may not be the creep values but the relaxation values which are decisive for long-term behaviour.
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