**Physical-Mechanical Properties of Technical Textiles: Foundation for Performance Engineering**

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**Abstract.** In this extensive paper, an overview of the basic physical-mechanical properties characterizing the behavior of technical textiles is drawn. Beyond traditional textile metrics, this manuscript,a systematization that explains how mechanical properties,tensile, tear and bursting strength,resistance to abrasion,puncture and dimensional stabilityare interconnected with physical responses: permeability porosity thermal conductivity electrical characteristics. It is shown that such properties are not specific features, but rather form an integrated system enabling functionality in targeted applications. Based on literature review on test methods (ASTM, ISO, EN standards) and its relationship with the performance in reality, the current review bridges laboratory measurement to engineering design criteria in geotextiles, medical textile fabrics and products applications of protective clothing and automotive textiles filtration. Particular emphasis is placed on anisotropic behavior of textile structures and the role played by fiber selection, yarn construction, fabric design and finishing treatments on the overall property profile. This paper also reviews sophisticated characterization techniques such as digital image correlation, micro-CT analysis and dynamic mechanical analysis for a better understanding of the deformation mechanisms. By providing property-property and property-structure relationships, together with a detailed overview of processing technologies, including case studies and best practices, this book will be an excellent reference for engineers and scientists working in the design, development and production of technical textiles.as well as material developers and product developers looking to address markets such as automotive, civil or protective clothing.

**Keywords:** tear resistance, abrasion resistance, permeability anisotropic behavior and standards of testing, structure-property relationship, mechanical properties and physical properties.

**INTRODUCTION**

Technical textiles are opposite to regular textiles which primarily address the aesthetic and comfort aspects of a product, meaning that aesthetics is regarded as one of the main influencers over technical durability and functionality. In contrast to classic textiles, technical textiles are engineered products with clearly defined requirements for physical-mechanical properties as the key product features. These features are what might decide whether a geotextile will stabilize a slope for decades, surgical mesh will endure all physiological load without bursting, or protective garments will save life in adverse situations [1-4].

The physical-mechanical property profile of technical textiles refers to measurable mechanical responses of the material in relation to applied forces, as well as its inherent properties governing the response to environmental actions. Mechanical properties consist of tensile, tearing and bursting behavior, abrasion resistance, and dimensional stability; physical properties involves permeability, porosity, thermal aspects and electrical behaviour. It is not the value of these properties, but the degree to which they can be predicted and relied upon under given service conditions that marks out technical textiles.

The paper here offers a systematic investigation of these key properties and builds their relationships, showing how they can be engineered through the material selection and structural design. The review spans basic property definitions and common testing methods to advanced techniques for characterising materials, all the way down to correlating laboratory measurements with real-world needs in their principal application arenas. Understanding these property foundations enables engineers to optimize material specifications and researchers to work toward the development of new-generation textile solutions [5-9].

**FUNDAMENTAL MECHANICAL PROPERTIES: DEFINITIONS AND MEASUREMENT**

Tensile properties are the basic mechanical parameters describing a material's behaviour under direct axial loading. For technical textiles tensile properties are usually anisotropic, with significant differences between machine and cross directions (warp/vertical and weft/transverse).

**TABLE 1.** Key Tensile Properties and Their Significance

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Property** | **Definition** | **Standard Test Methods** | **Primary Influence Factors** | **Typical Range (Woven Tech. Textiles)** |
| **Tensile Strength** | Maximum stress a material can withstand while being stretched before failure. | ASTM D5035, ISO 13934-1 | Fiber type, yarn linear density, fabric count, weave pattern | 500-5000 N/5cm |
| **Breaking Elongation** | Percentage increase in length at the point of rupture relative to original length. | ASTM D5035, ISO 13934-1 | Fiber polymer, yarn twist, fabric structure | 5-40% |
| **Modulus of Elasticity** | Ratio of stress to strain in the elastic deformation region; indicates stiffness. | ASTM D5035, ISO 13934-2 | Fiber modulus, yarn construction, fabric architecture | 1-100 GPa (fiber dependent) |
| **Tensile Toughness** | Total energy absorbed per unit volume up to failure (area under stress-strain curve). | ASTM D5035, ISO 13934-2 | Combination of strength and elongation | Varies widely by application |
| **Poisson's Ratio** | Ratio of transverse strain to axial strain under tensile loading. | Specialized instrumentation | Fabric structure, fiber orientation | 0.2-0.8 for most textiles |

The deformation behaviour of technical textiles is generally non-linear from first loading indicating the complex interaction between fibre extension, yarn decrimping and fabric structural re-arrangements. High-performance fibers, which include aramids (Kevlar®, Twaron®), ultra-high molecular weight polyethylene (UHMWPE, Dyneema®, Spectra®), and carbon fibers have high strength and modulus coupled with limited elongation to break, typically <5%, whereas polyester or polypropylene provide more balanced property profiles.

Tear is the measurement of a material’s overall resistance to the opening up of an existing cut or tear. Note that this property can be very important in applications when failure is initiated by puncture or cutting and may grow under load; examples are tarpaulins, protective clothing, geotextiles etc.

Three predominant methods test various types of tear propagation:

Trapezoidal Tear (ASTM D5587): The force needed to tear through a sample, previously cut with an initiating incision.

Elmendorf Tear (ASTM D1424): Force per unit thickness required to tear a material using a pendulum instrument.

02 2010-06 CD 004 Tongue Tear (ASTM D2261): Evaluates ability to withstand tearing of two parallel cuts under perpendicular tension.

The fabric construction is the primary factor related to the tear strength. Woven fabrics usually have higher tear resistance than knits of equal weight because the greater frictional forces between interlocking yarns. In woven fabrics binding in effect that implies a certain number of yarns must be broken not sequentially but simultaneously resulting the fabric has higher strength from tear. Fiber mobility and yarn slip have noticed effects, low twist yarn may better compact the stress due to reorienting ability of its structure so that faster fabrics are not always weaker.

Whereas tensile testing is used for uniaxial force, with bursting the resistance to multiaxial hydraulic or pneumatic pressure is measured. This property is of particular application in applications, such as filtration membranes, airbags and some geotextile applications wherein the pressure is applied normal to the plane of fabric.

**TABLE 2.** Bursting Strength Test Methods and Applications

|  |  |  |  |
| --- | --- | --- | --- |
| **Test Method** | **Principle** | **Application Relevance** | **Standard References** |
| **Hydraulic Diaphragm** | Applies increasing hydraulic pressure through a rubber diaphragm until specimen rupture. | Geotextiles, filtration media, industrial fabrics | ASTM D3786, ISO 13938-1 |
| **Pneumatic** | Uses compressed air to apply pressure directly to the specimen. | Lightweight technical textiles, medical membranes | ASTM D3786 (modified) |
| **Ball Burst** | A steel ball is forced through a clamped specimen. | Quality control for knits and nonwovens | ASTM D3787 |

Burst strength is associated with tensile and elongation properties and provides an overall measurement of biaxial strength. For isotropic nonwoven geotextiles, bursting strength becomes more meaningful in-experiment than unidirectional tension testing. Particularly materials subjected to multiaxial stress are benefited by such a test.

Abrasion resistance is the ability of a material to resist surface wear caused by the rubbing or friction of another material. This property is indicative of service life in applications ranging from conveyor belts to protective workwear.

Abrasion testing employs various mechanisms: Martindale (ASTM D4966): fabric rubs against a standard abradant in a figure eight.

Taber Abraser (ASTM D3884): Utilizing abrasive wheels that mechanically travel around the surface with a specified force Wyzenbeek (ASTM D4157) Oscillatory motion of fabric and the number of cycles required to abrade a hole.

The abrasion resistance varies with the types of polymers, type of weave and treatment applied to Ylon® fibers. Synthetic fibers having high-tenacity are typically stronger than natural fibers. Fabric structure is also a big factor – twills often have better abrasion resistance than plain weaves because they have longer floats that spread out the wear, and tightly woven fabrics shield individual fibers from the elements..

**CRITICAL PHYSICAL PROPERTIES**

Permeability is the ability for a fluid (liquid or gas) to flow through a material and porosity is the percentage of void space in the material. Such properties are essential for filtration, geotextile, medical and various composite applications.

**TABLE 3.** Permeability and Porosity Characteristics by Fabric Type

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Fabric Type** | **Typical Porosity (%)** | **Air Permeability Range (cfm/ft²)** | **Water Permeability (mm/sec)** | **Primary Controlling Factors** |
| **Woven Monofilament** | 30-50 | 100-500 | 0.1-10 | Yarn diameter, weave pattern |
| **Woven Multifilament** | 20-40 | 10-100 | 0.01-1 | Fiber denier, fabric count |
| **Knitted** | 50-80 | 200-1000 | 1-50 | Stitch density, yarn type |
| **Nonwoven (spunbond)** | 70-90 | 50-300 | 10-100 | Fiber diameter, bonding method |
| **Nonwoven (needle-punched)** | 60-85 | 100-800 | 5-80 | Needle density, punch depth |

In geotextiles, permeability is determined by permittivity (cross-plane flow) and transmissivity (in-plane flow); ASTM D4491 and ASTM D4716, respectively. For filtration, it is important to know the relationship between pore size distribution and particle retention (e.g., based on bubble point test or porometry).

Can be read more thermal behavior conductivity resistance and specific heat capacity. For the insulation, protective clothing and aerospace technical textiles must be very well managed in terms of thermal performance.

Key thermal properties include:

Thermal Conductivity (λ):It is the rate of heat transfer through unit thickness per degree temperature difference, for a material over a surface area x and with a time y The SI unit of λ is W/m·K.

Thermal resistance factor: The reciprocal of the thermal conductivity expressing insulating value (m²·K/W)

Specific Heat Capacity (Cp): The amount of heat energy that is needed to increase the temperature of a unit mass by one degree K. (J/kg·K)

Multilayer insulation fabrics generally have trapped air spaces because of the low thermal conductivity (0.024 W/m·K) of air. PCMs (phase change materials) incorporated in textiles can dynamically regulate heat by absorbing or releasing latent heat during phase changes.

"Electrical behavior is becoming more important in applications where static dissipation, EMI (electromagnetic interference) shielding or conductive properties are necessary."

**TABLE 4.** Electrical Properties and Their Applications in Technical Textiles

|  |  |  |  |
| --- | --- | --- | --- |
| **Electrical Property** | **Typical Values for Technical Textiles** | **Measurement Standard** | **Application Examples** |
| **Surface Resistivity** | 10³-10¹² Ω/square | ASTM D257 | Static control flooring, cleanroom garments |
| **Volume Resistivity** | 10²-10¹⁰ Ω·cm | ASTM D257 | Conductive composites, heating elements |
| **EMI Shielding Effectiveness** | 20-80 dB (depending on frequency) | ASTM D4935 | Electronic enclosures, military shelters |
| **Dielectric Strength** | 10-100 kV/mm | ASTM D149 | Electrical insulation, high-voltage applications |

Conductive textiles incorporate metallic fibers (stainless steel, silver-coated), conductive polymers (PEDOT:PSS), or carbon-based materials (carbon fibers, nanotubes, graphene). The percolation threshold—the minimum conductive filler concentration needed to form continuous conductive pathways—is a critical design parameter.

**STRUCTURE-PROPERTY RELATIONSHIPS**

The performance level of a technical textile is determined at the outset, essentially by fiber design and applying polymer chemistry and physical morphology. High-performance fibers exhibit outstanding, but varied property packages: aramids have high tensile strength (≈3000 MPa) and thermal resistance; ultra-high molecular weight polyethylene (UHMWPE) excels in highest specific strength and energy absorption; carbon fibers feature superior stiffness (modulus 200-500 GPa) and electrical conductivity; glass fibers offer a cost-beneficial strength profile; basalt fibers show good chemical resistance—in addition to an eco-friendly character. In addition to the polymer itself, fiber morphology (e.g., diameter, hollow cores for weight savings or trilobal cross sections to optimize IBB) serves as a critical design knob to achieve targeted properties.

Then these basic fiber properties are controlled and arranged at the yarn level. Factors such as the degree of twist establish a trade-off, with increased twist adding to yarn cohesion and abrasive wear resistance at the cost of relative tensile strength as fiber angles increase. Ply construction improves uniformity, and fatigue resistance; whereas blending dissimilar fiber types, for example aramid/cotton, allows properties to be hybridized (e.g., protection/comfort). It is how these yarns are ultimately assembled into a particular fabric structure—be it woven, knitted or braided—that controls these micro-scale features in the final macroscale property profile, governs the mechanical behavior of the textile, its porosity and its overall functional performance.

This hierarchical approach to design ends with post-formation treatments which provide definitive setting of the functional properties of the textile. For nonwoven fabrics, the bonding process directly drives the property basis line: -Needle-punching generates dimensional stability and high in-plane strength based on mechanical entanglement of fibers; -Thermal bonding is suitable for tailoring porosity and hand; chemical bonding can improve specific properties as stiffness despite generally lower throughput porosity and permeability. 9.1 Transformation as final step, by surface modifications and functional coatings.

**TABLE 5.** Effect of Weave Pattern on Mechanical Properties

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Weave Pattern** | **Tensile Strength** | **Tear Resistance** | **Abrasion Resistance** | **Drape / Flexibility** | **Dimensional Stability** |
| **Plain (1x1)** | High (maximum interlace) | Low (high interlace restriction) | Moderate | Low | Very High |
| **Twill (2x2, 3x1)** | Moderate-High | High (good yarn mobility) | High (long floats distribute wear) | Moderate-High | High |
| **Satin (4x1, 5x1)** | Moderate | Moderate-High | Very High (very long floats) | High | Moderate |
| **Basket (2x2)** | High | High | High | Moderate | High |

In applications such as permeable/waterproof membranes(w/e g ePTFE、PU), pore structures are designed to block entr other liquid water body and transmit vapor. The flame-retardant treatments function by chemical mechanisms or forming insulating char barriers and the antimicrobial finishes inhibit biodegradation. Advanced methods, for example, plasma treatment may selectively alter the surface energy to enhance wettability or adhesion without adversely effecting the useful bulk mechanical properties developed by selection of material and structure above. It is therefore in the combination of these three steps that the final performance of a technical textile ultimately lies: in how (i) we can create order and orientation from the characteristics of our chosen fibres through yarn spinning and fabric patterning; (ii) lock this into place through bonding processes; and (iii) fine-tune it to achieve specific surface recurrence scales using tailored surface engineering.

**ADVANCED CHARACTERIZATION TECHNIQUES**

Macroscopic analysis went beyond standard tests for a deeper understanding:

Through full-field strain mapping, the localized deformation at stress concentrations and anisotropic features under complex loading are identified. The DIC has clarified tear mechanism of fabric in the woven and stress distribution in composites reinforcements.

Quantitative fiber orientation, pore connectivity and damage progression can be measured by means of three-dimensional (3D) internal structure visualization. Image-based μ-CT allows non-invasive examination of composite impregnation and filter media structure.

Describes viscoelasticity—how polymers respond to stress over time. DMA tests for storage (elastic behavior), loss (viscous behavior), and tan(δ) values of the composites as a function of temperature, frequency are necessary to ascertain the material performance under dynamic loading.

Service condition Simulation from temperature extremes, UV exposure, chemical contact to cyclic loading offers critical accelerated aging data helpful in predicting service life, especially for geotextiles and outdoor applications.

**APPLICATION-SPECIFIC PROPERTY REQUIREMENTS**

Geotextiles need good combination of mechanical and hydraulic properties. Spacers require excellent poke resistance (ASTM D6241) and tensile strength with moderate flow properties. Drainage applications require the in-plane flow capacity (transmissivity) and sufficient compressive strength to withstand soil loading. For reinforcement applications, high tensile modulus and low creep properties are preferred; however, the actual long-term design strength is usually limited by both installation damage (creep and chemical/biological degradation).

Surgical implants (hernia meshes, vascular grafts) demand biocompatibility but must have matched mechanical properties with host tissues to avoid stress shielding or excessively different compliances. In the case of bioabsorbable materials, the degradation profile should correlate with tissue regeneration rates. Wound covering dressings need to have controlled MVTR (≈ 2000-2500 g/m²/day for optimal wound healing) and breathability and barrier properties function.

Property standards by hazard type are:

Ballistic protection: High tensile strength and high modulus for energy absorption with multi-hit capability

Cut Protection: Blend of hard (abrasion resistant) and soft (energy absorbing) fibers

Does not catch fire: Low thermal conductivity, high heat capacity and char formation to resist airflow [pvhtl 6]

Chemical: Protection against specific chemicals with comfort for the wearer

The airbag fabrics should be permeable to a controlled extent, so as to exhibit appropriate inflation characteristics, and maintain high tensile strength for containing the internal pressure in order to avoid burst and have coating adhesion for long standing use. Furnishing fabrics require abrasion resistance (usually >50,000 cycles Martindale), some degree of stain resistance, and the necessary flame retardancy. Compatibility with the resin systems, drapability for forming and stable mechanical properties at service temperature are required for composite reinforcements.

**FUTURE PERSPECTIVES AND RESEARCH DIRECTIONS**

In future, more and more functionalities will be combined in one element of a technical textile structure: structural health monitoring in composite reinforcements or self-healing capabilities in protective clothing. This necessitates a simultaneous design of mechanical, electrical and chemical properties.

Sophisticated models can be developed considering microstructural variation for predicting macroscale response from constitent material and architecture. (2019). Digital twins of textile structures for virtual testing and optimisation prior to physical prototyping. Textile Research Journal:1-12.

Creating bio-based and recycled materials that have the same performance as synthetic ones, which are produced from petroleum, is one of those hurdles. This will involve developing greater knowledge in how to obtain required mechanical properties using less homogeneous natural fibers or recycled feedstocks, through the design of novel spinning, construction and finishing processes.

Materials with properties that respond to environmental changes—temperature, humidity, pH, mechanical stress4—provide adaptive behavior. Shape memory polymers, moisture responsive pore structures, and mechanochromic materials are very promising avenues for advancing the new generation of technical textiles.

**CONCLUSION**

The physical-mechanical properties of technical textiles are an integrated system and their functions are defined in different application areas. These properties are not material constants, but dependent upon the fabric's construction. Knowledge of the orders of magnitude relation in such structure-property relationships can direct material design toward predetermined performance.

Standard test methods establish critical specifications and quality control measures, while advanced characterizations tools provide intimate details concerning deformation and failure mechanisms. The growing complexity of the applications for technical textiles requires greater and greater control and integration of these properties, thus creating opportunities for innovation in materials, manufacturing, tests etc.

With the growing-in market opportunities and applications in technical textiles ranging from wearable electronics to sustainable construction, their physical-mechanical property basis will continue to be at the heart of their performance, reliability and ultimately success. The multidisciplinary efforts to design, fabricate and utilize new generation multifunctional and adaptable materials with sustainable lifetimes must maintain an integrity of structure at such levels.

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