Performance characteristics and practical applications of common building polymeric materials for building envelope

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Abstract
The urgent need to reduce the energy used in the heating, cooling and lighting of buildings has brought about significant changes in the way buildings are designed and built. Because buildings encompass complex interactions between different requirements and subsystems, care must be taken when changes are made to any one aspect of building performance to ensure that this does not have a detrimental effect on other building functions. Obviously one of the great potential impacts building performance is the building skin. Over the time textile architecture has become increasingly popular; fabrics and foils are more and more used as skins for permanent and enclosed buildings. There is an ongoing method, though, employing flexible and intelligent fabric materials and the force of tension applied on building skins. Buildings with polymeric materials have attracted considerable attention due to excellent material properties, good architectural performance and structural behavior in comparison with other materials. This paper has been based on much research surrounding the topic of membrane materials within architectural design. The aim of this study is to identify typical and essential features of plastic materials in order to decrease the rate of energy consumption. To achieve goal, this paper review and compares available theoretical, experimental and numerical studies on materials properties of polymeric materials, architectural performance and structural behaviors. The achievements and gaps of the use of materials for public buildings are summarized and concluded. Moreover reasonable recommendations on performance enhancement of building are made for future study.

Keywords: Polymeric, Membrane, Materials, Roof application, new construction technologies.

1. Introduction

Over the last few decades, more and more attempts have been made to create building that is becoming an increasingly complex task, due to a growing demand to satisfy more ambitious environmental, societal and economical performance requirements. Lightweight constructions, for example those made of textiles, can met most modern- day requirements.

Lightweight construction represents one of the greatest opportunities and prospective growth areas for the building sector. It is used to describe methods for increasing economic efficiently, which can reduce the weight of building construction together with costs and work time by the use of particular building materials, methods and structural forms.

Today the range of applications for membrane constructions extend from the simple camping tent for short- term residential use, temporary or durable shelters, cultural and sport center.

Before the advent of the 20th century, buildings and the building process were shaped by local social systems, living arrangements and modes of working on the one hand, and by locally available materials and construction methods on the other. During the 20th century, with globalization progressing apace, local traditions increasingly took a back seat. In the late 1980s, a somewhat diverging tendency could be observed in central Europe where it became of more and more significance that façades don’t just have to “look good”. More than that the building skin is mainly relevant for the building`s fitness for purpose and durability, as well as for protecting people and property. The acceptance of advanced concepts is closely linked to the quality of comfort, as well as the wellbeing of people (**G**. Phol, & B. Baier, **2010).**

2. Literature Review: history of membrane development and materials used for construction

Since the moment of existence, human beings have always been inclined to cover his body in fabrics, to surround the vacancy in a physical environment. In this way, human beings began to add the circumference space into his living space for the first time, distinguished between the interiors and exteriors, and used clothing as a dividing element. They are a mixture of the nature, that is to say, composed of clothing, animal hides, wool woven articles and dried plants that provide softness and insulation (Acim, M., 2010; Drew, P., 2008).

Table 1, history of membrane development and materials used for construction

Type	Location	Application
Bedu	Arabic	military tents, sultan's tents,local marketplaces
Yurd tents	Central Asia Turks	living and military
	to Europe	
Teflon Coated, glass-fibrous clothing	Cambridge Schlumberger Research Centre	
Plastic Film		
air-supported systems	American pavilion	Osaka Exhibition
Inflatable Systems		

The high quality and durability of today's membrane building materials enable the construction of covered surfaces or free spans in orders of magnitude which are limited in practice only by the construction costs. Constructional membranes can create structures which are hard t achieve with other building methods (Drew, P. 2008).

3. Fibres

Figure 1, categories fibers according to their origins.

3.1 Fibers from natural polymers

The most common polymer fiber from natural sources is viscose, which is made from cellulose fibers obtained from wood [G. Phol, 2010].

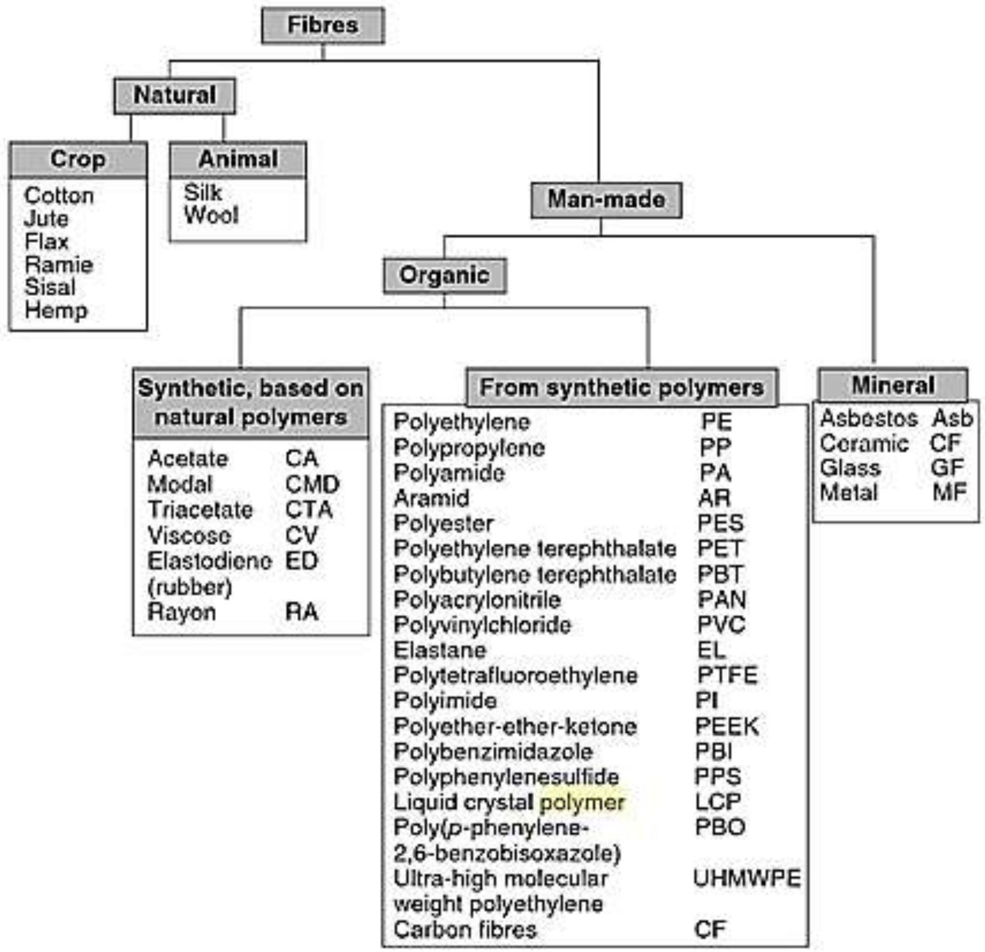

Figure1. Categories of fiber materials

3.2 Fibers from synthetic polymers

Many synthetic fibers are available such as organic fibers based on petrochemicals. The most common of these are polyester, polyamide, acrylic, high performance fibers like glass, carbon, aramid (**G. Phol, 2010**).

4. Types of Membranes technology Used in Architecture

Textile formation processes offer different means of creating products from fibers. Each procedure has its own special advantages and individual price (Hearle, J.W.S, 2002).

Table 2. Overview of textile formation technology and its features.

Features / **Materials**	Elongation	Flexible	Strength	Elasticity	Shape retention	Recovery from bending	Superior vapor transmission	Outdoor App.	Indoor App	Load carrying structure
Woven fabrics	□	□	■	□	□	□	□	■	□	□
Flat knitting, weft knitting and warp knitting	■	■	□	■	■	■	■	□	■	■

□ Low

■ High

Woven fabrics(Fig.3, Fig, 4) which are heavier in weight usually applied in outdoor application due to their high strength. Moreover, weaving pattern and fabric density define translucency, watertightness and sound damping. In contrast to the low strength and high elongation of standard knitted fabrics it is allowed to the use of these fabrics in load-carrying structural application (**G. Phol, 2010**).

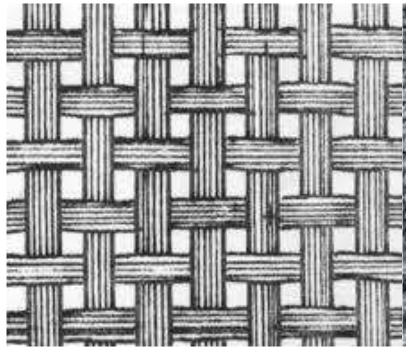
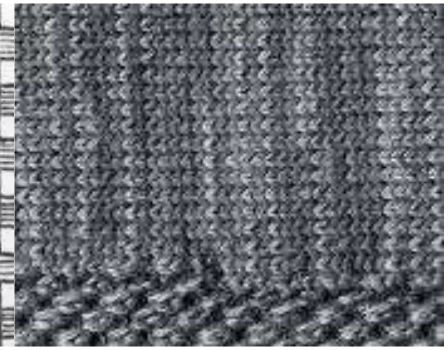

Fig. 3 Woven fabric Fig. 4 knitted fabric

5. fabric membrane materials for building applications

The term membrane derived from the Latin world membrane (= skin). It describe the flexible material that is very thin relative to its surface area. In biology this term stands for a thin layer of skin.

The products used for membranes has divided into two main groups: anisotropic materials and those that approximate an isotropic state. (Kaltenbach, 2004). Coating fabric membrane material is a type of composite material and is generally composed of a substrate, coating and surface course, shown in Figure 5, substrate is weaved through various textile fibers which determine the properties and structural mechanics of the membrane (Tian, 2011; Kaltenbach, 2004; Knippers, Cremers, Gabler, Lienhard, 2011).

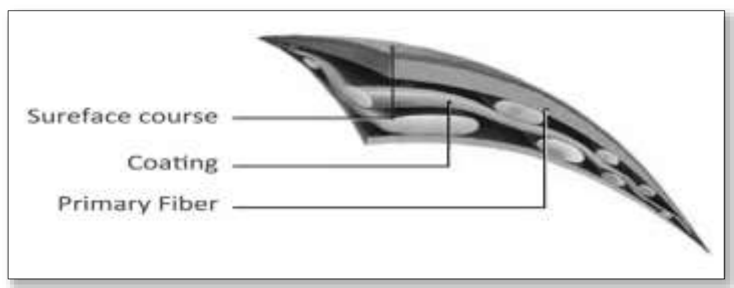

Figure 5, membrane materials layers

5.1 Foils for building

Thermal polymerization compounds membrane materials the term foil should be reserved for very thin metals. However, it has become appointed in the building industry for a homogeneous polymer material that is very thin due to its surface area (Knippers, Cremers, Gabler, Lienhard, 2011). Foil used in construction must satisfy demanding specifications regarding strength, weather resistance, UVstability, surface quality properties because they have to transmit a load in architectural application. Design utilizing foil materials established pneumatically with a pressure below atmospheric pressure. However this type of application must be considered very carefully when using foil because unfiltered air, dust and dirt could be stocked in which ruin the optical quality and the appearance (**G. Phol, 2010 &** Knippers, Cremers, Gabler, Lienhard, 2011; B. Baier,2010).

Table 3. Synthetic foil materials behaviors

Feature / Foils	Stability	Tensile strength	Thickness	Weight	span	Affected by Environment	Self cleaning ability	Transparency
PVC	√	√						Very high
ETFE	√√√	√	0.1mm to 0.25mm	√	Bigger span length than glass; 20-50m^2	×	Better than glass	Better than glass
THV		√				×	Poor	
PTFE			1μm up to >100 μm			×		

Foil made from ethylene tetrafluoroethylene (ETFE) is the only foils that can be used in outdoor application due to its highly stability. Foils which are not heavy in their weight can cover large area. Consequently their span length is expected to be high.

If a micro-perforation is applied to the foils, they will offer very good acoustics absorption like ETFE and PC. The further advantages is low thermal load in terms of fire. Like ETFE, polycarbonate is also flame retardant, (Knippers, Cremers, Gabler, Lienhard, 2011; Pohl, 2010; **Rudorf-witrin, 2006**).

5.2 Coated fabrics, Coating for building

A large variety of desirable properties for membranes may be provided by the fibers themselves or by their finishing and post-treatment before the production of the fabric. If these do not provide the required properties such as watertightness, dirt and oil repellence, UV protection, flame resistance, the fabric must be coated or laminated. Coating may consist of one to three layers, depending on cost and quality. High quality coatings have a base or tie coat, an intermediate or filler coat, and finally a top coat. The base coat ensures enough adhesion to the textile materials. Intermediate coat is responsible for the system volume and mechanical characteristics. Top coat determines the appearance and surface properties (see Fig, 6). Where the coating, itself does not provide all the desired properties, top coats or top finishes, will be applied as a final environmental barrier, providing UV stability, durability, self-cleaning features (B. Baier, 2010).

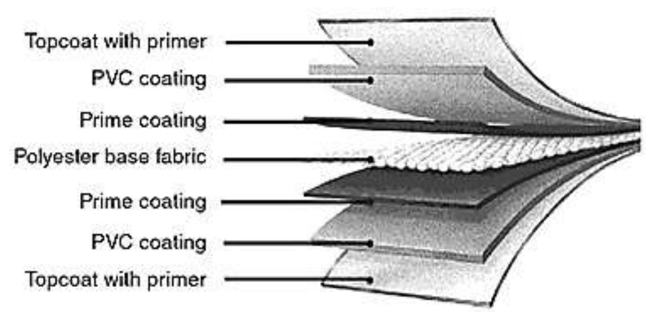

Figure6, Typical section of PVC- coated polyester fabric with topcoat

5.3 Combined materials to form composite elements

In many cases, the desired properties of a buildtech textile can only be achieved through combining a fabric having high tensile strenght with a coating. Nowadays, most of the membrane structure have been constructed by just two material combination; PTFE- coated glass fabric, PVC-coated polyester and ETFE foil. In the table 3 , the most important and practical composite materials are analyzed in detail (B. Baier, 2010; G. Phol, 2010).

Table 4, Properties of composite elements

	Tensile strength	Length	Weight	UV protection	Price	Life span	Self-cleaning	Translucency
PVC coated polyester	2000N to 10000N	5cm	0.6kg/m^2 1.7kg//m^2	With additional PVE topcoat	√	15years		
PTFE-coated glass	1000N to 8000N	5cm	0.4kg/m^2 1.6kg/m^2		√√	30 years	√√	Up to 25% adjusted by weight-Low-e properties
PTFE-coated high tensile PTFE	4000N	5cm		√	√√√		√√	Good
THV coated ETFE and PTFE	Highly durable	-	-	Highly stable	-	30 years	Poor	Very high

√ good **√√ very good** **√√√ excellent**

PVC coated aramid, THV coated ETFE and PTFE, PUR coated light polyester and Silicon coated glass are among the other composite materials in which THV coated ETFE and PTFE and Silicon coated glass have excellent translucency in comparison whit PVC coated polyester, PTFE-coated glass and PTFE-coated glass.

6.5 The application of PV in foil and membrane structures

As renewable energy becomes a global priority, solar power is an increasingly viable solution to the world's energy demand issues, generating sustainable power from a source readily available to everyone. As the industry moves forward, manufacturers are suddenly faced with a growing number of choices when it comes to photovoltaic (PV) module products (Pohl,2010). A layer of photovoltaic solar cells is laminated to a base of flexible roofing material, which roofing material is commonly termed a membrane. These solar cells, after lamination, are further encapsulated and sealed in a flexible intermediate layer of solar radiation transparent plastic, which in turn is protected by a cover layer of weather-proof solar radiation transparent plastic. The size and shape of the solar cells, and the pattern in which they are laminated to the roofing material base, is arranged in a manner which allows continued flexibility of the roofing material after the said lamination takes place. Examples of roofing materials to which solar cells are or may be laminated, include reinforced flexible thermoplastic sheet, modified bituminous sheet, and vulcanized or non-vulcanized elastomeric sheet. One recent product innovation is ethylene-tetrafluoroethylene (ETFE) films for PV module components.In the field of photovoltaics, white and black Fluon® ETFE FILM is used in the manufacture of backsheets. Transparent ETFE film is also used in frontsheets (Figure 14).

For many reasons the integration of photovoltaics in buildings (Building Integrated Photovoltaic - BIPV) offers a lot of future potential (**Stegimaier, T**. 2.004) Benefits mostly reported are amongst others:

- The PV does not require an additional sub-structure as it is an integrated part of the building envelope.
- From an aesthetical point of view, an integrated solution offers far more potential than any add-on application.
- The PV does not only provide electricity - in an appropriate application in transparent or translucent parts it might also provide necessary shading which reduces the solar heat gains in the building and thereby helps to minimize cooling-loads and energy

demand in summer. This synergy effect is of most importance because it principally helps to reduce the so-called balance of system (BOS) cost for the PV application (Stegimaier, T.2004).

In a report the International Energy Agency (IEA) gives an estimation of the BIPV potential of 23 billion square meters. This would be equivalent to approx. 1000 GWp at a low average efficiency of 5%. [2]

Figure 7, The PVC-PV tensile structure pavilion in the exhibition 'Under the Sun' for The Cooper Hewitt / National Design Museum (US) in 1998

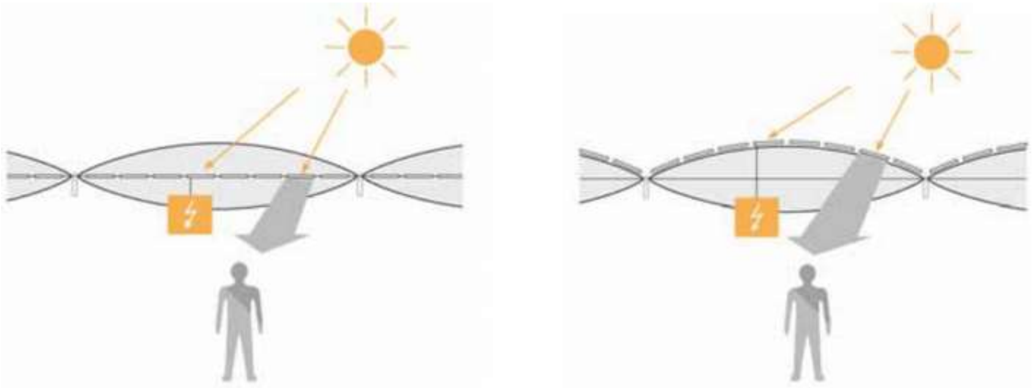

Figure 8: Principles of PV integration on pneumatic foil constructions - application on themiddle layer (left) or on the top layer (right).

Figure 9: The image on the right shows a photomontage of flexible PV integrated in a large scale membrane structure (here the Gottlieb-Daimler-Stadium in Stuttgart, Germany).

6. Discussion and Comparision of Membrane Materials

In this part various aspect of membrane materials were collected in Table 3, this properties included mechanical, aesthetic, energy efficiency and physical aspect etc.

Table 5 . Application of different membrane materials

Materials	**Applications**
Polyester	most used fiber due to reduced price, good mechanical performance and the expected lifespan - very common for temporary and seasonal structures
Polyethylene	used for low-budget applications, shorter life span compared to polyester, fire behaviour and the resistance to UV rays can be improved
Fiberglass	used for permanent heavy duty applications, high modulus of elasticity, high tensile strength, intrinsic high resistance to fire and UV degradation, quite brittle, crack easily.
Expanded PTFE	relatively new and commonly used for seasonal and deployable structures, high translucency, strength, flexibility, long life-span, high chemical resistance and very good soiling behaviour. high costs
Nylon	projects and products which require lightweight and stretchable fabrics with relatively low mechanical properties, used for small temporary and deployable structures both for indoor and outdoor applications.
Aramids	popular for nautical applications , extremely high modulus of elasticity and breaking strength, non-combustible, relative high price.
Acrylic	used for furnishing fabric, e reduced mechanical performance, good flexibility and good resistance to oils, chemicals and sunlight.
Polyurethane	used for indoor applications which require exceptional elasticity. low price and reduced risk of wrinkles, not suitable for wind and snow loads.
Cotton	relatively high elasticity and a high vulnerability to microbial attack and the consequent biological degradation
PVC	the most used coating for architectural fabrics. Fire resistance, expected lifespan(combined with adequate topcoats a life span of more than 20 years) , the self-cleaning, colour stability, low cost, the easy weld ability (high frequency, hot air) and the range of colours available, easily painted, nonstick surface, resistant to UV rays
Fluoropolymer Coatings	e higher price, the most common material, high resistance to UV radiation and to chemical and biological corrosion.
Silicone	Combined with woven glass fabrics, high flexibility, light transmission, excellent flame resistance and UV, cost effective, most environmentally sustainable coating, pick up airborne particles and dirt
Polyurethane	high cost and the progressive yellowing, used as as biogas plants and flexible tanks, easy to weld, used for pneumatic structures such as inflatable tents and boats.
Polyethylene	quite wide range of colours, high translucency
Synthetic Rubbers	high quality inflatables for heavy duty applications such as boats and tents.

Low E Coatings	better thermal performance
PVC-Coated Polyester Fabric	relatively good flex cracking resistance, e light transmittance, the resistance to soiling and the long-term stability, environmental impacts, recycling g the coated fabric.
THV-Coated Polyester Fabric	weathering resistance, self-cleaning properties, light transmittance and UV resistance
Silicone-Coated Glass-Fibre Fabric	susceptible to wrinkling, excellent light transmittance, flex cracking performance and resistance against chemical attack and UV radiation, not become brittle, high cost
Coated and Uncoated PTFE Fabric	extremely high flex cracking resistance, light transmission, long-term stability and resistance to soiling, used for convertible structures, high price,
	extreme flexibility and light transmittance, low mechanical performance used for small projects, easy to weld and good level of airtightness, used for pneumatic products.
Open Mesh Fabrics	Open mesh fabrics are the result of increasing use of permeable textile for the solar control. They are made by the same fibres and coating used for coated fabrics but they are designed with a specific level of permeability to light, wind and rain.
ETFE Foil	most stable chemical compounds, very good long-term stability, resistance to soiling and high light transmittance, good mechanical strength, extremely poor mechanical resistance, long-term stability and resistance to soiling, poor optical properties compared to ETFE, flexible, extremely low cost
PVC Foil	extremely low price, very poor UV and soiling resistance,
PE Foil	good flex cracking resistance and long-term stability, optical properties and resistance to soiling are considerably lower than ETFE , easily welded, lower mechanical and tearing resistance
THV Foil	flexible in cold weather, resistant to abrasion and air tightness, high price, e low elastic modulus (elongation at break up to 800 %, yellowing and the poor performance.

Table 6. General comparative properties of materials for tensile membrane.

	PVC- coated polyester fabrics	**THV- coated polyester fabrics:**	**PTFE- coated glass-fibre fabrics**	**Silicone- coated glass-fibre fabrics**
Applications, special features	Diverse application tions, very cheap standard material	High-quality surface, very high light transmittance	For permanent structures, high quality standard material	For permanent structures, high lighttrtransmittance
Jointing method	High-frequency and impulse welding	High-frequency and impulse welding	Impulse welding with intermediate foil	Vulcanizing (bond-ing)or stitching and gluing (combi-nation seam)
Long-term stability	Good stability with sufficiently thick coating, good chemical resistance	No data available	Very good UV stability, very good chemical resistance	Good UV stability, good chemical resistance
Sensitivity to flex cracking	Highly resistant to flex cracking, suitable for convertible systems	Resists flex cracking, suitable for convertible systems	Highly sensitive to flex cracking, unsuitable for convertible systems	Low sensitivity to flex cracking
Sensitivity to soiling	Vulnerable to soiling, better with top coat, e.g. fluoride lacquer	Good soiling behavior	Very good soiling behavior, self-cleaning	Vulnerable to soiling

	PVC- coated polyester fabrics	**THV- coated polyester fabrics:**	**PTFE- coated glass-fibre fabrics**	**Silicone- coated glass-fibre fabrics**
Light transmittance	5-15%	15-23%	8-20%	25-30%
Environmental impact	PVC degrades and forms chlorine/hydrochloric acid, collect and return network exists: polyester can be reused as short fibres	THV decomposes at high temperatures	Environmentally friend disposal of glass fibers, PTFE does not degrade but decomposes at high temperatures and produces fluorine	Environmentally friend disposal of glass fibers, silicone can be recycled
Reaction to fire(building materials class to DIN 4012)	B1	B1	A2(types 1 and 2) B1(type3 and 4)	B1
Standard colours	White as standard, other colours available	White as standard	White as standard, limited selection of colours	White and silver as standard, other colours

	PVC- coated polyester fabrics	**THV- coated polyester fabrics:**	**PTFE- coated glass-fibre fabrics**	**Silicone- coated glass-fibre fabrics**
Weight per unit area to DIN 55352[gr/m2]	Type 1: 750 Type 2: 900 Type 3: 1100 Type 4: 1300 Type 5: 1450	Type 1: 1150 Type 2: 1200	Type 1: 800 Type 2: 900 Type 3: 1200 Type 4: 1500	Type 0: 200 Type 1: 340 Type 3: 685 Type 4: 1100
Tensile strength(warp/weft) to DIN 53354 [N/50 mm]	Type 1: 3000/3000 Type 2: 4200/4000 Type 3: 5800/5400 Type 4: 7500/6500 Type 5: 10000/9000	Type 1: 3500/3000 Type 2: 5000/4500	Type 1: 3500/3500 Type 2: 5000/5000 Type 3: 7000/6000 Type 4: 8000/7000	Type 0: 2500/1750 Type 1: 3000/3000 Type 3: 5000/5000 Type 4: 8000/8000
Tear propagation resistance To DIN 53363	Type 1: 300/300 Type 2: 500/500 Type 3: 850/800 Type 4: 1200/1200 Type 5: 1800/1800	Type 1: 700/700 Type 2: 600/600	Type 1: 300/300 Type 2: 350/350 Type 3: 500/500 Type 4: 500/500	Type 0: 350/400 Type 1: 300/300 Type 3: 400/400 Type 4: 500/500

	PVC- coated polyester fabrics	THV- coated polyester fabrics:	PTFE- coated glass-fibre fabrics	Silicone- coated glass-fibre fabrics
Service life	15-20	No data available	> 25	> 20
Cost of raw materials	15-45%	60-140%	50-150%	110-180%

7. Conclusion

High-strength, high-modulus membranes are increasingly being used in the building and construction industry as a replacemenr for more traditional mateial, such as wood, concrete, masonry and steel. The mechanical properites of membarne made with aramid, polyester and fiberglass, combined with cross-linking resin systems to form a composite, provide civil engineers with a range of new materials that offer high strength to weight, high stiffness to weight, and extreme flexibility in design and use. Despite fiberglass having a high tensile strength, which is 350 N/mm2, it has very low densitybecause of its fibrous properties. PTFE film alone only has a tensile strength about 30 N/mm2. Yet when combined with the fiberglass, the tensile strength increases to more than 310 N/mm2 according to fiberglass. While it has the lowest hardness value in order to protect it against some dameges like scraching and UV radiation. So in order to increse its chemical properties, it is covered with polyemer such as PVDF. So due to high tensile strength, long-term stubility and chemical resistance PVC (Poly Vinyl Chloride) coated polyester and PTFE(Poly Tetra Fluoro Ethylene)coated fibre-glass applied for external use and can provide the safe aera for people.PTFE- coated glass-fibre fabrics well-known as a best fire resistance materials. Generally membrane fabric materials and construction system in comparsion to conventional materials such as glass (ETFE is 1% the weight of Glass) are so lightweight and flexible. PVC-coated polyester included the higest bending capacity. One of the most significant areas of fabric design is the lighting behavior of membrane-covered spaces. Their proper understanding could result in users comfort, energy reduction and dramatic appearance of membrane structures, which are dependent of features such as the colour of the material, its thickness, type of base and coating materials, general condition of cleanness and damage due to ageing. ETFE film is lightweight and provides excellent light transmittance about 95% of sun light. ETFE maintains transparency and strength for over 30 years. Due to applying TiO2 on top of ETFE It is a kind of material with self-cleaning properties. It is recyclable and decreases energy costs by around 30% when compared to glass, due to its capacity to allow in more natural light and heat retention properties.A single layer of either PVC/polyester or PTFE/glass with a typical weight of around 1200gm/m2 has a UV value of approx 4.5 W/m2K. In this respect it is very similar to glass so that a twin skin with a 200mm air gap will give a U Value of 2.6 W/m2K. Unlike glass or brittle panels fabric is highly resistant to impact damage from blunt objects. Thermal properties of membarne and foil materials are low. By using such nano materials like aerogel and PCM their thermal isulation performance can be improved.The insulation reduces HVAC energy consumption, requirements and costs.

References

1. **Gezer Turgay, H.** (2009). Mekan Örtüsü Tekstil Malzemesi,Maltepe Üniversitesi Yayınları, Turkey, 9789756760369.
2. **G. Phol,** Types and production of textiles used for building and construction, intitute for textile technology and process engineering Denkendorf(ITV), Germany.
3. **Tian, D.** (2011)**.** Membrane Materials and Membrane Structures in Architecture, University of Sheffield, sep 2011.
4. **Knippers, J., and Cremers, J,.andGabler,Ms,.andLienhardJ.** (2011). Construction Manual For Polymers +Membrane, Brikhauser, basel. ISBN-10: 3034607261, October 13, london.
5. **Kaltenbach, F.**(2004). Translucent materials: glass, plastic, metals. Basel, birkhauser, london, spring.
6. **B. Baier,** Technical characteristics and requirements of textiles used for building and construction, university of Duisburg- Essen, Germany , woodhead publishing, 2010.
7. **Stegimaier, T**. high performance and high functional fibers and textiles, ITB international textile bulletin, No.1(2004).
8. **Rudorf-witrin,w** .(2006). ETEF-Foil, The Flexible Glass. An Alternative To Glass Roofs?! Technical University Of Eindhoven, 8-198-8-202.
9. Bessey, P.(2012). Structural Design Of Flexible ETFE Atrium Enclosures Using A Cable-Spring Support System, The Faculty Of Brigham Young University.
10. **Bechthold, M.** (2008). Innovative Surface Structures: Technologies and Applications,Harvard university,Taylor & Francis, March 20, 0415419670.
11. **Beylerian, M.,and Dent, A.**(2007). Ultra Materials: How Materials Innovation Changing the World. Published In United States Of America By Thams& Hudson, New York.

12. **Chiu, Mark.** (2012). Tensiwall- The Case For A Multi-Layered Textile Façade System. *International conference on building envelope design and technology.* 14-15 june
13. **Wallner, G.** (2000). Polymeric Materials For Transparent İnsulation- Application Of Polymer And Modelling , Dissertation, Montanuniveristat Leoben, Austria
14. **Klassen, F.** (2004). Materials İnnovation: Transparent, Lightweight, Malleable & Responsive.Faculty Of İnterior Design. Toronto Ontario CANADA M5B2K3.