WELLINGTON SEARS HANDBOOK OF INDUSTRIAL TEXTILES

Sabit Adanur, Ph.D.

JOHNSTON INDUSTRIES GROUP

Skechers EX1062
Skechers v Nike

WELLINGTON SEARS HANDBOOK OF INDUSTRIAL TEXTILES

Sabit Adanur, B.S., M.S., Ph.D.

Assistant Professor, Department of Textile Engineering
Auburn University, Alabama, U.S.A.

TECHNOMIC PUBLISHING CO., INC.

LANCASTER • BASEL

Skechers EX1062
Skechers v Nike

Published in the Western Hemisphere by
Technomic Publishing Company, Inc.
851 New Holland Avenue, Box 3535
Lancaster, Pennsylvania 17604 U.S.A.

Distributed in the Rest of the World by
Technomic Publishing AG
Missionsstrasse 44
CH-4055 Basel, Switzerland

Copyright © 1995 by Wellington Sears Company
All rights reserved

No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording, or otherwise, without the prior written permission of Wellington Sears Company.

Printed in the United States of America
10 9 8 7 6 5 4 3 2 1

Main entry under title:
Wellington Sears Handbook of Industrial Textiles

Library of Congress Catalog Card No. 95-61229
ISBN No. 1-56676-340-1

HOW TO ORDER THIS BOOK
BY PHONE: 800-233-9936 or 717-291-5609, 8AM–5PM Eastern Time
BY FAX: 717-295-4538
BY MAIL: Order Department
Technomic Publishing Company, Inc.
851 New Holland Avenue, Box 3535
Lancaster, PA 17604, U.S.A.
BY CREDIT CARD: American Express, VISA, MasterCard

Skechers EX1062
Skechers v Nike

4.5

Knitting

R. P. WALKER
S. ADANUR

1. INTRODUCTION

As defined earlier, knitting involves the interlooping of one yarn system into continuously connecting vertical columns (wales) and horizontal rows (courses) of loops to form a knitted fabric structure. There are two basic types of knit structures as shown in Figure 4.1: weft knit and warp knit. Figure 4.46 shows a circular weft knitting machine.

In weft knitting, the yarn loops are formed across the fabric width, i.e., in the course or weft direction of the fabric. In warp knitting, the loops are formed along the fabric length, i.e., in the wale or warp direction of the cloth. In both knitting systems the fabric is delivered in the wale direction. Special needles are used to form the yarn loops as shown in Figure 4.47. The latch needle is the most common type in use for weft knitted fabrics and the compound needle is used mostly in warp knitting. Spring beard needles are becoming obsolete.

The basis of knit fabric construction being the continuing intersecting of loops, any failure of a loop yarn will cause a progressive destruction of the loop sequence and a run occurs. Thus, knitting yarns must be of good quality in order that yarn failures be kept at a minimum. Other important geometrical definitions relating the knit structures are as follows:

- count: total number of wales and courses per unit area of the fabric
- gauge: the number of needles per unit width (the fineness or coarseness of the fabric)
- stitch: the loop formed at each needle (the basic repeating unit of knit fabric structure)
- technical face: the side of the fabric where the loops are pulled toward the viewer
- technical back: the side of the fabric where the loops are pulled away from the viewer

Industrial application areas of knit structures include medical products such as artificial arteries, bandages, casts, and surgical gauze and flexible composites. Knit fabrics are used as reinforcing base for resins used in cars, boats, and motorcycle helmets.

2. WEFT KNITTING

Weft knit goods are made by feeding a multiple number of ends into the machine. Each loop is progressively made by the needle or needles. Figure 4.48 shows the loop forming process with a latch needle. The previously formed yarn loop actually becomes an element of the knitting process with the latch needle. This is why the latch needle is referred to as the "self-acting" needle. As the needle is caused to slide through the previous yarn loop, the loop causes the swiveled latch to open, exposing the open hook (head) of the needle. The newly selected yarn can now be guided and fed to the needle. If a simple knitted loop is to be formed, the previous loop (the one which opened the latch) must slide to a point on the needle stem allowing it to clear the latch. Having the needle reach this clearing position allows a reversal of the sliding action which

Skechers EX1062
Skechers v Nike

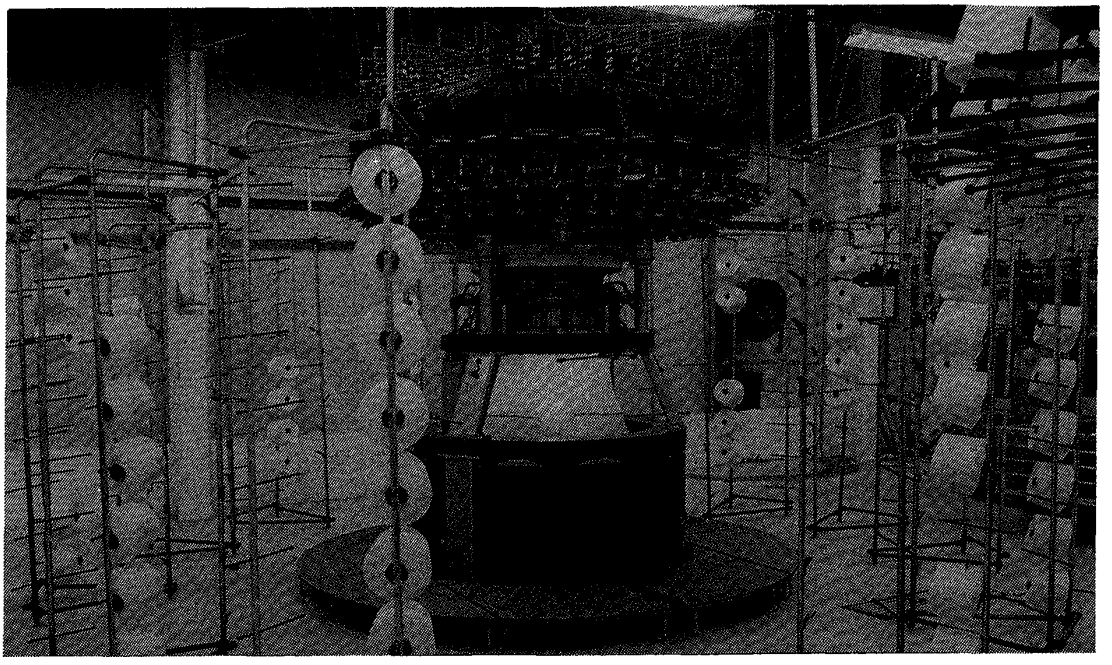


FIGURE 4.46 Circular weft knitting machine.

in turn pulls down on the new yarn and uses the previous yarn loop to close the latch trapping the new yarn inside the hook. The previous loop is now in a position to ride over the outside of the latch and be cast off the needle head, thus becoming a part of the fabric while the new yarn loop is pulled through the previous loop.

Depending on the structure in weft knitting, several types of knitting stitches are used including plain [Figure 4.1(c)], tuck, purl (reverse), and float (miss) stitch which are shown in Figure 4.49. The plain stitch fabric has all of its loops drawn through to the same side of the fabric. The plain fabric has a very smooth face and a rough back. Other stitches produce different effects depending on the arrangement of the loops. Special stitches are also available to prevent runs.

Weft knitting machines may be either flat or

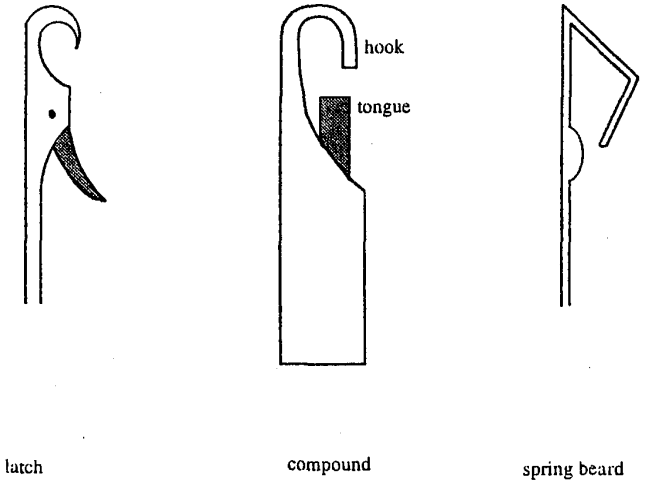


FIGURE 4.47 Needle types used in knitting.

Skechers EX1062
Skechers v Nike

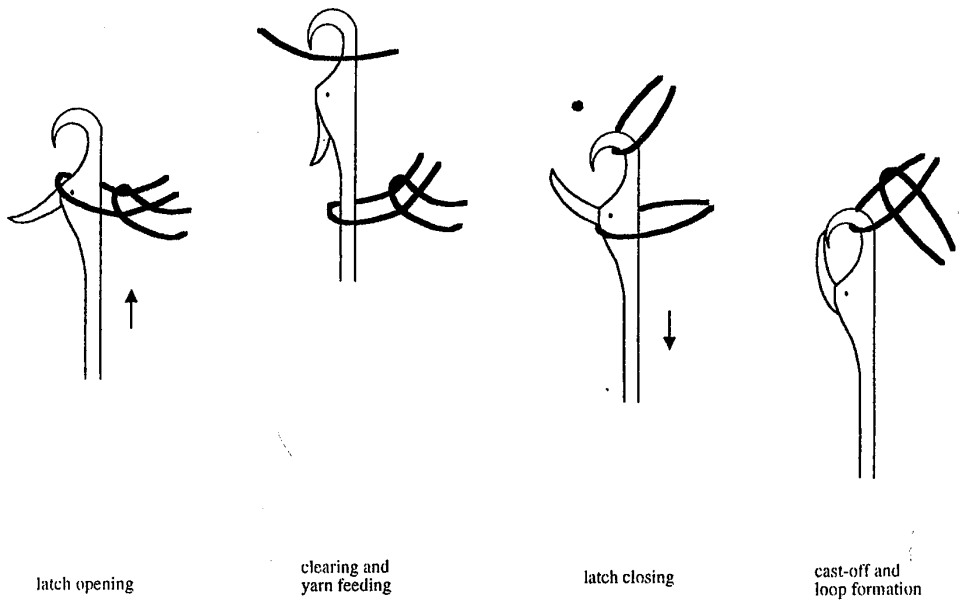


FIGURE 4.48 Loop forming on a latch needle.

circular, the former knitting a flat single layer of fabric, the latter knitting a continuous tube. No matter which machine configuration is used, weft knit manufacturing involves the same fundamental functions:

- yarn selection and feeding
- needle knitting action
- fabric control during knitting
- needle selection
- fabric take-up and collection

There are several devices added to weft knitting machinery for improving quality of the product and/or operation of the process. A partial list of these added features includes:

- yarn break sensors
- fabric hole detectors
- needle "closed latch" sensors
- air blowing systems to keep needles clear of lint
- centralized lubrication dispensing unit
- computer interfaces for production monitoring
- computer interfaces for pattern entry
- computer aided design systems

Knit fabrics can be classified as single knits and double knits. Single weft knits have one layer of loops formed with one yarn system. Three major types of single weft knits are jersey, rib and purl structures. Double knits have two insepa-

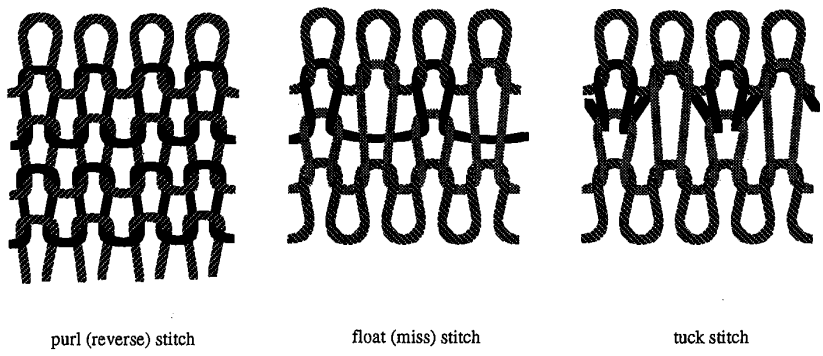


FIGURE 4.49 Types of stitching in weft knitting.

Skechers EX1062
Skechers v Nike

rable layers of loops. Each yarn forms loops that appear on both faces of the fabric. Two major types of double knits are rib double knit and interlock double knit.

The major characteristics of weft knit fabrics are as follows:

- can be either manufactured as net-shape or cut to shape and sewn
- form a run the wale direction if a yarn breaks
- have good stretch especially in the course direction
- do not ravel
- do not wrinkle easily and have good recovery from wrinkling and folding

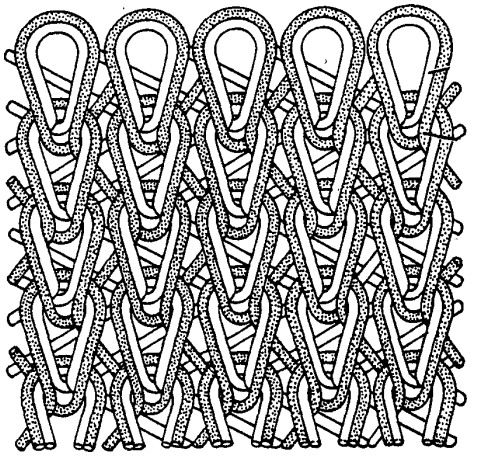


FIGURE 4.50 A two-bar tricot (courtesy of Noyes Publications).

3. WARP KNITTING

Warp knit fabrics are manufactured by preparing the equivalent of a warp beam containing several hundred ends. Each end passes through its own needle and is formed into loops which intersect with adjacent loops. Thus, a flat looped fabric is knitted using only "warp" yarns without the necessity of "filling" yarns being interwoven.

The two major types of warp knits are tricot and Raschel. Based on the number of yarns and guide bars used, tricot knits are identified as single [Figure 4.1(d)], two (Figure 4.50), three and four (or more) bar tricots. Raschel knitting is suitable for making highly patterned, lacy, crocheted or specialty knits (Figure 4.51). In general, Raschel machines are used for the production of knit structures for industrial applications. For increased structural support in the filling direction, additional filling yarns can be inserted as shown in Figure 4.52.

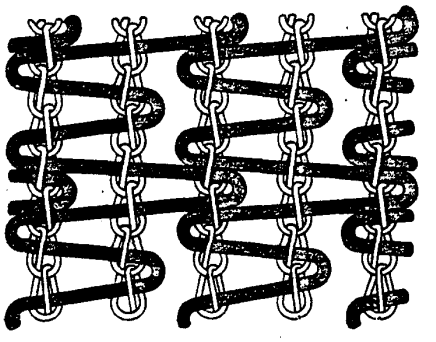


FIGURE 4.51 Simple Raschel crochet knit (courtesy of Noyes Publications).

Figure 4.53 shows a schematic of a warp knitting machine. The knitting elements required for a warp knitting machine include:

- needles arranged in one or more solid bar to function as a unit (called a needle bar)
- yarn guides, one for each warp yarn, arranged in solid bars, one for each different warp, to function as a unit (called guide bars)

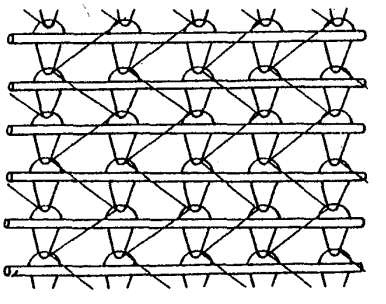


FIGURE 4.52 Weft inserted warp knit structure (courtesy of Karl Mayer).

Skechers EX1062
Skechers v Nike

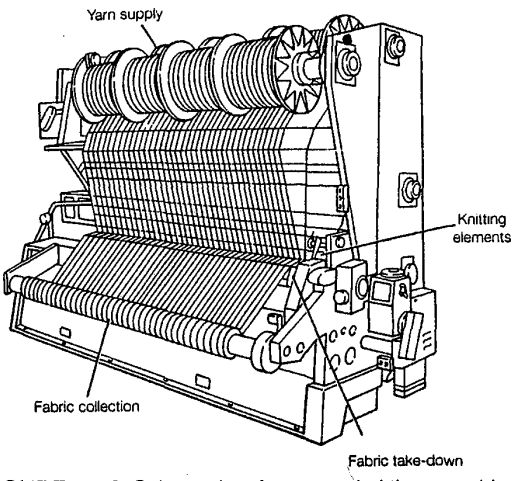


FIGURE 4.53 Schematic of a warp knitting machine (courtesy of Noyes Publications).

- sinkers arranged in a solid bar to function as a unit (called a sinker bar)
- presser bar functioning on spring beard needle bars only
- pattern chains or cams to control the side-to-side motion of guide bars
- in Raschel knitting, over the self-acting latch needle, no pressure bar is needed; in its place, a latch guard and a face plate, over which the old loops are "knocked-over," are used

Stitch formation on warp knit machines differs from weft knitting in that a complete course of loops is formed by one cycle of the needle bar(s) rather than individually acting needles forming loops within a course.

It is estimated that 85% of the knit structures used directly or as composites in the field of industrial textiles are warp knits.

Open and closed warp knit structures are used in protection from insects, sun protection, harvesting nets and heavy fishing nets.

Three dimensional warp knit structures such as sandwich structures are made on machines with two separate needle bars working independently of each other and forming a separate fabric on each side. Another fully threaded guide bar fills the sandwich by overlapping both needle bars. Knit fabrics can also be coated and molded into three-dimensional honeycomb structures.

Mono- and multi-axial knit structures are produced by inserting layers of straight reinforcement yarns into the knit construction. These structures are also called directionally oriented

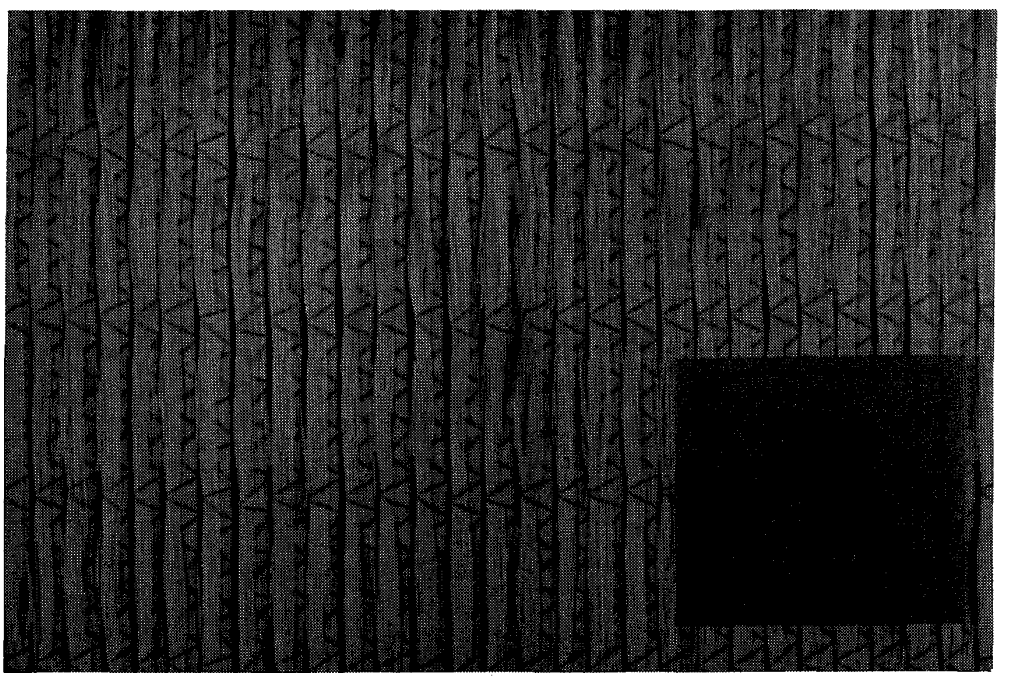


FIGURE 4.54 No-crimp fabric structure (courtesy of Tech Textiles).

Skechers EX1062
Skechers v Nike

structures (DOS) or no-crimp fabrics. The reinforcement fibers can be oriented at various directions including 0°, 90°, 45°, etc., as shown in Figure 4.54. Some of these structures are used for composite reinforcement (Chapter 7.0).

4. KNIT FABRIC CHARACTERISTICS

The basic knit structures have the following general characteristics:

- High extendibility is seen.
- elastic recovery: Knit fabrics recover well from deformation since the loops attempt to return to their original position.
- shape retention: When the loops do not recover from deformation, the fabric stretches out of shape or it bags.
- Knits generally crease or wrinkle less than woven fabrics since the loops act as hinges (which is a problem when crease is needed).
- Relaxation shrinkage of knit fabrics can be high, especially if the fibers are hydrophilic.
- Pliability and form-fitting due to the loop structure and to the low twist in some weft knit yarns.
- Pilling and snagging due to ease of catching a loop and pulling it to the fabric surface.
- insulative ability and air permeability: Knit fabrics, which are open structures, are ideally suited for providing thermal insulation in still air conditions. Knit structure contributes a desirable cooling effect in summer and a chilling effect in winter due to wind.
- running or laddering: Knit fabrics may run or ladder if a yarn in the structure is broken.

Skechers EX1062
Skechers v Nike

17.0

FIBER PROPERTIES AND TECHNOLOGY

Skechers EX1062
Skechers v Nike

17.1

Fiber Properties and Technology

S. ADANUR

The major properties of textile fibers that have important industrial textile usage are included in this chapter. There are many synthetic fibers of the same generic class, manufactured by different companies. For those fibers which are reasonably well known or widely used, properties are listed generically and by trade names. Fibers with lesser known trade names are grouped under their proper generic class, with ranges of values being given wherever possible. The continual introduction of new man-made fibers makes it a genuinely impossible task to present a tabulation which will remain up-to-date for any reasonable length of time. Fiber names, types, and properties are constantly changing. Therefore, caution should be exercised in using the numerical data presented in the following tables. This chapter also discusses the significance of fiber properties as they influence the performance characteristics of yarns and fabrics.

Appendix 4 lists the characteristics, industrial uses and manufacturers of generic man-made fibers and trade names. Figure 17.1 shows longitudinal and cross-sectional photographs of selected industrial fibers.

1. REFRACTIVE INDEX

The refractive index (n) of a substance is defined as the ratio of the velocity of light in a vacuum to the velocity of light through the substance. Because of the molecular orientation within fibers, the speed of light along the fiber axis is usually different from that transverse to the fiber axis. The greater the amount of orientation and degree of crystallinity, the greater will be the difference between the refractive indices which are parallel with, and transverse to, the fiber axis. The difference is called the "birefringence." For all fibers except Saran® the parallel index n_ϵ is greater than the transverse index n_ω, and so the birefringence is always positive. Refractive indices are useful for identifying fibers and, in research, indicating the nature of molecular order in experimental fibers. While refractive index may influence fiber luster, the effect of fiber crimp and the state of aggregation of fibers in yarns and yarns in fabrics are of far greater significance in obtaining or preventing fabric luster. Except as it is a measure of molecular order, which in turn may influence the tensile and elastic properties of fibers, refractive index is of no special significance in the industrial textile picture. Table 17.1 lists refractive indices and birefringences of natural and man-made fibers.

2. DENSITY (SPECIFIC GRAVITY) OF FIBERS

Table 17.2 lists densities of fibers. Density is defined as the ratio of a substance's unit volume weight to that of water at 4°C.

3. FIBER FINENESS AND DIAMETERS

Table 17.3 lists fiber diameters (μm) based on filament deniers for selected fibers.

4. FIBER STRENGTH AND TENACITY

While it might be desirable to catalog the absolute breaking strengths of individual fibers,

Skechers EX1062
Skechers v Nike

Name
Asterisk denotes trademark

Photomicrographs
Cross section, 500X
Longitudinal, 250X

Polyester

***A.C.E.**
***Compet**
Allied

*** Dacron**
Du Pont

***Fortrel**
Wellman

4DG
Eastman

***Tairilin**
Nan Ya Plastics Corp., America

***Trevira**
Hoechst Celanese

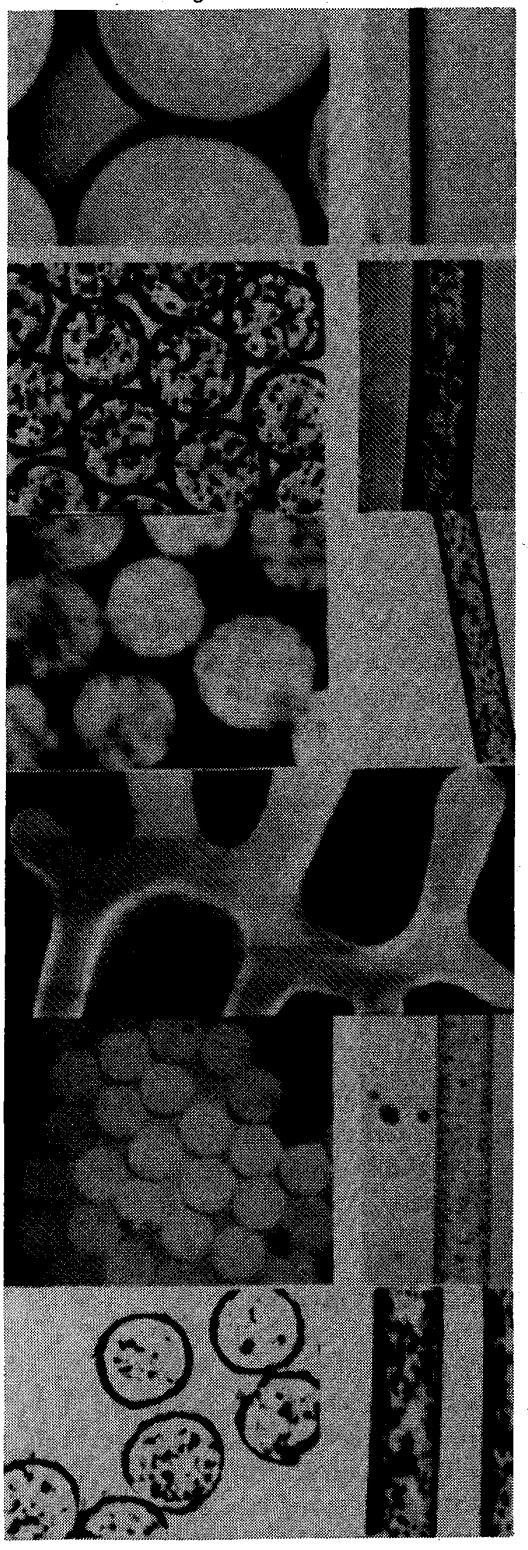


FIGURE 17.1 Photomicrographs of man-made fibers (courtesy of McLean Hunter Publishing Co.).

Skechers EX1062
Skechers v Nike

Name
Asterisk denotes trademark

Photomicrographs
Cross section, 500X
Longitudinal, 250X

Carbon

***Thornel**
Amoco

Nylon

Nylon 6

Nylon 6,6

Lyocell

*** Tencel**
Courtaulds

Rayon

***Fibro**
Courtaulds

Cuprammonium

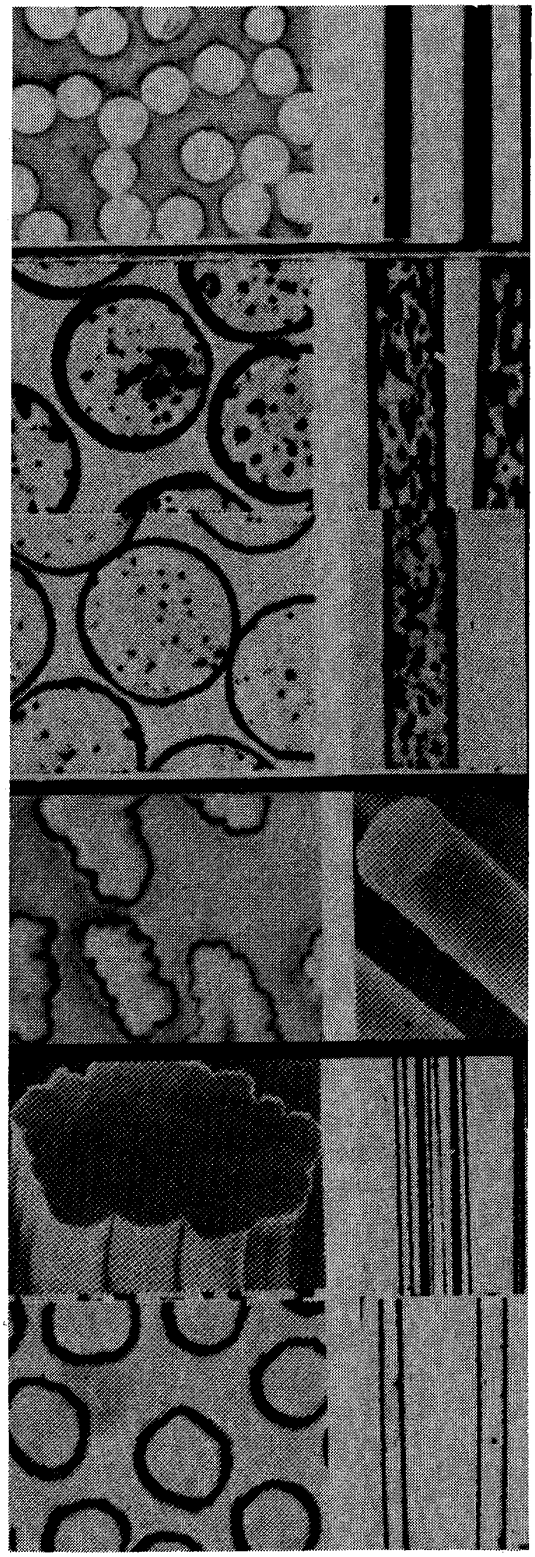
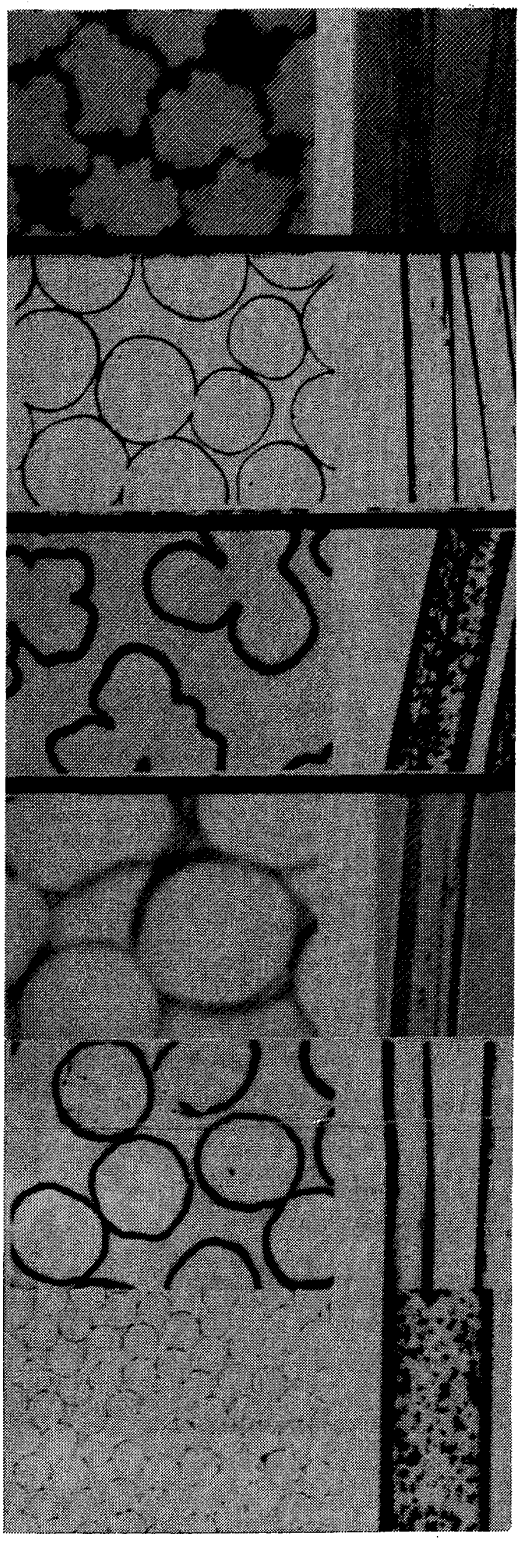


FIGURE 17.1 (continued) Photomicrographs of man-made fibers (courtesy of McLean Hunter Publishing Co.).

Skechers EX1062
Skechers v Nike

Name
Asterisk denotes trademark

Photomicrographs
Cross section, 500X
Longitudinal, 250X



Rayon
North American Rayon Corp.

***Saran**
Pittsfield Weaving

Acetate

Acetate

Sulfar

***Ryton**
Amoco
(Licensed by Phillips)

Acrylic

*** Acrilan**
Monsanto

***Creslan**
***MicroSupreme**
Cytec

FIGURE 17.1 (continued) Photomicrographs of man-made fibers (courtesy of McLean Hunter Publishing Co.).

Skechers EX1062
Skechers v Nike

Name
Asterisk denotes trademark

Photomicrographs
Cross section, 500X
Longitudinal, 250X

Modacrylic

*** SEF**
Monsanto

Olefin

Polyethylene
Hercules

*** Herculon**
Hercules

***Marvess**
***Alpha**
Amoco

***Essera,**
***Marquesa Lana,**
***Patlon III**
Amoco

***Spectra 900**
***Spectra 1000**
Allied

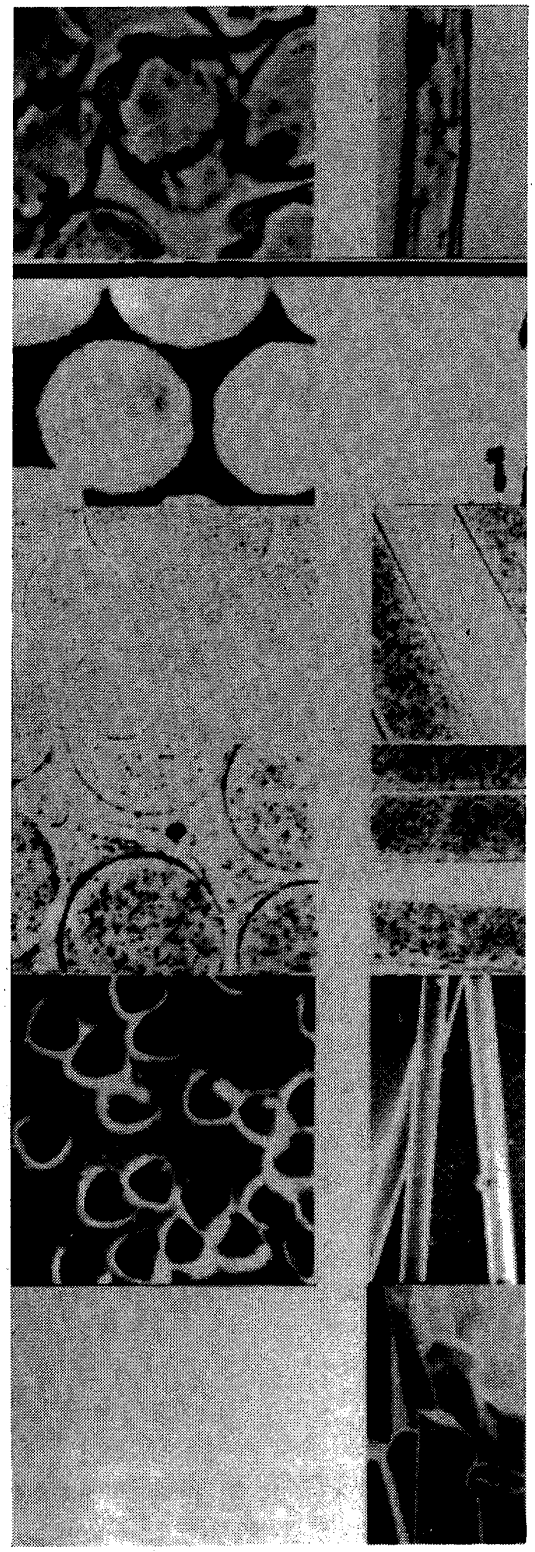


FIGURE 17.1 (continued) Photomicrographs of man-made fibers (courtesy of McLean Hunter Publishing Co.).

Skechers EX1062
Skechers v Nike

Name
Asterisk denotes trademark

Photomicrographs
Cross section, 500X
Longitudinal, 250X

***Fibrilon**
Synthetic Industries

Spandex

***Glospan/ Cleerspan, S-85**
Globe

*** Lycra**
Du Pont

Glass

Glass

Aramid

*** Kevlar**
Du Pont

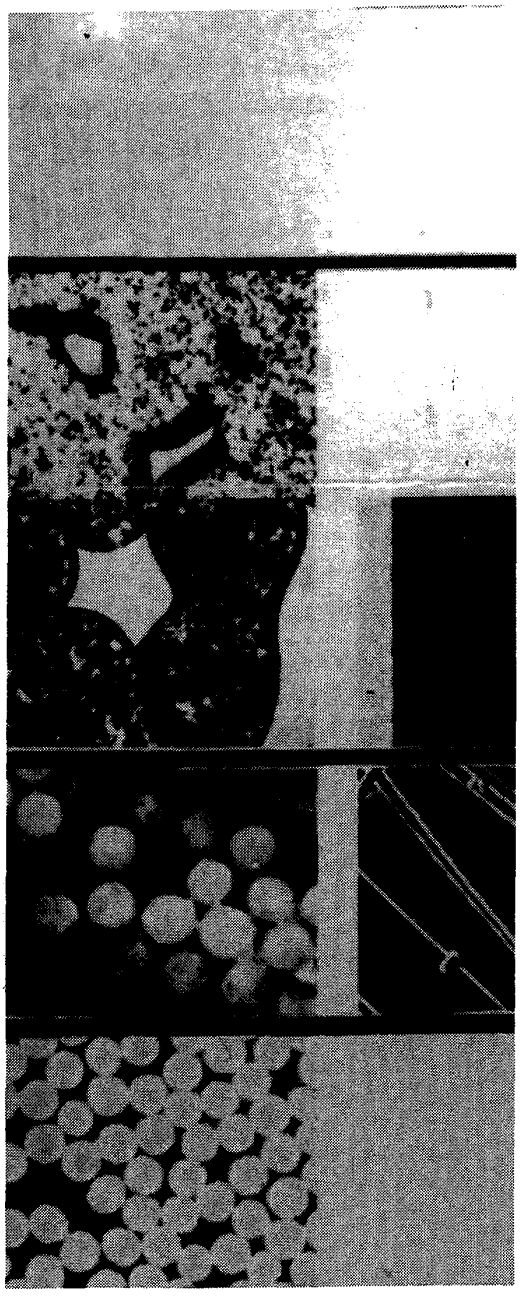
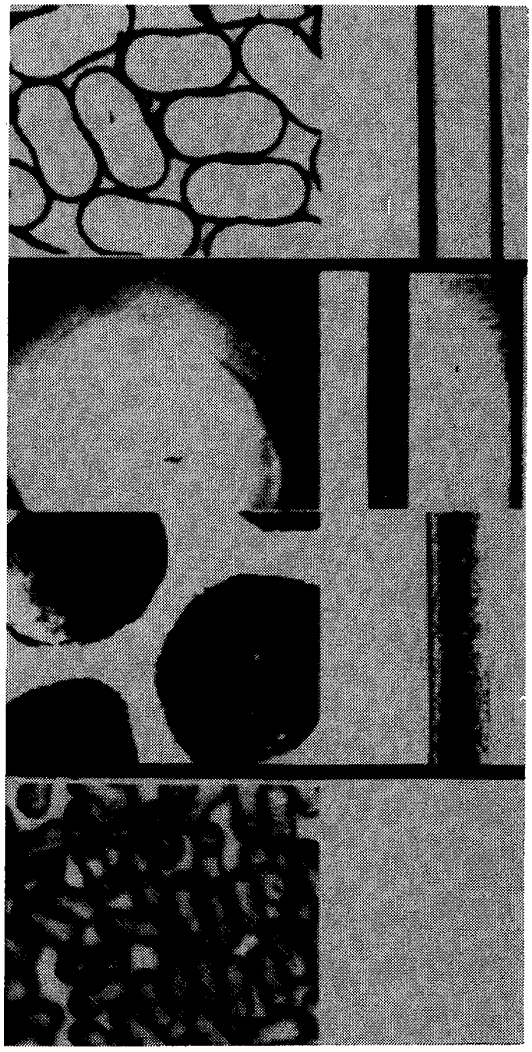


FIGURE 17.1 (continued) Photomicrographs of man-made fibers (courtesy of McLean Hunter Publishing Co.).

Skechers EX1062
Skechers v Nike

Name
Asterisk denotes trademark

Photomicrographs
Cross section, 500X
Longitudinal, 250X



*** Nomex**
Du Pont

Fluorocarbon

*** Gore-Tex**
W. L. Gore

*** Teflon**
Du Pont

Polybenzimidazole

PBI
Hoechst Celanese

FIGURE 17.1 (continued) Photomicrographs of man-made fibers (courtesy of McLean Hunter Publishing Co.).

Skechers EX1062
Skechers v Nike

TABLE 17.1 Refractive Indices and Birefringences of Fibers ([1], Fiber Manufacturers' Data).

Fiber	Refractive Index		Birefringence
	Parallel (n_ϵ)	Transverse (n_ω)	($n_\epsilon - n_\omega$)
Acetate	1.479	1.477	0.002
Acrylic	1.525	1.520	0.004
Aramid			
Nomex®	1.790	1.662	0.128
Kevlar®	2.322	1.637	0.685
Asbestos	1.5–1.57	1.49	0.01–0.08
Cotton, raw	1.580	1.533	0.047
Cotton, mercerized	1.57	1.52	0.05
Fluorocarbon	1.37	–	–
Glass	1.547	1.547	0.000
Modacrylic	1.536	1.531	0.005
Novoloid	1.650	1.648	0.002
Nylon			
Nylon 6	1.568	1.515	0.053
Nylon 6,6	1.582	1.519	0.063
Nytril	1.484	1.476	0.008
Olefin			
Polyethylene	1.556	1.512	0.044
Polypropylene	1.530	1.496	0.034
Polycarbonate	1.626	1.566	0.060
Polyester			
Dacron®	1.710	1.535	0.175
Kodel®	1.632	1.534	0.098
Cuprammonium rayon	1.548	1.527	0.021
Viscose rayon	1.547	1.521	0.026
Saran	1.603	1.611	−0.008
Silk	1.591	1.538	0.053
Spandex	1.5	–	–
Triacetate	1.472	1.471	0.001
Vinal	1.543	1.513	0.030
Vinyon (PVC)	1.541	1.536	0.005
Wool	1.556	1.547	0.009

Skechers EX1062
Skechers v Nike

TABLE 17.2 Density of Fibers [1,2].

Fiber	Density (mg/mm³)
Polyester	
ACE®	1.38
Compet®	1.38
Dacron®	1.34–1.39
Fortrel®	1.38
Tairilin®	1.38
Trevira®	1.38
Thornel® carbon	
High strength	1.77
High modulus	1.77
Ultra-high modulus	1.96
Nylon 6	1.14
Nylon 6,6	1.13–1.14
Tencel® lyocell	1.56
Viscose rayon	1.52
Cuprammonium rayon	1.53
Saran	1.62–1.75
Acetate	1.32
Ryton® sulfar	1.37
Acrylic	1.17
Modacrylic	1.35
Nytril	1.20
Polyethylene, low density	0.92
Polyethylene, high density	0.95
Polypropylene	0.90
Spectra® olefin	0.97
Lycra® spandex	1.2
E-glass, single filament	2.54–2.69
S-glass, single filament	2.48–2.49
Glass, multifilament	2.5
Aramid	
Kevlar®	1.44
Nomex®	1.38
Fluorocarbon	
Gore-Tex®	0.8–2.2
Teflon®	2.1
Polybenzimidazole	1.43
Asbestos	2.1–2.8
Flax	1.54
Cotton	1.54
Novoloid	1.28
Polycarbonate	1.21
Silk	1.35
Vinyon (PVC)	1.40
Wool	1.31

cross-sectional shapes and areas of fibers can vary widely. When subjected to a tensile force, the total strength of a fiber is dependent upon both its intrinsic ability to remain intact and upon its dimensions. The absolute value of a fiber's strength may be meaningless until it is related to its cross-sectional area or its linear density, i.e., weight per unit length. As is the custom with all engineering materials, fiber breaking strengths can be listed on a pounds per square inch (psi) basis. More commonly, however, the textile trade uses the term "tenacity" to describe strength on a grams per denier (gpd) basis. This is because it is easier to determine a fiber's or yarn's weight per length than its weight per cross-sectional area, because yarn weight is an important textile physical and economic factor. Since denier is based upon weight per unit length, it is obvious that tenacity is influenced by the specific gravity of the fiber, while strength per unit area is not. The relationship between these properties is:

$$\text{tensile strength (lb per sq. in. or psi)} = 12{,}800 \times \text{tenacity (grams per denier or gpd)} \times \text{specific gravity} \tag{17.1}$$

In Table 17.4 tensile strengths are listed in psi and grams per denier for various fibers. The relationship between tex and denier is:

$$\text{tex} = \frac{\text{denier}}{9} \tag{17.2}$$

Textile fibers are relatively light, therefore they can be highly efficient on a strength-to-weight ratio basis. High tenacity nylon, for example, with a specific gravity of 1.14 may have a tenacity of 9 grams per denier (81 grams per tex) as compared with a high strength steel (500,000 psi) or about 3.5 gpd. On a cross-sectional area basis, high tenacity nylon has a strength exceeding 100,000 psi.

While textile fibers may have high tenacities, often the corresponding strength of the textile fabric is disproportionately lowered, due to the inefficient translation of fiber strength into yarn strength and yarn strength into fabric strength. This is particularly true with staple fibers. Because of non-uniform fiber lengths, interfiber slippage, random fiber orientation within the yarn, and the helical path of fibers due to yarn

Skechers EX1062
Skechers v Nike

TABLE 17.3 Fiber Diameters of Various Textile Fibers [3].

Denier	Viscose Rayon	Acetate and Vinyon	Nylon	Polyester	Olefin
1	9.6	10.3	11.1	10.1	12.5
2	13.6	14.5	15.7	14.3	17.7
3	16.7	17.8	19.3	17.5	21.7
4	19.3	20.6	22.3	20.2	25.0
5	21.6	23.0	24.9	22.6	28.0
6	23.6	25.2	27.3	24.8	30.7
7	25.5	27.3	29.5	26.8	33.1
8	27.3	29.1	31.5	28.6	35.4
9	28.9	30.9	33.4	30.4	37.5
10	30.5	32.6	35.2	32.0	39.6
12	33.4	35.7	38.6	35.1	43.3
14	36.1	38.5	41.7	37.9	46.8
16	38.6	41.2	44.5	40.5	50.1
18	40.9	43.7	47.3	42.9	53.1
20	43.1	46.1	49.9	45.3	56.0

twist, only a part of the theoretically available strength, based upon the number of fibers in the yarn cross section, will actually result in the yarn.

Cotton has a tenacity of about 3.0 to 4.9 gpd (27 to 44 gpt). Because it exists only as staple, its fiber strength is not completely convertible into equivalent yarn strength, the efficiency of the conversion being on the order of magnitude of 50%. Thus, cotton yarns usually have tenacities not in excess of about 3 gpd (27 gpt). The competitive advantages of multi-filament high tenacity rayon, nylon, or other synthetic yarns become obvious.

It should be apparent that strength per se is not the only criterion by which the performance of textiles should be judged. Textile yarns and fabrics are normally used because they have flexibility and moderate strength, coupled with the ability to deform or strain under load, thereby absorbing energy, and the ability to recover or retract when the load is removed. Many other chemical and physical properties will influence the ultimate selection of the fiber and the yarn and fabric into which it is converted.

5. FIBER BREAKING ELONGATION

Table 17.5 lists breaking elongations or strains which fibers can undergo up to the point of failure. As a general rule it can be stated that an inverse relationship exists between fiber strength and elongation. For natural cellulosic fibers, linen and ramie are stronger but have lower elongations than cotton; the animal fibers are much weaker but have greater elongations than the cellulosics. Glass fibers are very strong but very brittle, i.e., they have low elongations. In the manufacture of man-made fibers, for a particular generic type, a range of inverse strength-elongation values is normally obtainable. Thus nylon can be made with a tenacity of 9 gpd (81 gpt), an elongation of 12% or 5 gpd (45 gpt) and an elongation of 30%.

6. FIBER LOAD-ELONGATION DIAGRAMS

Figure 17.2 shows fiber tenacity (gpd) versus percent elongation diagrams. Often such diagrams are popularly but somewhat erroneously called "stress-strain" curves. Actually the tenacity scale should be converted to a pounds per square inch (psi) scale in order to produce a true stress versus strain diagram. A variety of fibers with a wide range of tenacity-elongation diagrams is available. The selection of a fiber for a particular purpose, of course, is dependent upon many property requirements. The shape of a fiber's load-elongation diagram, initially and after the fiber has been cyclically loaded and

Skechers EX1062
Skechers v Nike

TABLE 17.4 Tensile Properties of Fibers [2].

Fiber	Breaking Tenacity (gpd) Standard	Breaking Tenacity (gpd) Wet	Tensile Strength (psi)
Polyester			
A.C.E® and Compet®			
Filament–HT	8.3–9.0	9.0	135,000–160,000
Dacron®			
Staple and tow	2.4–7.0	2.4–7.0	39,000–106,000
POF	2.0–2.5	2.0–2.5	33,000–42,000
Filament–RT	2.8–5.6	2.8–5.6	50,000–99,000
Filament–HT	6.8–9.5	6.8–9.5	106,000–168,000
Fortrel®			
Staple series 400–RT	4.8–6.0	4.8–6.0	85,000
Staple series 300–HT	6.0–6.8	6.0–6.8	102,000
PO filament	2.0–2.5	2.0–2.5	80,000–88,000
Tairilin®			
POY	2.0–3.0	2.0–3.0	33,000–42,000
Staple	4.5–7.0	4.5–7.0	80,000–102,000
Trevira®			
Staple	3.5–6.0	3.5–6.0	41,000–105,000
POF	2.0–2.5	2.0–2.5	33,000–42,000
Filament–HT	7.2–8.2	7.2–8.2	118,000–140,000
Thornel® carbon			
High strength	24.1	24.1	550,000
High modulus	21.3	21.3	500,000
Ultra-high modulus	10.8	10.8	270,000
Nylon			
Nylon 6			
Staple	3.5–7.2		62,000–98,000
Monofil. and filament–RT	4.0–7.2	3.7–6.2	73,000–100,000
BCF–RT	2.0–4.0	1.7–3.6	
Filament–HT	6.5–9.0	5.8–8.2	102,000–125,000
Nylon 6,6			
Staple and tow	2.9–7.2	2.5–6.1	
Monofil. and filament–RT	2.3–6.0	2.0–5.5	40,000–106,000
Filament–HT	5.9–9.8	5.1–8.0	86,000–134,000
Tencel® lyocell–HT	4.8–5.0	3.8–4.2	
Rayon			
Fibro®			
RT–Multi-lobed	2.3	1.1	
IT–0.9 den or 0.25 in and up	3.0	1.5	
Cuprammonium, filament	1.95–2.0	0.95–1.1	
Rayon			
Filament–RT	1.9–2.3	1.0–1.4	
Filament–HT	4.9–5.3	2.8–3.2	
Saran®, monofilament	1.2–2.2	1.2–2.2	15,000–27,000
Acetate, filament and staple	1.2–1.4	0.8–1.0	20,000–24,000
Ryton® sulfar, staple	3.0–3.5	3.0–3.5	35,000–40,000
Acrylic			
Acrilan®, staple and tow	2.2–2.3	1.8–2.4	30,000–40,000
Creslan®, staple and tow	2.0–3.0	1.6–2.7	30,000–45,000
MicroSupreme, staple	2.0–3.0	1.6–2.7	30,000–45,000
SEF® modacrylic, staple	1.7–2.6	1.5–2.4	29,000–45,000

(continued)

Skechers EX1062
Skechers v Nike

TABLE 17.4 (continued).

Fiber	Breaking Tenacity (gpd) Standard	Breaking Tenacity (gpd) Wet	Tensile Strength (psi)
Olefin			
Polyethylene			
Monofilament, low density	1.0–3.0	1.0–3.0	11,000–35,000
Monofilament, high density	3.5–7.0	3.5–7.0	30,000–85,000
Herculon®			
Staple	3.5–4.5	3.5–4.5	41,000–52,000
Buff filament	3.0–4.0	3.0–4.0	35,000–47,000
Marvess® and Alpha®			
Staple and tow	2.0–5.0	2.0–5.0	60,000–100,000
Multifilament	2.5–5.5	2.5–5.5	20,000–50,000
Essera®, Marquesa Lana®, Pation® III			
BCF	2.5–3.5	2.5–3.5	30,000–40,000
Staple	2.5–4.0	2.5–4.0	30,000–45,000
Spectra® 900	30	30	375,000,000
Spectra® 1000	35	35	425,000,000
Fibrilon®			
Staple	2.5–5.5	2.5–5.5	12,000–60,000
Fibrillated	3.5–5.0	2.5–5.0	40,000–60,000
Multifilament–RT	2.5–5.5	2.5–5.5	20,000–50,000
Spandex			
Glospan®/Cleerspan, S-85, multifilament	0.7		11,000
Lycra®			
Type 126, 127	1.0		11,000–14,000
Type 128	0.8		
Glass			
Single filament–E-glass	15.3	15.3	450,000–550,000
Single filament–S-glass	19.9	19.9	650,000–700,000
Multifilament	9.6	6.7	313,000
Aramid			
Kevlar®			
Kevlar 29/Kevlar 49	23	21.7	425,000
Kevlar 149	18		340,000
Kevlar 68	24.0		425,000
Kevlar HT (129)	26.5		490,000
Nomex®, staple and filament	4.0–5.3	3.0–4.1	90,000
Fluorocarbon			
Gore-Tex®	3.0–4.0	3.0–4.0	85,000–115,000
Teflon®			
TFE multifil., staple, tow, flock	0.9–2.0	0.9–2.0	40,000–50,000
FEP, PFA monofilament	0.5–0.7	0.5–0.7	14,000–20,000
PBI, staple	2.6–3.0	2.1–2.5	50,000
Asbestos	2.5–3.1		80,000–300,000
Cotton	3.0–4.9	3.3–5.39	59,500–97,000
Silk	2.4–5.1	1.75–4.01	38,500–88,000
Wool	1.0–1.7	0.85–1.44	16,500–28,000
Steel	3.5	3.5	512,500

HT: high tenacity.
POF: partially oriented filament.
POY: partially oriented yarn.
RT: regular tenacity.
IT: intermediate tenacity.

Skechers EX1062
Skechers v Nike

TABLE 17.5 Breaking Elongation, Elastic Recovery, Stiffness and Toughness of Fibers [2].

Fiber	Breaking Elongation (%) Standard	Breaking Elongation (%) Wet	Elastic Recovery (%)	Average Stiffness (gpd)	Average Toughness (gpd)
Polyester					
A.C.E.® and Compet®					
Filament–HT	13–22	13–15	77 at 5%; 75 at 10%	55–56	0.7–0.9
Dacron®					
Staple and tow	12–55	12–55	82 at 3%	12–17	0.2–1.1
POF	120–150	120–150			1.3–1.8
Filament–RT	24–42	24–42	76 at 3%	10–30	0.4–1.1
Filament–HT	12–25	12–25	88 at 3%	30	0.5–0.7
Fortrel®					
Staple series 400–RT	44–55	44–55			1.3–1.8
Staple series 300–HT	24	24			
PO filament	120–150	120–150			
Tairilin®					
POY	120–170	120–170			1.3–1.8
Staple	28–6	28–55	88 at 3%	10–30	0.3–1.5
Trevira®					
Staple	18–60	18–60	67–86 at 2% 57–74% at 5%	7–31	0.28–1.50
POF	130–145	130–145			1.3–1.8
Filament–HT	10–20	10–20	99 at 1%	54–77	0.35–0.55
Thornel® carbon					
High strength	1.6	1.6	100	1,500	
High modulus	1.0	1.0	100	2,300	
Ultra-high modulus	0.38	0.38	100	3,000	
Nylon					
Nylon 6					
Staple	30–90	42–100	100 at 2%	17–20	0.64–0.78
Monofil. and filament–RT	17–45	20–47	98–100 at 1–10%	18–23	0.67–0.90
BCF–RT	30–50	30–60			
Filament–HT	16–20	19–33	99–100 at 2–8%	29–48	0.75–0.84
Nylon 6,6					
Staple and tow	16–75	18–78	82 at 3%	10–45	0.58–1.37
Monofil & filament–RT	25–65	30–70	88 at 3%	5–24	0.8–1.25
Filament–HT	15–28	18–32	89 at 3%	21–58	0.8–1.28
Tencel® lyocell–HT	14–16	16–18		30	0.34
Rayon					
Fibro®					
RT–Multi-lobed	18–22				
IT–0.9 den or 0.25 in and up	18–22				
Cuprammonium, filament	8–14	24–28			
Rayon					
Filament–RT	20–25	24–29			
Filament–HT	11–14	13–16			
Saran®, monofilament	15–25	15–25	95 at 5–10%	5–10	0.165–0.265
Acetate, filament and staple	25–45	35–50	48–65 at 4%	3.5–5.5	0.17–0.30
Ryton® sulfar, staple	35–45		100 at 2%; 86 at 10%	10–20	
Acrylic					
Acrilan®, staple and tow	40–55	40–60	99 at 2%; 89 at 5%	5–7	0.4–0.5
Creslan®, staple and tow	35–45	41–50		6–8	0.62
MicroSupreme, staple	30–40	30–40		6–8	0.62
SEF® modacrylic, staple	45–60	45–65	100 at 1%; 95 at 10%	3.8	0.5

(continued)

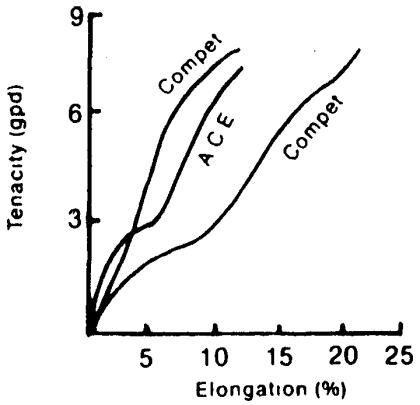
Skechers EX1062
Skechers v Nike

TABLE 17.5 (continued).

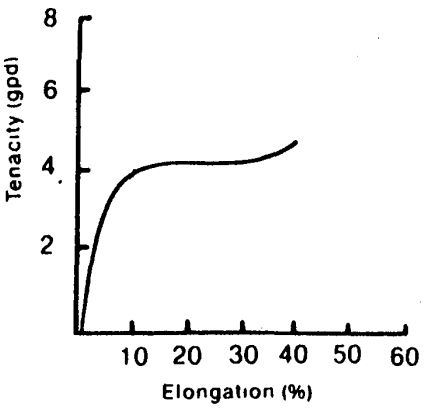
Fiber	Breaking Elongation (%) Standard	Breaking Elongation (%) Wet	Elastic Recovery (%)	Average Stiffness (gpd)	Average Toughness (gpd)
Olefin					
Polyethylene					
Monofilament, low density	20–80	20–80	Up to 95 at 5% 88 at 10%	2–12	0.3
Monofilament, high density	10–45	10–45	Up to 100 at 1–10%	20–50	
Herculon®					
Staple	70–100	70–100	96 at 5%; 90 at 10%	20–30	1–3
Buff filament	80–100	80–100	96a at 5%; 90 at 10%	20–30	1–3
Marvess® and Alpha®					
Staple and tow	60–100	80–98	90–93 at 5%; 83 at 10%	3–10	1.5–4
Multifilament	20–50	85–99	92–96 at 5%; 87 at 10%	12–25	0.75–3.00
Essera®, Marquesa Lana®, Pation® III					
BCF	40–60	40–60	90 at 5%; 65–90 at 10%	5–10	0.9–1.05
Staple	30–450	30–450			
Spectra® 900	3.6	3.6		1,400	
Spectra® 1000	2.7	2.7		2,000	
Fibrilon®					
Staple	30–150	30–150	93 at 5%; 85 at 10%		
Fibrillated	14–18	14–18	85 at 5%; 75 at 10%		
Multifilament–RT	30–100	30–100	95 at 5%; 85 at 10%	12–25	0.75–3.00
Spandex					
Glospan®/Cleerspan, S-85, multifilament	600–700		99% at 50% (S-7) 98% at 200% (S-5)	0.17 (S-7) 0.05 (S-5)	
Lycra®					
Type 126, 127	400–625		97 at 50%	0.13–0.20	2.00
Type 128	800		99 at 200%		
Glass					
Single filament–E-glass	4.8	4.8	100	320	0.37
Single filament–S-glass	5.3–5.7	5.3–5.7	100	380	0.53
Multifilament	3.1	2.2	100	310	0.15
Aramid					
Kevlar®					
Kevlar, Kevlar 29/Kevlar 49	4.0/2.5	4.0/2.5	100 at 1%, 2%, 3%	500/900	
Kevlar 149	1.5		100 at 1%	1,110	
Kevlar 68	3.0		100 at 1%, 2%	780	
Kevlar HT (129)	3.3		100 at 1%, 2%	755	
Nomex®, staple and filament	22–32	20–30		70–120	
Fluorocarbon					
Gore-Tex®	5–20	5–20			
Teflon®					
TFE multifil., staple, tow, flock	19–140	19–140		1.0–13.0	0.15
FEP, PFA monofilament	40–62	40–62		7.0	0.10–0.12
PBI, staple	25–30	26–32		9–12	0.40
Cotton	3–7		74 at 2%; 45 at 5%	60–70	0.15
Silk	10–25		92 at 2%; 51 at 10%	60–116	0.4–0.8
Wool	25–35	25–50	99 at 25%; 63 at 20%	4.5	0.35

HT: high tenacity.
POF: partially oriented filament.
POY: partially oriented yarn.
RT: regular tenacity.
IT: intermediate tenacity.

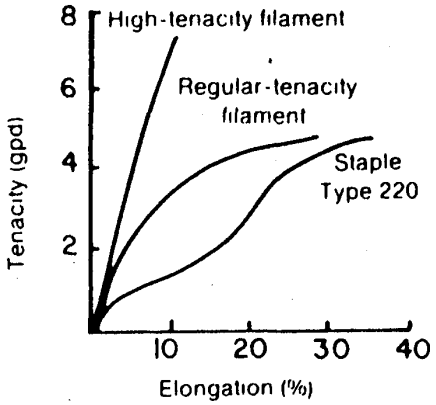
Skechers EX1062
Skechers v Nike



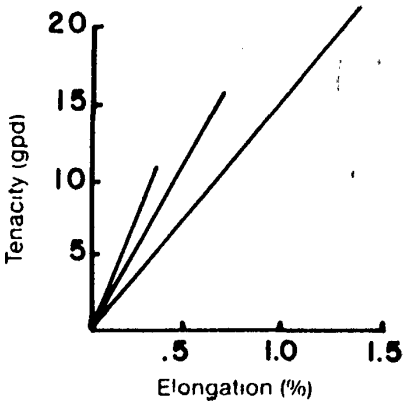
A.C.E.*, Compet*
Polyester



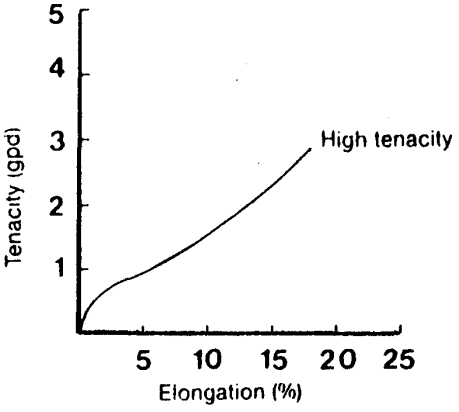
Polyester



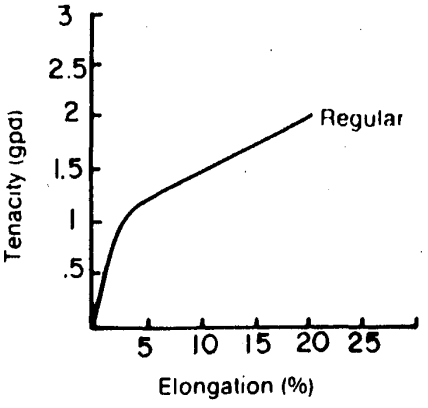
Trevira*
Polyester



Thornel*
Carbon



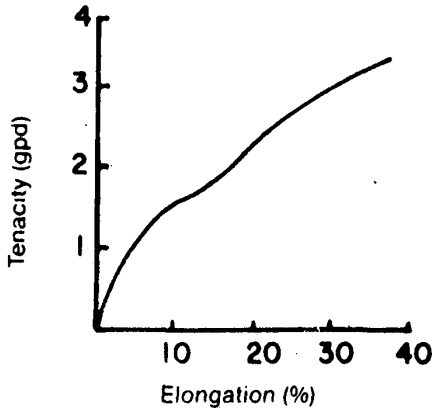
Fibro*
Rayon



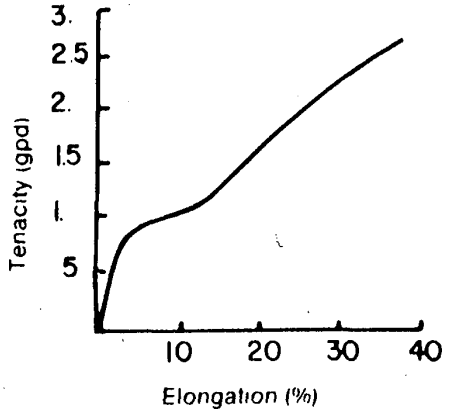
Cuprammonium

FIGURE 17.2 Typical tenacity versus elongation diagrams of fibers (courtesy of McLean Hunter Publishing Co.).

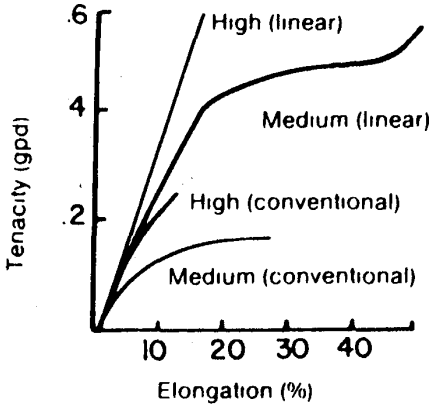
Skechers EX1062
Skechers v Nike



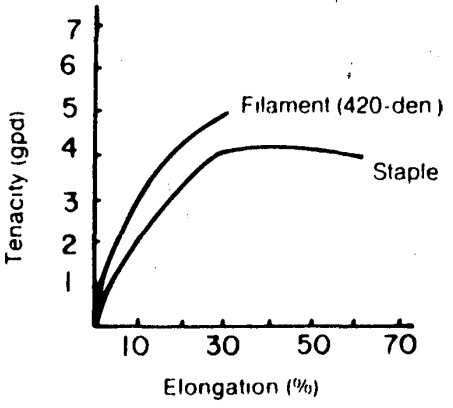
Ryton*
Sulfar



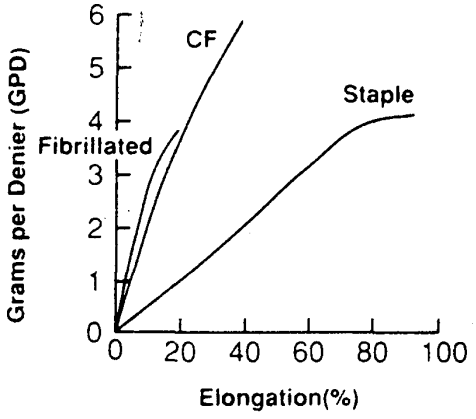
Acrilan*
Acrylic



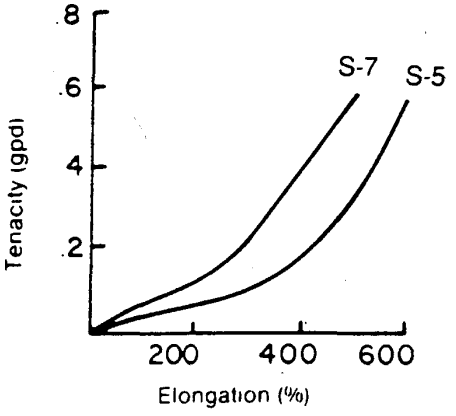
Polyethylene



Herculon*
Olefin



Fibrilon*
Olefin



Glospan*
Spandex

FIGURE 17.2 (continued) Typical tenacity versus elongation diagrams of fibers (courtesy of McLean Hunter Publishing Co.).

Skechers EX1062
Skechers v Nike

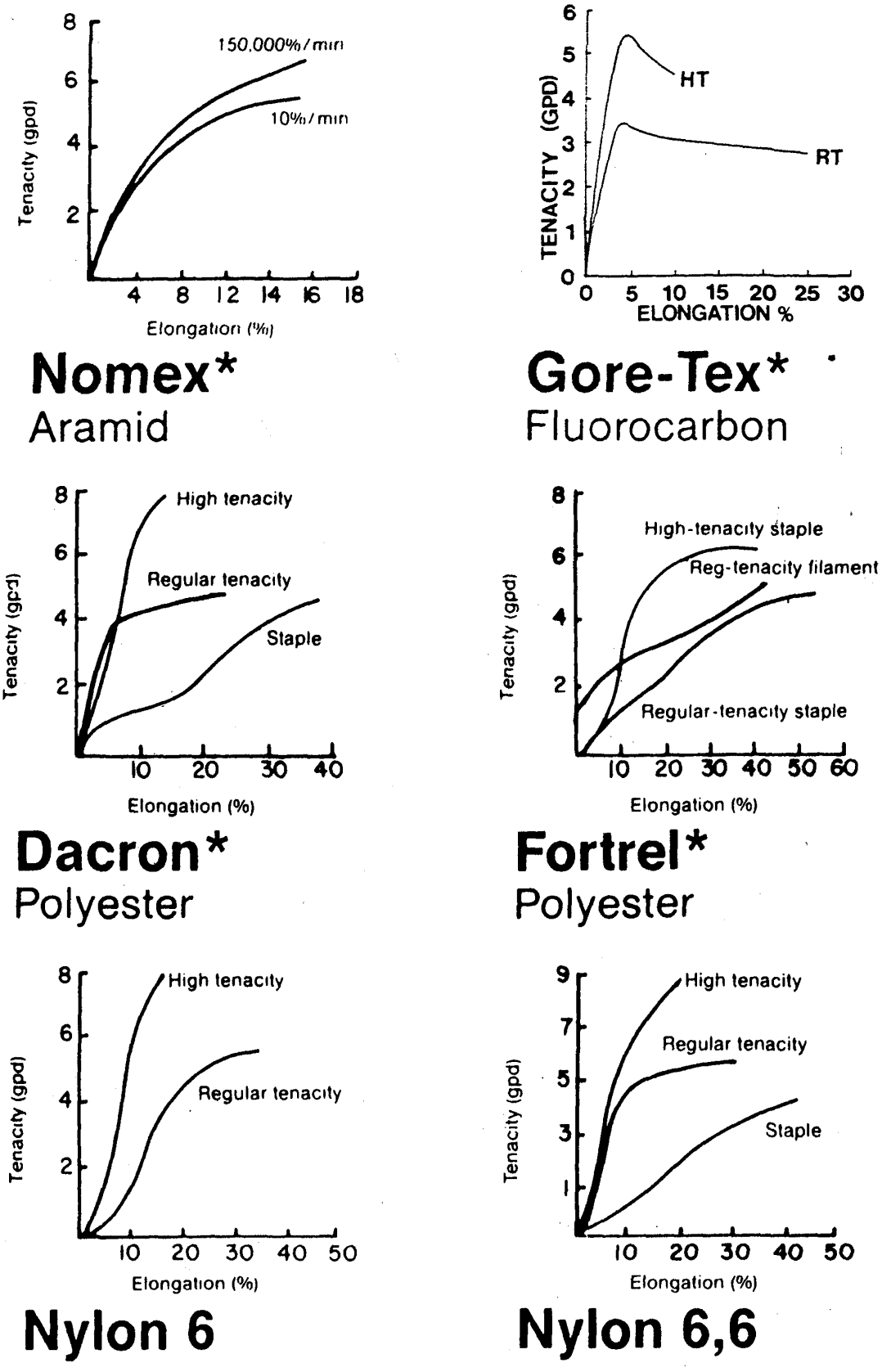


FIGURE 17.2 (continued) *Typical tenacity versus elongation diagrams of fibers (courtesy of McLean Hunter Publishing Co.).*

Skechers EX1062
Skechers v Nike

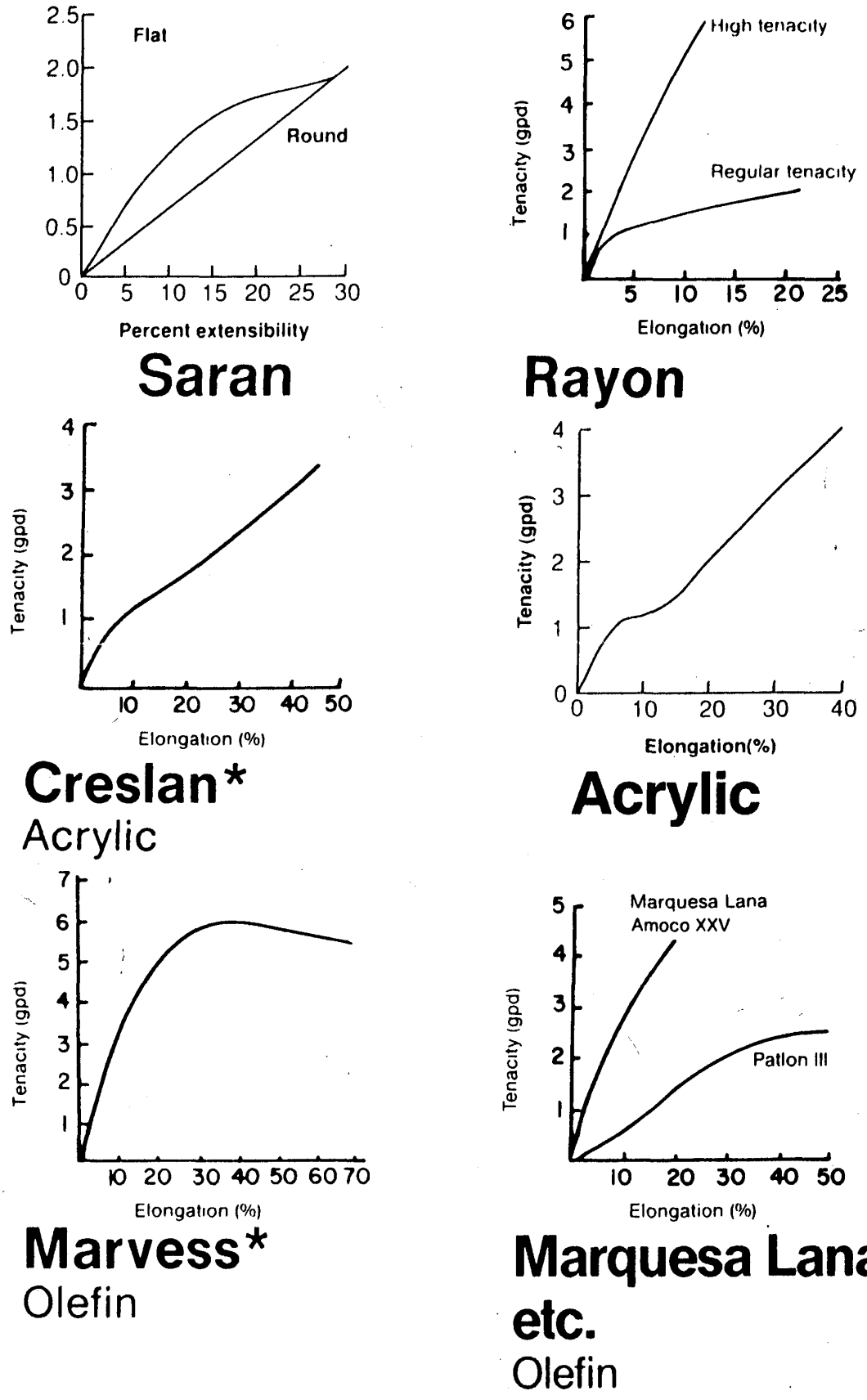
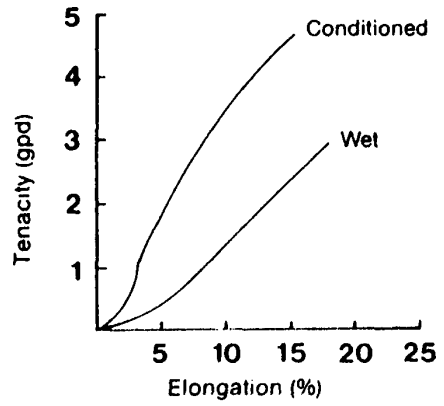
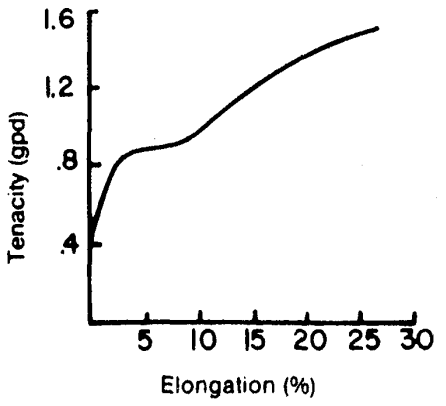


FIGURE 17.2 (continued) Typical tenacity versus elongation diagrams of fibers (courtesy of McLean Hunter Publishing Co.).

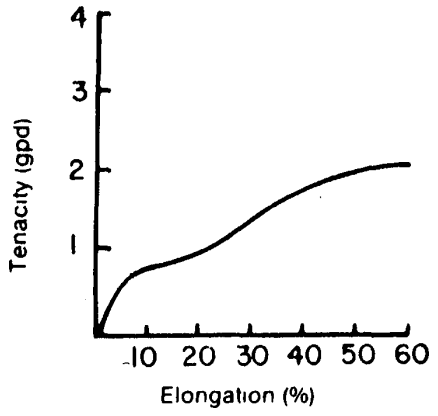
Skechers EX1062
Skechers v Nike



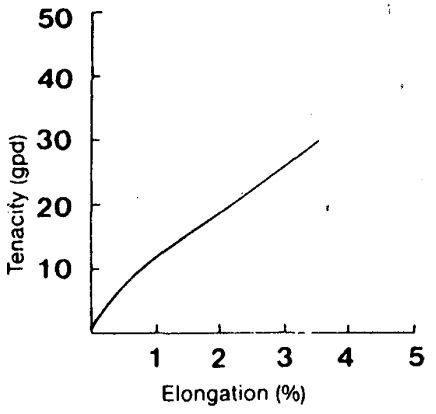
Tencel*
Lyocell



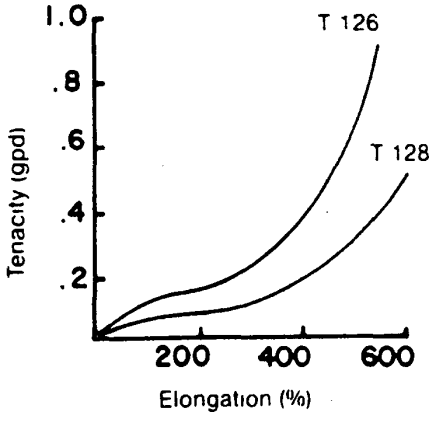
Acetate



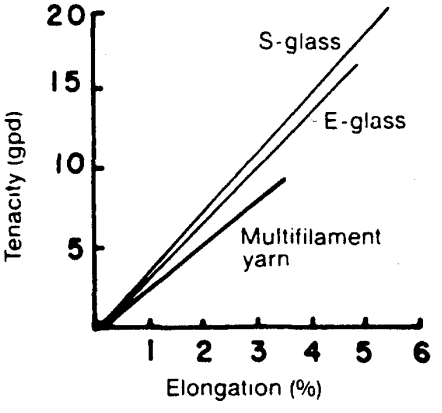
SEF*
Modacrylic



Spectra 900*
Olefin



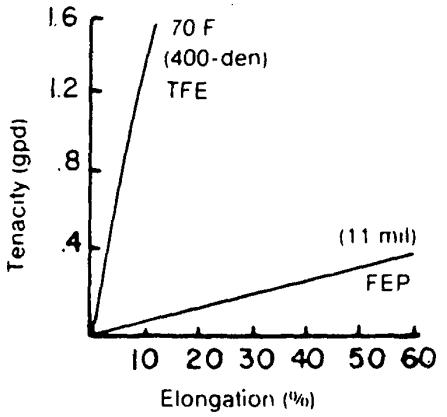
Lycra*
Spandex



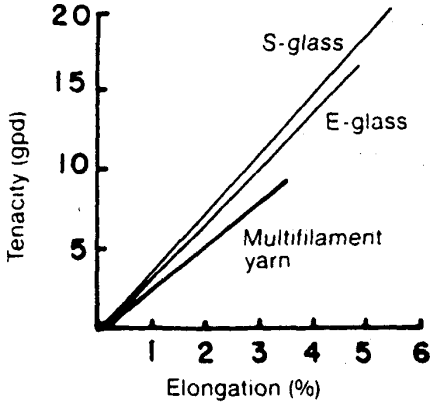
Glass

FIGURE 17.2 (continued) Typical tenacity versus elongation diagrams of fibers (courtesy of McLean Hunter Publishing Co.).

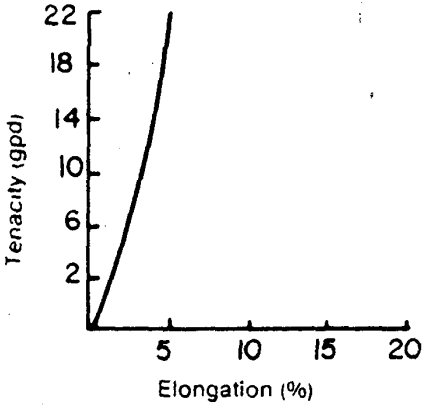
Skechers EX1062
Skechers v Nike



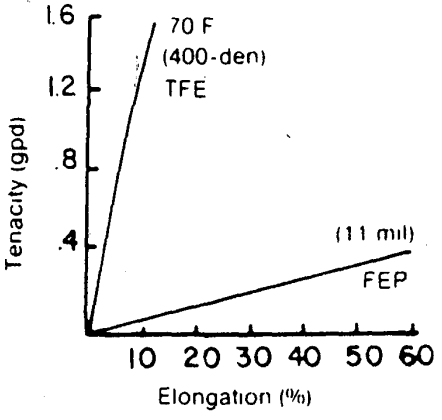
Teflon*
Fluorocarbon



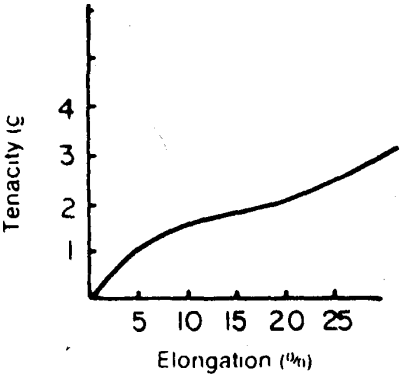
Glass



Kevlar*
Aramid



Teflon*
Fluorocarbon



PBI
Polybenzimidazole

FIGURE 17.2 (continued) Typical tenacity versus elongation diagrams of fibers (courtesy of McLean Hunter Publishing Co.).

Skechers EX1062
Skechers v Nike

unloaded at loads below rupture, is important in terms of the fiber's influence on such fabric properties as breaking and tear strength, energy absorption, dimensional stability, and abrasion resistance.

7. VISCOELASTICITY

Examination of fiber load-elongation diagrams shows that they are normally "non-Hookean," i.e., they do not obey Hooke's law which states that the strain (elongation) is linearly proportional to the applied stress (load). Figure 17.3 for a typical polyester, for example, shows an original region OA which is approximately linear. Point A is called the "proportional limit." Beyond this point, region AB develops where additional incremental loads produce proportionately larger increases in elongation, due to the propensity of the fiber to "creep," or slowly elongate under load. A slope change occurs at point B, followed by a stiffening region BC where additional loads beyond B cause smaller changes in elongation. Finally there is a second flow region CD.

Textile fibers and other high polymers such as rubbers, elastomers, films, and plastics which exhibit such varying "stress-strain" properties are stated to be "viscoelastic." The molecular and structural nature of these materials is such that during selected periods of progressive loading, they may function in a perfectly "elastic" or "spring-like" manner. During other periods of loading a "viscous flow" or creep type of deformation occurs. These two mechanisms most often act in varying contributory amounts at the same time and thus produce a viscoelastic type of stress-strain response.

The above description pertains to the application of a tensional force in one time loading to rupture. If a specimen is strained (elongated) to a value below rupture and the strain producing force is then removed, a strain recovery will usually take place. Repeated load applications and removals produce strains and recoveries which are dependent upon the material's viscoelastic properties. The phenomenon becomes complex, giving rise to hysteresis [Figure 17.10(b)]. The elongation recovery or "repeated stress" characteristics of fibers is discussed later in the chapter. They are of great significance because they influence such properties as fabric dimensional stability, wrinkle resistance, abrasion resistance, and energy absorption.

8. ELASTIC MODULUS

The ratio of stress to strain is called the "modulus" of a material. High modulus materials are stiff; they show small elongation under

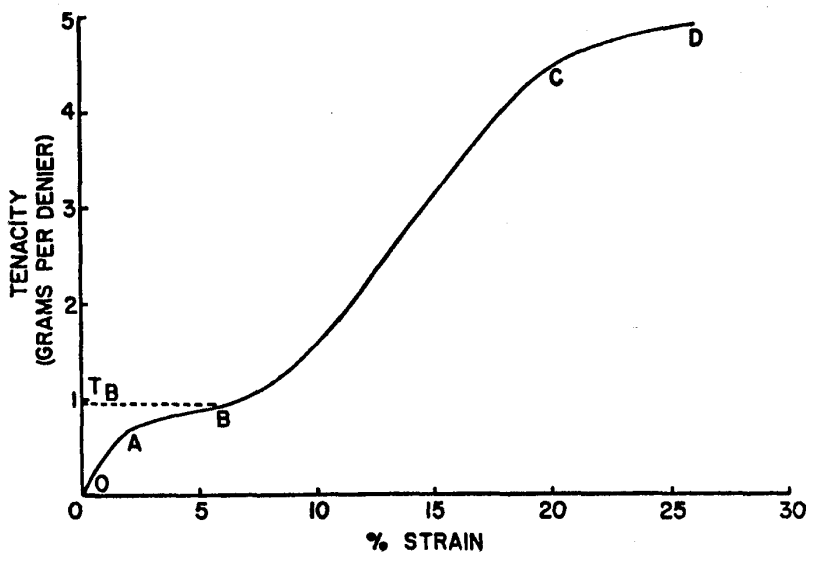


FIGURE 17.3 Analysis of a typical polyester tenacity-elongation diagram.

Skechers EX1062
Skechers v Nike

load. Low modulus materials are extensible; they show high elongation under load. "Young's modulus" is defined by ASTM as the ratio of change in stress to change in strain within the elastic limit of the material. The ratio is calculated from the stress, expressed in force per unit cross-sectional area, and the strain, expressed as a fraction of the original length. Young's modulus is of great value to the engineers utilizing wood, structural steel, and concrete since these materials are used below their elastic limits, and small deformations under load can be calculated with a reasonable degree of precision. The textile engineer and technologist also make use of this ratio, but because load-elongation diagrams of textiles are not usually linear over their entire use range, the "tensile modulus" of a fiber is not a constant and should be used only under conditions where it is properly defined. ASTM also lists the following moduli definitions for textile materials:

- initial modulus: the slope of the initial straight-line portion of the stress-strain curve
- chord modulus: the ratio of the change in stress to the change in strain between two specified points in the stress-strain curve

8.1 Determination of Initial Modulus

In the case of a fiber exhibiting a region that obeys Hooke's law (i.e., has a linear region), a continuation of the linear region of the curve is constructed as shown in Figure 17.4. The intersection point B is the zero-strain point from which strain is measured. The initial modulus is

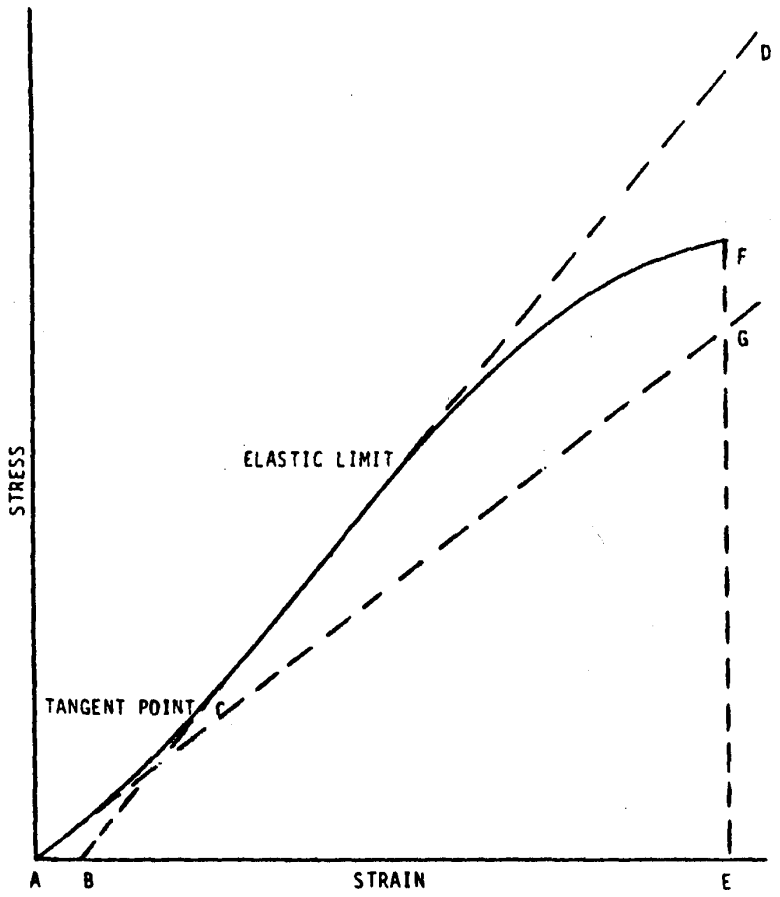


FIGURE 17.4 Construction of initial modulus for materials with Hookean region [4].

Skechers EX1062
Skechers v Nike

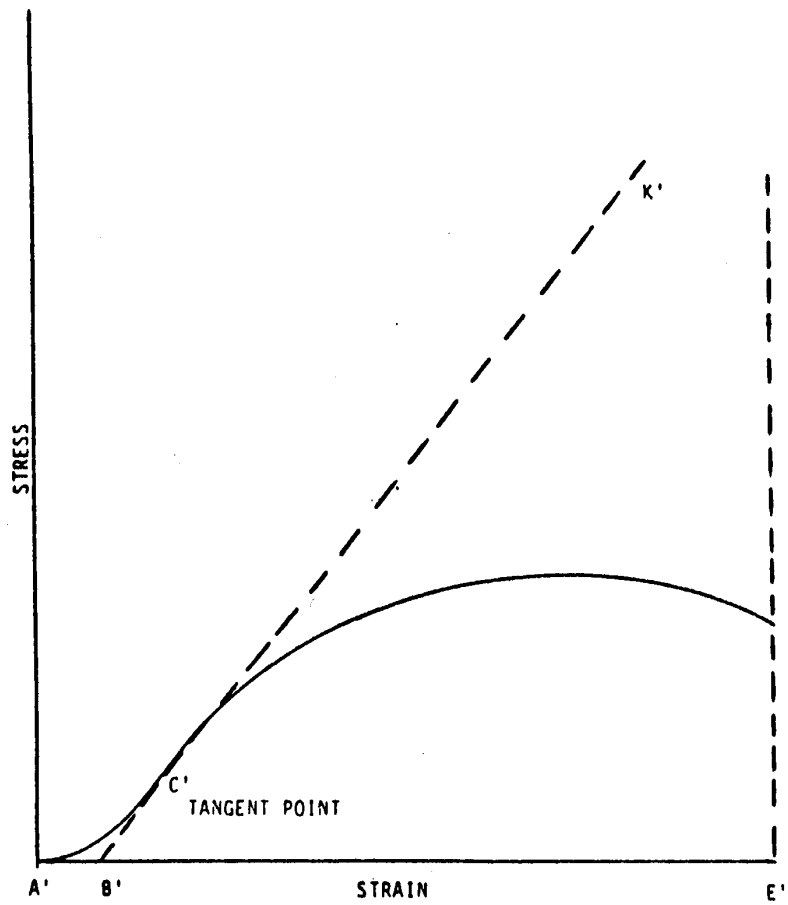


FIGURE 17.5 Construction of initial modulus for materials with no Hookean region [4].

determined by dividing the stress at any point along the line BD by the strain at the same point (measured from point B). Point C, the point where line BD first touches the stress-strain curve is the tangent point.

In the case of a fiber that does not exhibit any linear region (Figure 17.5), a tangent K′B′ is constructed to the maximum slope. Point B′ is the zero point from which strain is measured. Point C′, the point where line K′B′ first touches the stress-strain curve, is the tangent point. The initial modulus is determined by dividing the stress at any point along line B′K′ by the strain at the same point (measured from point B′).

8.2 Determination of Chord Modulus

In a typical stress-strain curve, a straight line is constructed through the zero-stress axis, such as zero strain point A″ and a second point, such as 10% strain, point M″ (Figure 17.6). The chord modulus is determined by dividing the stress at any point along line A″M″ (or its extension) by the strain at the same point.

Figure 17.6 also represents a straight line constructed through any two specified points, point Q″ and point R″, other than zero and 10% strain. In this case, the line extends through the zero stress axis at point B″. This intersection is the zero strain point from which strain is measured. The chord modulus can be determined by dividing the stress at any point along line Q″R″ (or its extension) by the strain at the same point (measured from point B″).

The modulus is also called the "stiffness" of the material since the higher the modulus the greater the resistance to deformation.

Skechers EX1062
Skechers v Nike

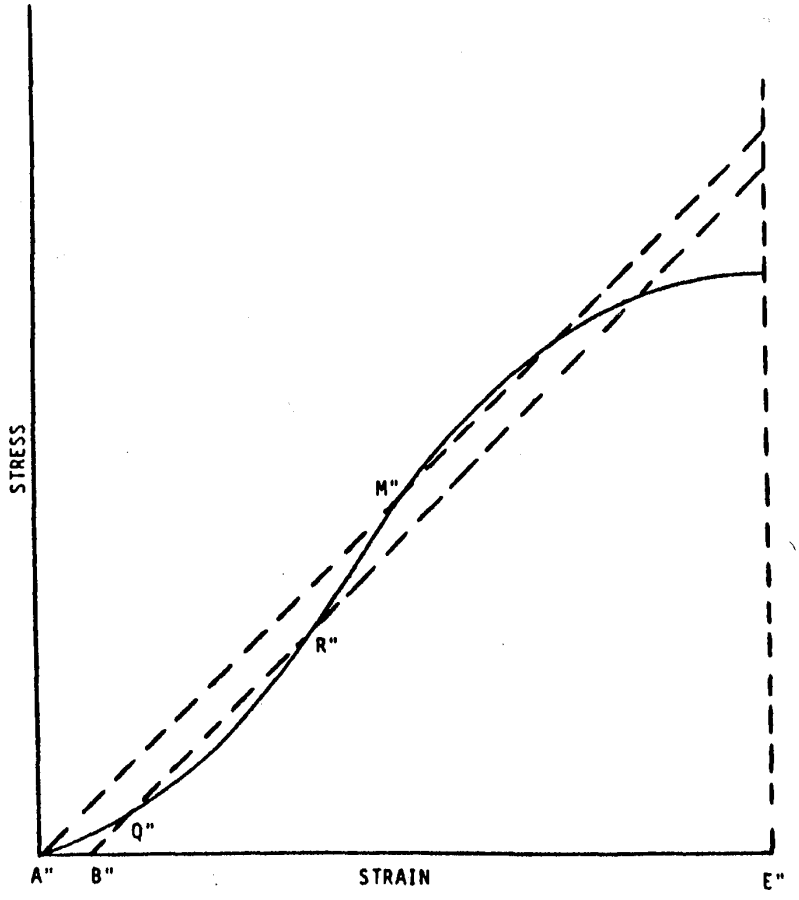


FIGURE 17.6 *Construction of chord modulus* [4].

Since engineering stress is given in pounds per square inch, modulus units for engineering materials normally are reported as psi per unit strain, or simply psi. Again, because convenient textile nomenclature uses the denier system, Young's moduli of fibers are reported as grams per denier per unit strain, i.e., the hypothetical tenacity required to strain the filament 100%, presuming strain extended at a rate equal to that of the initial slope of the stress-strain curve. The modulus (stiffness) is usually reported simply as "grams per denier." Moduli of major textile fibers are given in Table 17.5. Extensible fibers such as wool, acetate and acrylic have low textile moduli. Nylon and polyester can be drawn to varying degrees so that their moduli may have varying ranges (on the average, polyester slightly higher than nylon). Glass at 300 has a high modulus. However, carbon, Spectra® olefin, and Kevlar® aramid fibers have moduli far above the range of other textile fibers. This is why these high modulus fibers, yarns, or fabrics are used in plastic laminates where minimum distortion under load is required. However, because of their high modulus and inability to deform under load (i.e., brittleness), excessively high stress concentrations may be induced in these fibers, and they may fail. In other low modulus fibers, the high strains resulting from the application of the non-uniform loads reduce the stress concentration, and the fiber can remain intact. This, among other reasons, is why high modulus fibers have not found wide use in textile fabrics where repeated flexing and abrasion, both being examples of non-uniform loading, are required. In uses where deformations are necessary, particularly under impact conditions, low modulus ma-

Skechers EX1062
Skechers v Nike

terials are advantageous, for the material will then extend rather than permit the buildup of an excessive force.

9. TOUGHNESS OR ENERGY ABSORPTION

The load-elongation diagram is a measure of work done or energy absorbed by the filament. This property is also called "toughness." Units normally are grams per denier (or tex). Table 17.5 lists energy absorption capacities of the various fibers.

Figure 17.7 shows that equal areas (i.e., energies) under a load-elongation diagram can be obtained via many different paths. For example, the area bounded by OBC is equal to OB′C′; but for Case I it is obtained via high strength and low elongation, while for Case II the strength is lower but the elongation is higher.

Except in those cases where energy must be absorbed with a minimum amount of deformation or elongation in the specimen, in order that the material maintain its dimensional stability, a combination of load bearing and elongation capacities is usually desirable. For example, glass is strong but its elongation is too low to be a good energy absorber. Wool is weak but is quite extensible, and so can absorb significant amounts of energy. However, because its load supporting capability is low and because the wool yarn, cord or fabric would become highly distorted, normally it is not used for industrial purposes. Cotton, high tenacity rayon, and especially polyester and nylon are tough, and hence have been widely used in ropes, conveyor belts, bagging, webbings, tents, awnings, and a wide array of industrial uses where a combination of lightness, strength, and toughness is required. Such end items usually are used many times, and therefore a further requirement is that they can repeatedly deform and absorb energy under load, and retract when the load is removed.

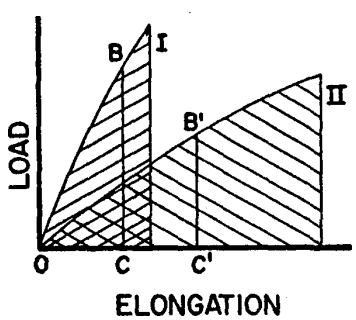


FIGURE 17.7 Energy absorption diagram.

10. ELONGATION-RECOVERY PROPERTIES

If a vertically suspended textile fiber is dead-loaded with a weight equal, for example, to about half of its breaking load, the fiber will immediately elongate a fixed amount (Figure 17.8, part A). This elongation from 0 to 1 is called the "instantaneous elastic deflection" (IED). If the weight is then left hanging on the fiber for many minutes or hours, the fiber will continue to elongate or "creep" at a slow rate from 1 to 2 (part B). If the weight is then removed, the fiber will immediately and instantaneously recover or spring back by an amount approximately equal to the original IED. The recovery (from 2 to 3, part C) is called the "instantaneous elastic recovery" (IER). If the weight is then kept off, the fiber will tend to "creep back" and return to its original length. The amount which it recovers (3 to 4, part D) is called "primary creep" or "creep recovery." The amount by which it fails to return to its original length (4 to 0), is called "secondary creep" or "permanent set." Diagrammatically, the elongation versus time curve is depicted in Figure 17.9.

The instantaneous elastic deflection obeys Hooke's law, which states that the strain (elongation) is linearly proportional to the applied stress. Thus, if progressively increasing weights are hung on the fiber, the resulting IED's will be proportional to the applied loads and a linear load-IED diagram results. The creep portion of the elongation is the viscous effect referred to earlier. While, in practice, textiles may be dead loaded under a constant force, more often they are subjected to a heterogeneous combination of repeated below-rupture stresses and strains. When a specimen is progressively loaded to a

Skechers EX1062
Skechers v Nike

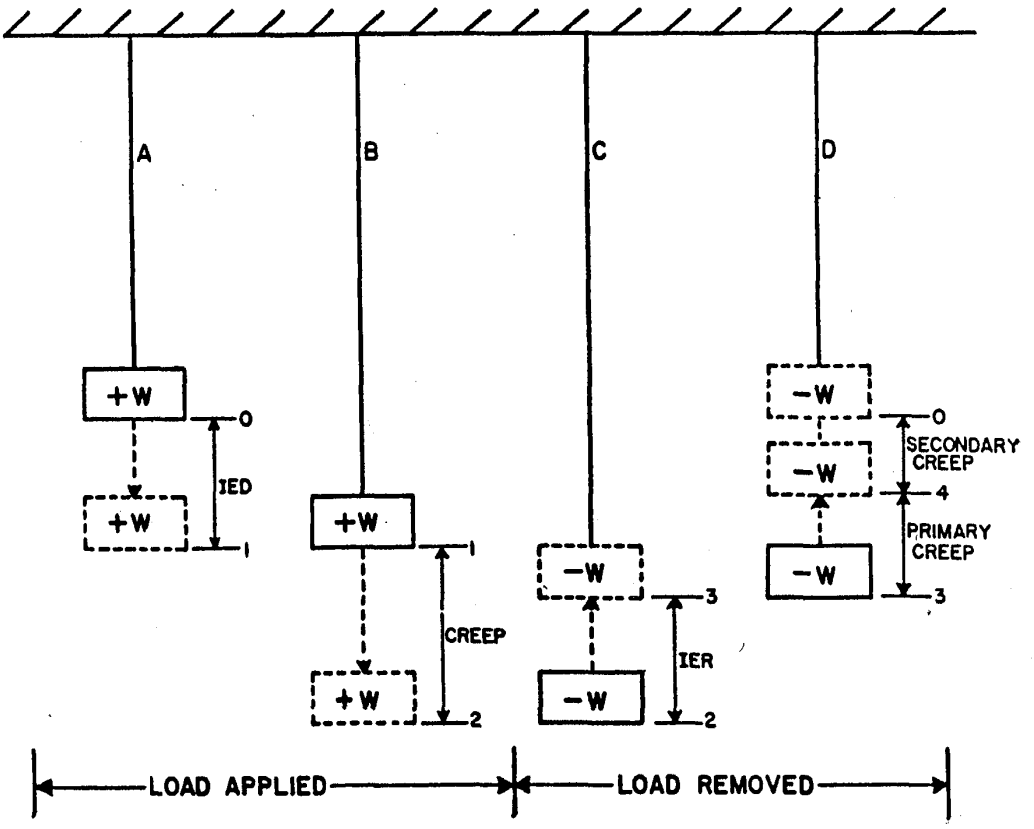


FIGURE 17.8 Elongation properties of a fiber under constant load.

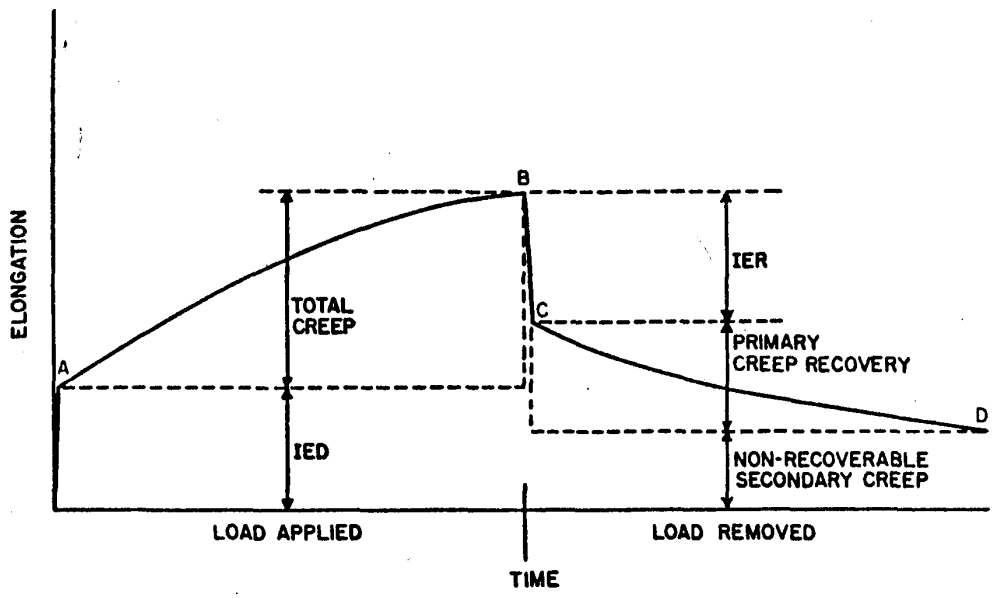


FIGURE 17.9 Elongation as a function of time under constant load and load removal.

Skechers EX1062
Skechers v Nike

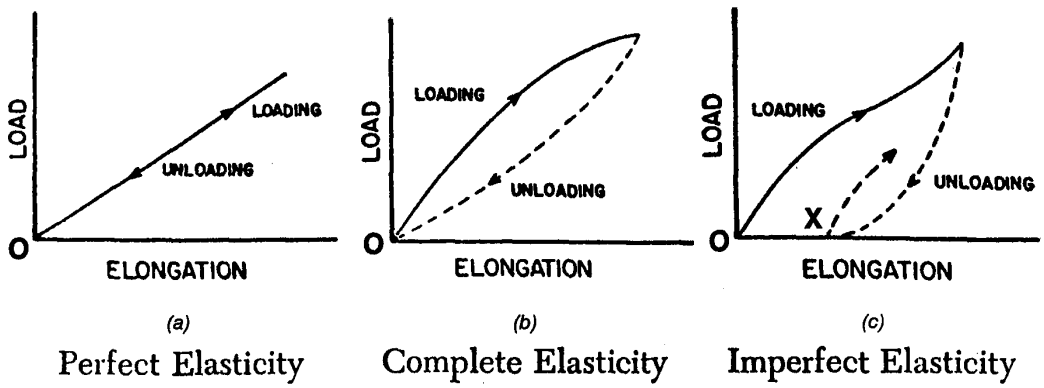


FIGURE 17.10 Three types of elasticity.

level below its rupture point, and then the load is progressively removed, one of the three types of load-elongation-recovery diagrams shown in Figure 17.10 will result.

Figure 17.10(a) depicts a truly Hookean material where the strain (elongation) is proportional to the applied stress (load) over the entire curve. Only instantaneous elastic deflection and recovery exist, thus producing a straight line for both loading and unloading, the two lines being superimposed at all points. Such a condition represents "perfect elasticity."

Figure 17.10(b) represents a condition where the strain is not proportional to the load, thus creep causes additional elongation. However, all the creep is primary, and upon load removal, complete recovery takes place, but via a path different from the loading curve, thus producing a "hysteresis" area. The primary creep recovery, while complete, is delayed and requires a longer recovery than the original loading time to be completed. Such a condition represents "complete elasticity." Figure 17.10(c) also represents a condition where the strain is not proportional to the load, thus creep causes additional elongation. Here, however, secondary as well as primary creep exists. Upon load removal recovery is incomplete, and a "permanent set" represented by O-X results. Such a condition represents "imperfect (and incomplete) elasticity."

Significance of Elongation-Recovery Properties

The abilities to deform upon load application and recover upon load removal are two of the most important properties which textile fabrics must have. Several pertinent examples are cited.

(1) Ability to absorb energy repeatedly—In order to be repeatedly useful, pump diaphragms, aircraft arrestation cables, conveyor belts, tire cords, fire hoses, crane slings, and the like must be capable of retracting absorbing energy. This is accomplished by the materials' elongation under load. If a fabric is to be used more than once, it must be capable of retracting to its original dimension after use in order that it again will have the ability to absorb an equal amount of energy on second or subsequent uses. If most of the elongation is non-recoverable secondary creep, the energy absorption capacity on a subsequent use will be significantly reduced to the point where failure may result.

(2) Ability to maintain dimensional stability—A tarpaulin, truck cover, auto seat cover, or tent may be subjected to deforming forces resulting from handling, or wind and weather. Its ability to deform or "roll with the punch" on load application, and return to its original dimension on load removal is necessary if the fabric is to be capable of absorbing stresses and strains repeatedly without becoming distorted and out-of-shape. In the case of conveyor belts, while high modulus-low elongation fabrics are usually demanded to keep "stretch" to a minimum, nevertheless the ability of the material to "give" slightly under load and recover upon load removal is a prerequisite.

Skechers EX1062
Skechers v Nike

(3) Wrinkle resistance—When fabrics are creased, yarns and fibers are bent in a manner such that some portions are in compression, and others are in tension. Creases which develop will be removable as a function of the ability of the fibers to recover from the imposed strains.

(4) Abrasion resistance—As will be discussed later in the chapter, a fabric's abrasion resistance is governed in part by the capacity of its fibers to absorb energy repeatedly at stresses below rupture. The fibers must be able to deform under the force produced by the abrasive action and to recover when the force is removed. Then, upon a subsequent abrasion stroke, the fibers again can deform and absorb energy without failure.

Table 17.5 shows the percent recovery of fibers which have been strained by varying amounts. After being strained 2%, staple Nylon 6, upon load removal, will recover to its original unstrained dimension. The Nylon 6 is thus said to recover 100% from the 2% strain. After 3% strain, regular tenacity Nylon 6,6 recovers 88%. This recovery capability, coupled with its high energy absorption permits it to repeatedly absorb large quantities of energy, thus accounting for nylon's excellent abrasion resistance.

11. RATE OF RECOVERY PROPERTIES

The more quickly and completely a fiber recovers from an imposed strain, the more nearly perfectly elastic it is. The ratio of the instantaneous elastic deflection to the total deflection may be used as a criterion of elasticity. The integrated closeness from a theoretical graph of perfect elasticity versus elongation is also used as a criterion under the term "elasticity index."

12. BENDING, COMPRESSION, SHEAR, AND TORSION STRAINS

In addition to tensile forces and strains, there are four other types of deformations to which engineering materials including textiles, may be subjected. These are simple compression, shear, torsion, and bending (Figure 17.11).

One of the outstanding attributes which a textile fiber must have is flexibility. In fact, this requirement probably should be included as an integral part of the definition of a textile fiber. The ability of the fiber repeatedly to bend and recover without failure is vital for most fabric uses. The stiffness of a textile fiber or any structural beam, is directly proportional to its elastic modulus, and to the fourth power of its diameter. The modulus is governed by the intrinsic nature of the fiber substance, i.e., the arrangement of atoms in the molecule, the amount of crystallinity, and the molecular orientation.

Organic fibers, in general, have stiffness moduli in the range of 10 to 200 grams per denier (Table 17.5). Rubbery or elastomeric materials have moduli of about 0.1 to 0.5 gpd. Glass, metals, and ceramics are in the range of 250 to 350. Conventional organic fibers have sufficient flexibility for most textile uses when their diameters are in the 10 to 70 micron range. In order for glass, ceramic, and metallic fibers to enjoy equal flexibility, they must be of even smaller diameter because of their higher moduli. Furthermore, the stiffness increases in direct proportion to the fourth power of the diameter, and so it becomes obvious that high modulus fibers must be drawn to very fine diameters if they are to be sufficiently flexible to perform as textiles. Furthermore, the specific gravities of glass, ceramics, and metals are considerably higher than the organic polymers. Therefore, inorganic fiber diameters must be small, not only to attain flexibility, but also to reduce fiber weight.

In simple compression, forces act in opposition to the direction they assume for tension. In the case of textiles, unless the fiber, yarn, or fabric is very short; true and complete compression does not exist, for the fiber will buckle and bending will result. This produces tension on the outside portion of the fiber and compression on the inside. Similarly, torsion and shear forces are negligible in flexible textile fibers, since the initial development of such forces produces strains in the material of such a magnitude that the forces immediately become tensional.

Skechers EX1062
Skechers v Nike

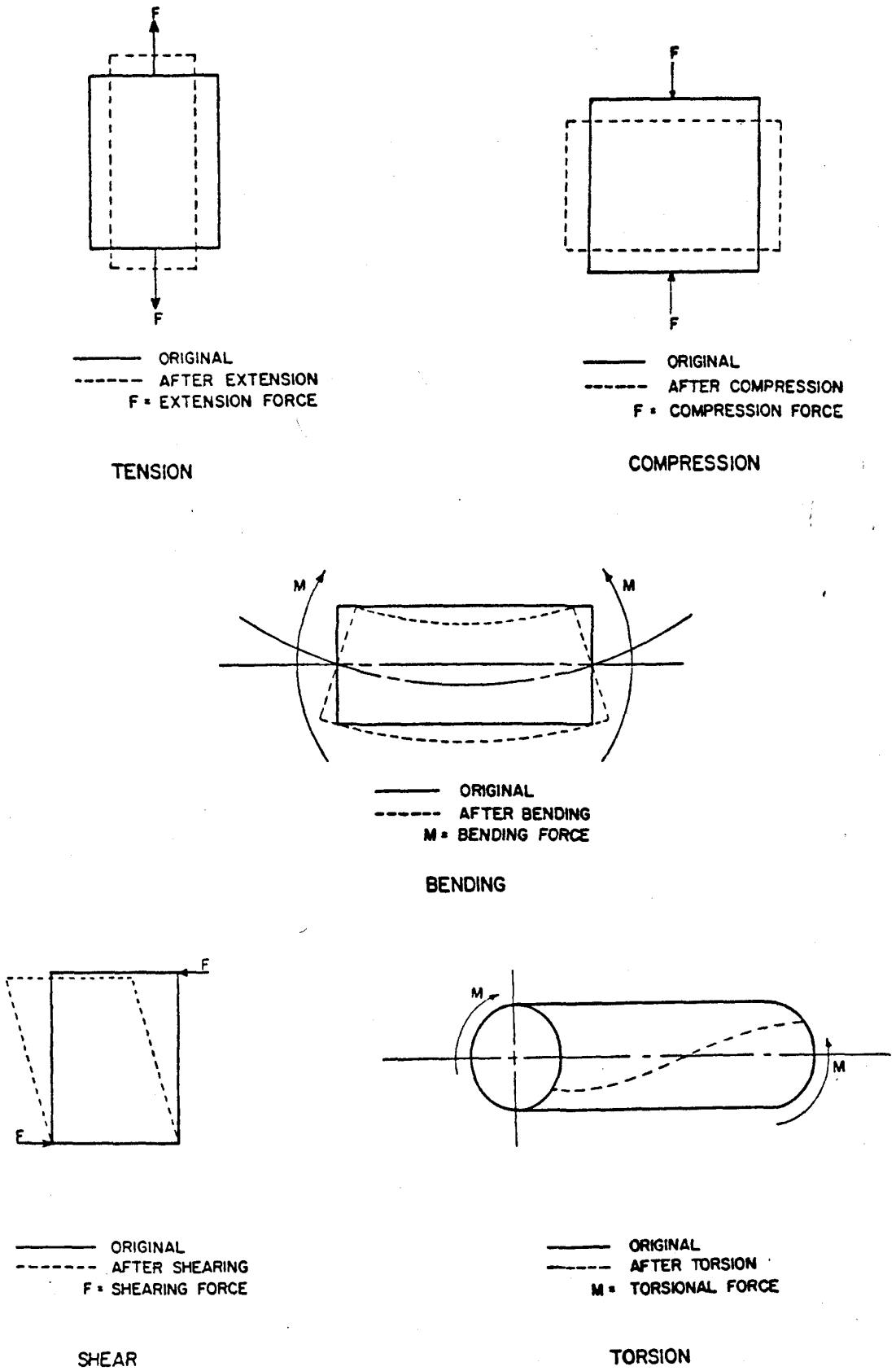


FIGURE 17.11 Types of forces and resulting strains.

Skechers EX1062
Skechers v Nike

13. LOOP STRENGTH

Table 17.6 lists fiber loop and knot strengths. The loop strength test consists of looping one length of a fiber through another loop as shown in Figure 17.12, and elongating the loops until rupture occurs. As the rupture elongation increases, the loop strength efficiency also increases. The reason being that in low elongation brittle fibers, high stresses are quickly built up and tensile failure occurs. High elongation fibers can extend rather than fail, and a more efficient break ultimately results. When a fiber is bent around itself, a tension strain develops on the outside and a compression strain on the inside.

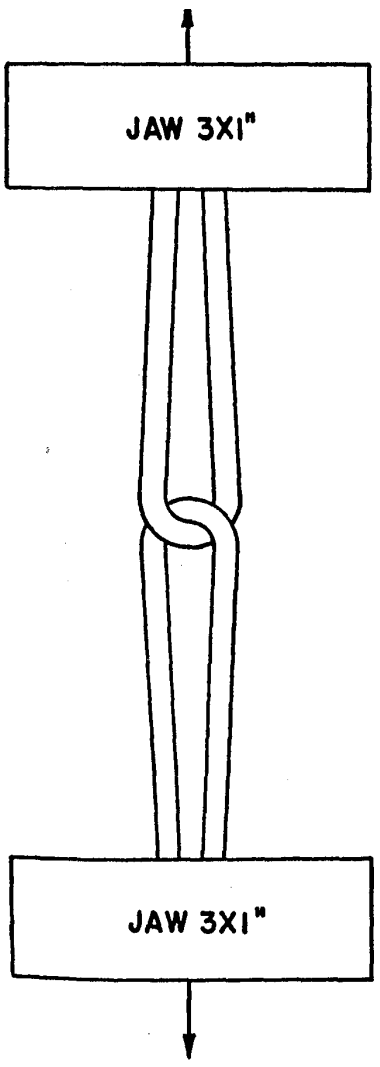


FIGURE 17.12 Loop strength test.

The greater the rupture elongation, the greater is the ability of the fiber to bend without failing.

High modulus fibers have low loop strength efficiences and weak, extensible fibers have higher efficiencies. Remember, however, that a less efficient, but originally stronger, fiber may have a higher absolute loop strength than a more efficient weaker fiber. Cotton has a remarkably high loop strength accompanying its nominal elongation. Aramids, nylon and polyester being tough, strong fibers, exhibit high absolute loop strength.

14. KNOT STRENGTH

Knot strengths of several fibers are listed in Table 17.6. The knot test consists of making a simple overhand loop (Figure 17.13) and then subjecting the specimen to a tensile pull. The general efficiencies (i.e., the ratio of knot to tensile strength) of knot strengths are about the same as for loop strengths, and for the same reasons.

Loop and knot strengths of yarns and cords are functions of the intrinsic fiber properties and the geometry of the yarn or cord structure. The actual formation of a knot can cause selected fibers, depending upon their position within the yarn, cord, or rope, to be bent into a configuration so that the resulting strain exceeds the fiber's rupture elongation, and therefore some fiber breakage occurs. Other fibers in the knot are not so strained, and so complete failure of all fibers is avoided. The higher its rupture elongation the greater is the opportunity for the fiber to be strained without failure. After a knot is formed in a yarn and it is then subjected to a loading force, the necking down or compacting of the knot into a smaller, denser structure can also produce excessive strains in certain fibers, depending upon their position. All of the fibers within the knot are not subjected to the same amount of strain. This maldistribution of stresses and strains among the fibers causes some to fail prematurely. The load they were carrying then is transferred to the remaining intact fibers. However, this added load may then exceed the capacity of the adjacent fibers and they, too, fail. Thus, the failure proceeds from fiber to fiber and the entire cord or rope fails.

Skechers EX1062
Skechers v Nike

TABLE 17.6 Fiber Loop and Knot Strengths [2].

Fiber	Loop Strength (gpd)	Knot Strength (gpd)
Polyester		
A.C.E® and Compet®, filament–HT	6.0–7.0	5.0–6.0
Dacron®		
Staple and tow	2.1–6.4	2.1–6.4
Filament–RT	2.5–5.2	
Filament–HT	5.6–5.8	
Fortrel®		
Staple series 400–RT	4.4–5.6	
Staple series 300–HT	5.6–6.0	
Tairilin®, staple	2.0–5.6	
Trevira®		
Staple	1.2–5.6	2.0–5.6
Filament–HT	4.4–6.7	4.0–6.3
Nylon		
Nylon 6		
Monofil. and filament–RT	3.8–5.6	3.8–5.5
BCF–RT	2.0–3.0	2.0–3.0
Filament–HT	5.1–10.1	4.8–6.7
Nylon 6,6		
Staple and tow	3.7–5.9	3.7–5.9
Monofil. and filament–RT	2.0–5.1	2.0–5.1
Filament–HT	5.0–7.6	5.0–7.6
Tencel® lyocell–HT	2.2–2.6	2.1–2.3
Cuprammonium rayon, filament	2.15–2.25	
Saran®, monofilament	0.7–1.1	1.0–1.7
Acetate, filament and staple	1.0–1.2	1.0–1.2
Acrylic		
Acrilan®		1.9–2.6
Creslan®, staple and tow	1.9–2.3	
MicroSupreme, staple	2.5–3.0	
SEF® modacrylic, staple		1.6–2.5
Olefin		
Polyethylene		
Monofilament, low density		1.0–2.5
Monofilament, high density	2.5–4.0	2.5–4.5
Herculon®		
Staple	3.0–4.0	
Bulk filament	2.5–3.5	
Glass, multifilament	4.0	0.9
Aramid		
Kevlar®		
Kevlar 29/Kevlar 49	10.5	7.6
Nomex®, staple and filament	4.0–5.0	
Fluorocarbon		
Gore-Tex®	2.5–3.3	2.5–3.3
Teflon® TFE multifil., staple, tow, flock	0.8–1.4	0.8–1.4
Cotton, mercerized	2.5	

HT: high tenacity.
POF: partially oriented filament.
POY: partially oriented yarn.
RT: regular tenacity.
IT: intermediate tenacity.

Skechers EX1062
Skechers v Nike

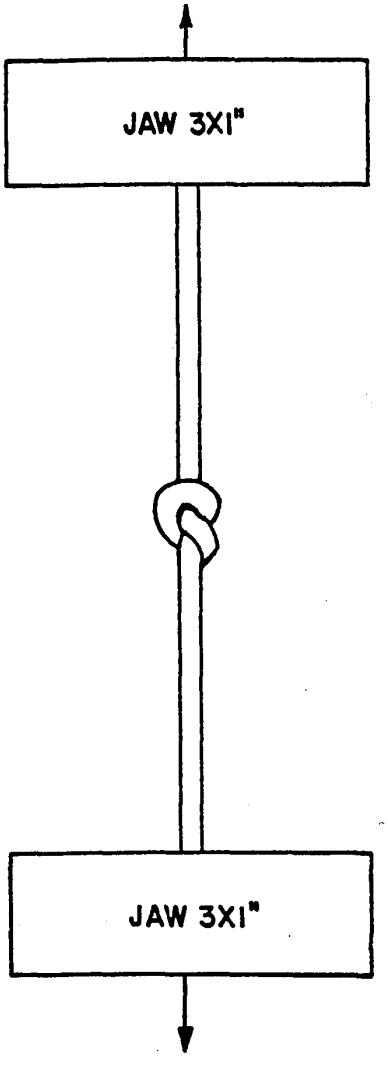


FIGURE 17.13 Simple knot test.

The same mechanisms described above for fibers in a yarn, or strands in a rope, exist with respect to individual filaments. Here the cells or fibrils of a natural fiber, or the molecular chains or crystals in natural or man-made fibers, may be considered to be similar, with respect to the fiber, as are fibers with respect to yarns. Individual fibrils are strained non-uniformly and failure ultimately results. The lower the elongation capacity of the units making up the fiber, the less the opportunity for elongation balance adjustment, and the lower the knot and loop strength efficiency.

15. FRICTION

In textile processing, fibers or yarns move relative to each other, or over metal or ceramic parts and frictional forces are generated. Carding, drafting, combing, spinning, winding, weaving, and finishing are all influenced by friction. Spun yarn strength and elongation, fabric smoothness and "hand," abrasion resistance, tendency to generate static dimensional stability, and seam slippage are also dependent upon this important property.

When one body slides over the surface of another, a resistance to the relative motion is developed which is called "frictional force," or more simply, "friction." Static or starting friction is the force which opposes the tendency of a body at rest to start to slide over another. Kinetic friction is the force which opposes the motion of two surfaces sliding by each other. When the frictional force F is divided by the normal force N which develops between the two sliding surfaces, the resulting quotient is called the friction coefficient (Figure 17.14):

$$\mu = \frac{F}{N} \tag{17.3}$$

where

μ = coefficient of friction
F = frictional force
N = normal force

The friction which develops in textile processing or use can be fiber-to-fiber or fiber-to-other material surfaces. Therefore, in listing friction coefficients it is necessary to specify the two materials involved. The direction of rubbing of fibers or yarns, whether longitudinally or transversely, will influence friction coefficients. Even the directions of longitudinal motion along a fiber can and do produce significant and useful differences in frictional effects. For example, the ability of wool to felt is partly attributable to a greater resistance to sliding motion in the tip-to-root direction of the fiber, rather than from root-to-tip. The difference is called the differential friction effect (DFE). The

Skechers EX1062
Skechers v Nike

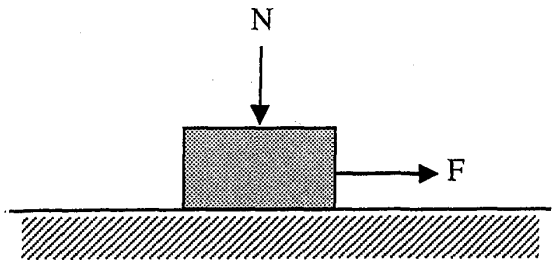


FIGURE 17.14 Frictional forces between two sliding surfaces.

scale structure of wool and other fur fibers is considered to act as a ratchet which allows motion in one direction, but resists it in the other, thus producing DFE (Figure 17.15).

16. ABRASION AND WEAR RESISTANCE

It is necessary to define these two terms at the outset. Textile technologists generally agree that the "abrasion" is confined to the pure action of rubbing, as exemplified by most of the standard abrasion machines (Chapter 20.0, Textile Testing) which function on the basis of a repetitive rubbing or abrasive action. The term *wear* is employed in a much broader sense and encompasses all of the interacting factors which may cause fabrics to fail; for example, rubbing, flexing, snagging, impacting, stretching, twisting, and exposure to chemicals, wind, sunlight, weather, wetting, drying, heating, and the like.

Much time and effort have been expended; the technical literature is replete with articles, and the industry is constantly faced with the problems of predicting the abrasion and wear resistance of new fibers and fabrics. The problems are complex. They include the selection of laboratory abrasion test methods and specifications, determination of the intrinsic abrasion resistance of new candidate fibers, the influence of yarn and fabric geometry, and the degree to which laboratory abrasion and other physical

1. 2. 3. 4. 5. 6. 7.

FIGURE 17.15 Surface of various fibers: 1. wool, 2. cashmere, 3. mohair, 4. camel, 5. mink, 6. cotton, 7. rayon (courtesy of Albany International).

Skechers EX1062
Skechers v Nike

tests correlate with service performance. It is beyond the scope of this book to discuss in great detail and review the work of the many people who have engaged in research in this important area of textile technology. However, the following sections discuss the concepts which various investigators have proposed with respect to the intrinsic abrasion resistance of textile fibers and other materials. The influence of yarn and fabric structure on abrasion resistance and a description of laboratory abrasion testers is given in Chapter 19.0, Fabric Properties and Technology.

The criteria selected to judge abrasion or wear resistance must be based upon the fabric's function. For example, for a tarpaulin, maintenance of breaking and tear strength is required. Changes in fabric thickness, weight, water permeability, electrical resistivity, surface luster, color, air permeability, the initial appearance of broken threads, or formation of a hole, are other criteria that are used or have been considered. Probably the three most widely used laboratory criteria are:

(1) Direct visual comparison of fabric appearance against a known standard, after both the test sample and the standard have been abraded for a selected number of cycles
(2) Determination of the number of abrasion cycles required to form a hole or for the fabric to fail
(3) Determination of the strength loss caused by a selected number of abrasion cycles or, more properly, a graph of abrasion cycles versus strength loss

Abrasion Mechanisms

Backer [5] proposed three mechanisms which may develop during the abrasion of a textile fiber:

(1) Smooth frictional wear such as occurs when two smooth metal surfaces are rubbed together—This kind of abrasion would be typified by sliding a fabric over a polished wooden table.
(2) Surface cutting or grinding of the fiber by a sharp abradant of small particle size relative to the fiber diameter—This action would be typified by rubbing the fabric with a fine piece of emery cloth, and is representative of the way many laboratory abrasion testers abrade fabrics.
(3) Fiber rupture or slippage caused by rubbing the fiber with an abradant where the particle size is large compared with the fiber diameter—The fiber is then caught and plucked like a violin string. The fiber may be broken, or partially or completely pulled away from its neighbors in the yarn and fabric, thus producing a disrupted appearance.

In addition to fiber degradation or attrition, these mechanisms particularly the third, can significantly alter the positions of the yarns in the fabric, cause the fabric to distort, and otherwise change the fabric structure. Backer also pointed out that transverse rubbing action across a fiber can produce tension within the fiber.

Hamburger [6] examined the influence of the tensional repeated stress properties of fibers on abrasion resistance. He states that abrasion is a repeated stress application caused by the cyclical application and removal of stresses of a low order of magnitude. For the fiber to be abrasion resistant, it must be capable of repeatedly absorbing the energy imparted to it by the abrasive action. Therefore, it must have the ability to elongate under load application, and recover to its original dimension upon load removal. This ability to deform and recover completely is governed by the relationship between instantaneous elastic deflection, primary creep, and secondary creep. Since secondary creep is removed during the first (or second or few) loading (abrasion) cycles, the energy represented by secondary creep contributes little to abrasion resistance. Hamburger proposes that intrinsic abrasion resistance is correlative with the energy absorption of "mechanically conditioned" fibers free of secondary creep. He lists five fiber properties requisite for high abrasion resistance:

- low elastic modulus
- large immediate elastic deflection

Skechers EX1062
Skechers v Nike

- high ratio of primary to secondary creep
- high magnitude of primary creep
- high rate of primary creep

Hamburger determined an "energy coefficient" which is a measure of the fiber's residual energy absorption after secondary creep has been removed, and a "durability coefficient" which is a laboratory measure of the rate of loss of fiber strength with abrasion cycles. A linear correlation between these two factors appears to exist, and demonstrates that apparently abrasion resistance is dependent upon the repeated capacity of the fiber to absorb energy.

Susich [7] observed that staple yarns were always more severely abraded than corresponding multifilament yarns. He stated that although high elastic energy of fibers is the main factor necessary to prevent inherent abrasion damage, yarn extensibility, surface, and friction must also be taken into account.

In a general assessment of fiber abrasion resistance, it appears reasonable to state that types 6,6 and 6 nylon are most outstanding in their abrasion resistance. Polyester fiber is often considered as second only to nylon. Cotton has good abrasion resistance, and probably follows behind nylon and polyester. Since cotton is stronger when wet than dry, this is an added advantage which most other fibers do not have. Its wet strength and toughness give cotton excellent wet as well as dry abrasion resistance, and explains why cotton fabrics are still used in industrial applications. Wool, because of its high elongation and recovery properties, has remarkably good abrasion resistance. The acrylic fibers, viscose, acetate and regenerated protein fibers probably follow about in that order. Polyvinyl alcohol, polypropylene, and polyethylene all appear to be in the range approaching nylon for abrasion resistance.

17. MOISTURE ABSORPTION PROPERTIES

All of the natural fibers, as well as the regenerated cellulosic and protein fibers, are hygroscopic; that is, they have the ability to absorb water in the form of vapor or liquid. Hygroscopic material will absorb moisture from, or release moisture to, the surrounding air until an equilibrium moisture content is attained. Figure 17.16 shows a plot for cotton of percent moisture regain, defined below, as a function of progressively increasing relative humidity. If a dry fiber is brought to equilibrium in an increasingly humid atmosphere the water content at any relative humidity will be less than that which would result from bringing the fiber to equilibrium from a wet condition. Thus, Figure 17.16 shows moisture absorption and desorption curves which superimpose only at the 0 and 100% rh values, an area of hysteresis resulting when fabrics are conditioned from the dry versus the wet side. The moisture content of a textile material will influence its weight, its general dimensions, and many of its physical properties.

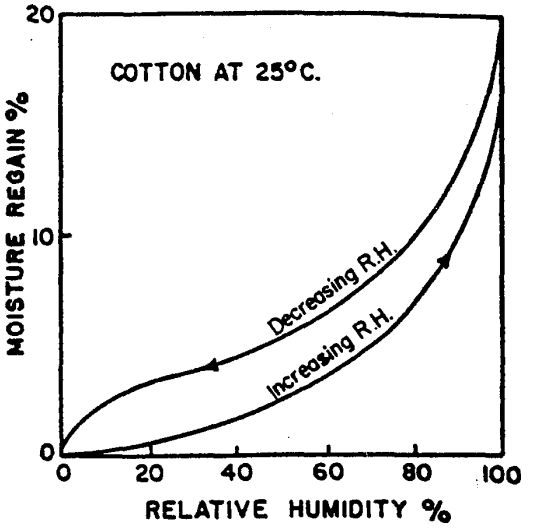


FIGURE 17.16 Relative humidity versus percent moisture regain of cotton fiber.

The amount of moisture is usually determined by weighing a specimen on a balance of proper sensitivity, bone drying in an oven at about 220°F and reweighing the bone dry specimen (Chapter 20.0, Textile Testing).

Percent moisture content is defined as the weight of water calculated as a percentage of the original weight of sample:

Skechers EX1062
Skechers v Nike

% moisture content

$$= \frac{\text{original weight} - \text{bone dry weight}}{\text{original weight}} \times 100 \tag{17.4}$$

Percent moisture regain is defined as the weight of water calculated as a percentage of the bone dry weight:

% moisture regain

$$= \frac{\text{original weight} - \text{bone dry weight}}{\text{bone dry weight}} \times 100 \tag{17.5}$$

17.1 Standard Moisture Regain of Fibers

Because many textile materials vary in physical dimensions, weight and properties as a function of their moisture content, it is necessary to describe precisely the water content of the air with which the textile is in equilibrium if a property is to have any meaning. In the United States, standard atmospheric conditions are 65% relative humidity and 70°F (21°C). Table 17.7 lists moisture regains of the various fibers when brought to equilibrium under these conditions of humidity and temperature. All other physical properties of fibers, yarns, or fabrics given in this book are the values obtained at standard conditions unless otherwise designated.

17.2 Commercial Moisture Regains for Fibers

Depending upon conditions of harvesting or manufacturing, hygroscope fibers can vary widely in moisture regain with a concomitant variation in true fiber weight. Therefore, for economic reasons the purchase or sale of cotton, wool, rayon, etc. must be based upon a standard amount of moisture. The normal practice is for a laboratory, often an independent organization agreeable to both buyer and seller, to measure the average moisture regain of the entire fiber lot. The actual weight of the lot is then corrected to a standard regain agreed upon by the trading parties. Table 17.8 lists accepted commercial regains established by the separate industries for their fibers. Because of the fiber price per pound, and the size of the lots, the regain must be determined accurately. Proper selection of the test sample so that it is in fact truly representative of the lot is of equal importance.

The "as received" weight of a lot may be corrected to the accepted commercial regain weight by the following formula

$$W_c = W_l \frac{100 + R_c}{100 + R_l} \tag{17.6}$$

where

W_c = lot weight calculated to accepted commercial regain
W_l = lot weight "as received"
R_c = percent accepted commercial regain
R_l = percent regain of "as received" lot

The bone dry weight of a lot may be corrected to the accepted commercial regain weight as follows:

$$W_c = W_b \frac{100 + R_c}{100} \tag{17.7}$$

where W_b is bone dry weight of lot.

18. FIBER SWELLING PROPERTIES

Table 17.9 lists the swelling properties of fibers when immersed in water. Upon wetting, most hygroscope textile fibers exhibit a slight increase in length and a considerable increase in diameter and cross-sectional area. The influence of all of these interacting effects on fabric air and liquid permeability and on shrinkage are discussed in Chapter 19.0, Fabric Properties and Technology on "Cover Factor," "Fabric Density and Packing Factor," "Air Permeability," and "Water Repellency." Since hygroscopic fibers themselves do not shorten upon wetting, fabric shrinkage must be caused by other mechanisms.

Skechers EX1062
Skechers v Nike

TABLE 17.7 Moisture Regain of Fibers [2].

Fiber	Moisture Regain (%) 70°F, 65% rh	70°F, 95% rh
Polyester		
A.C.E® and Compet®		
Filament–HT	0.4	
Dacron®		
Staple and tow	0.4	
POF		
Filament–RT	0.4	
Filament–HT	0.4	
Tairilin®, staple	0.4	0.6
Trevira®		
Staple	0.4	0.6
POF	0.4	0.6
Filament–HT	0.4	0.6
Nylon		
Nylon 6		
Staple	2.8–5.0	3.5–8.5
Monofil. and filament–RT	2.5–5.0	3.5–8.5
Filament–HT	2.8–5.0	3.5–8.5
Nylon 6,6		
Staple and tow	4.0–4.5	6.1–8.0
Monofil. and filament–RT	4.0–4.5	6.1–8.0
Filament–HT	4.0–4.5	6.1–8.0
Tencel® lyocell–HT	11.5	
Rayon		
Fibro®		
RT–Multi-lobed	11	27
IT–0.9 den or 0.25 in and up	11	27
Cuprammonium, filament	11	
Rayon		
Filament–RT	11	
Filament–HT	11	
Saran®, monofilament	0	N/A
Acetate, filament and staple	6.3–6.5	14
Ryton® sulfar, staple	0.6	
Acrylic		
Acrilan®, staple and tow	1.5	3.5
Creslan®, staple and tow	1.0–1.5	2.0–2.5
MicroSupreme, staple	1.0–1.5	2.0–2.5
SEF® modacrylic, staple	2.5	

(continued)

Skechers EX1062
Skechers v Nike

TABLE 17.7 (continued).

Fiber	Moisture Regain (%) 70°F, 65% rh	70°F, 95% rh
Olefin		
Polyethylene		
Monofilament, low density	Negligible	Negligible
Monofilament, high density	Negligible	Negligible
Herculon®		
Staple	0.01	
Bulk filament	0.01	
Marvess® and Alpha®		
Staple and tow	−0.1	
Multifilament	−0.1	
Essera®, Marquesa Lana®, Pation® III		
BCF	0.01–0.1	
Staple	0.01–0.1	
Spectra® 900	Negligible	Negligible
Spectra® 1000	Negligible	Negligible
Fibrilon®		
Staple	0.01	0.01
Spandex		
Glospan®/Cleerspan, S-85, multifilament	Less than 1	
Lycra®		
Type 126, 127	1.3	
Glass		
Single filament—E-glass	None	Up to 0.3
Single filament—S-glass	None	Up to 0.3
Multifilament	None	Up to 0.3
Aramid		
Kevlar®		
Kevlar 29/Kevlar 49	4.3	6.5/6.0
Kevlar 149	1.2	2.3
Kevlar 68	4.3	
Kevlar HT (129)	4.3	
Nomex®, staple and filament	4.5	7.5
Fluorocarbon		
Gore-Tex®	0	0
Teflon®		
TFE multifil., staple, tow, flock	0	0
FEP, PFA monofilament	0	0
PBI, staple	15	20
Asbestos	1.0	3.0
Cotton	8.5	15
Silk	11	25
Wool	16	29

HT: high tenacity.
POF: partially oriented filament.
POY: partially oriented yarn.
RT: regular tenacity.
IT: intermediate tenacity.

Skechers EX1062
Skechers v Nike

TABLE 17.8 Commercial Moisture Regain Values of Fibers [8].

Fiber	Moisture Regain (%)
Acetate (secondary)	6.5
Acrylic	1.5
Aramid, for	
Plastic reinforcement	3.5
Filtration fabrics and safety apparel	4.5
Reinforcement of rubber goods	7.0
Azlon	10.0
Cotton	
Natural cotton yarn	7.0
Dyed cotton yarn	8.0
Mercerized cotton yarn	8.5
Flax (raw)	12.0
Fluorocarbon	0.0
Glass	0.0
Hemp	12.0
Jute	13.75
Linen	8.75
Metallic	0.0
Modacrylic	
Class I	0.4
Class II	2.0
Class III	3.0
Nylon (polyamide)	4.5
Olefin	0.0
Polyester	0.4
Ramie	
Raw	7.6
Scoured	7.8
Rayon (regenerated cellulose)	11.0
Rubber	0.0
Saran	0.0
Silk	11.0
Spandex	1.3
Triacetate (primary)	3.5
Vinal	4.5
Vinyon	0.0
Wools (all forms)	13.6

19. WET FIBER STRENGTHS

Table 17.4 lists wet and dry fiber tenacities. Natural cellulosic fibers such as cotton, are 10 to 15% stronger when wet than when "dry" under standard conditions. This is of obvious advantage in end uses where fabrics are apt to become wet.

The natural cellulosics are the only fibers presently known whose wet strengths exceed dry strengths. The natural animal fibers, including silk and wool, have wet strengths which are 75 to 90% of dry strengths. Regenerated cellulose fibers such as viscose and cuprammonium rayons have wet strengths in the order of 45 to 60% of dry. The wet strengths of high modulus rayons range from 60 to 75% of dry. The modified cellulosics, such as acetate, also have wet strengths which are 60 to 80% of dry. Because many of the hydrophilic (water absorbing) hydroxyl groups in these fibers have been replaced by more hydrophobic (water resisting) acetate groups, the tendency for such fibers to absorb water is less, and so they are somewhat less sensitive to strength losses when wet.

As a general rule it can be stated that, for man-made fibers, the lower their moisture regains and liquid water absorption capacity, the less sensitive they are to wet strength losses. Thus nylon 6,6, with a moisture regain of 4.5% (Table 17.7), has a wet strength of about 85–90% of dry, while Dacron® polyester, with a regain of 0.4% has a wet strength just about equal to its dry strength. While the general rule is valid, care should be exercised in its employment, for the nature of the polymer also influences the strength loss upon wetting.

Wet Yarn Strengths

Because cotton has higher strength when wet than dry, it follows that yarns made from cotton will also be stronger at higher moisture regains as well as when wet. This is in fact the case, the increase for wet yarns being on the order of 25 percent. In addition to the intrinsic wet fiber strength increase, wet cotton fibers swell radially, thus causing a denser packing of fiber against fiber. The total frictional force increase reduces fiber slippage and so a stronger yarn results. For natural animal, regenerated cellulosic and synthetic fibers, generally the ratio of wet-to-dry yarn strengths is about the same as their respective wet-to-dry fiber strengths.

20. WET FIBER BREAKING ELONGATIONS

Table 17.5 lists wet rupture elongations. As a general rule, for both the natural and re-

Skechers EX1062
Skechers v Nike

TABLE 17.9 Fiber Swelling Properties.

Fiber	Length Increase (%)	Diameter Increase (%)	Cross-Sectional Area Increase (%)
Glass	–	–	0
Nylon 6,6 high tenacity	1.2	1.9–2.6	1.6–3.2
Polyethylene, low density	–	–	0
Dacron polyester, regular	0.1	0.3	0.6
Lycra spandex	Approx. 1.0		Approx. 1.0
Viscose rayon, regular	3–5	25–52	50–113
Viscose rayon, high tenacity	–	–	50
Cuprammonium rayon	4	32–53	56–62
Acrilan acrylic	–	–	Approx. 5
Orlon acrylic	0.2	2.4	4.8
Acetate	0.14	9–14	–
Cotton, raw	1.2	14–30	40–42
Cotton, mercerized	0.1	17	24–46
Flax	–	–	47
Jute	0.37	20	40
Ramie	–	–	37 (bleached)
Silk	1.7	16–20	19
Wool	1.2	16	25

generated hydrophilic fibers, the water absorbed may be considered as a plasticizer. The fiber's modulus is reduced and the total elongation-to-rupture increases. The increase for the natural cellulosic fibers, e.g., cotton, is small.

The regenerated cellulosic fibers normally have appreciably greater wet elongations than dry. Usually the greater their wet strength loss, the greater will be their rupture-elongation gain. For example, the high modulus rayons have higher wet strength than do the regular rayons, their wet elongations are concomitantly lower, and therefore they have better wet dimensional stability. The synthetic fibers are more hydrophobic and are therefore less sensitive to water. Thus there is little difference in the wet and dry strength-elongation properties of the acrylics, the polyesters, the polyolefins, and the like. Nylon, being somewhat hydrophilic, is proportionately sensitive to water.

21. EFFECT OF RELATIVE HUMIDITY ON TENACITY-ELONGATION DIAGRAMS

For all fibers except cotton, tenacities and moduli are lower and elongations are higher as relative humidity increases. Obviously the greater elongation resulting from the plasticity of wet fibers can either by recoverable or non-recoverable. For natural fibers the wet recovery properties often equal or surpass the dry properties, having high instantaneous elastic recovery, high primary creep recovery, and low permanent set. The regenerated hygroscopic fibers usually have poorer recovery properties. The hydrophobic synthetic fibers, being insensitive to water, show little or no change.

22. THERMAL PROPERTIES OF FIBERS

The influence of heat on the properties of fibers is of paramount importance with respect to textile processing as well as use. All of the natural fibers and the regenerated cellulosic and protein fibers are non-thermoplastic. They do not soften with heat, but instead char and decompose. Most synthetic fibers and the modified cellulosics such as acetate, are thermoplastic and have specific melting points.

Thermoplasticity in a fiber can be advantageous or disadvantageous, depending upon processing or requirements. Because of their cross-linked molecular structure, cotton and wool are essentially temperature insensitive and so do not soften in the 200–300°F range, nor

Skechers EX1062
Skechers v Nike

stiffen at temperatures below freezing. Thus they can be ironed with relative safety, and do not significantly shrink, stretch, or lose strength at elevated temperatures. For processing or end uses where plasticity is necessary, water and/or steam are used rather than heat as the plasticizing means.

The thermoplastic fibers are temperature sensitive. As temperature increases, strength normally is lowered, rupture elongation may increase, and the tensional modulus thus is reduced. Unless the fiber is permanently damaged by heat, the effect often is reversible. As the fiber cools it may reassume its original properties. However, the heat exposure may produce a permanent thermal shrinkage with an accompanying increase in rupture elongation and a decrease in both strength and tenacity. This shrinkage is removable only by restretching the fiber at an elevated temperature. Thermoplasticity is an attribute when it is desired to heatset the fibers within the yarn and fabric, i.e., to make them conform permanently to the position and form into which they are placed, or where the fabric itself must then be molded or reshaped. Thermoplasticity is a disadvantage when a fabric becomes excessively limp or tacky or shrinks or distorts at high temperatures, or becomes stiff and brittle at low temperatures.

Heat may influence the properties and functions of textiles in many ways. Important criteria to consider are (1) softening, melting, or decomposition temperatures; (2) tendency of the fiber and fabric to shrink when heat-relaxed, or stretch when heated and tensioned; (3) ability of the fabric to be heat set; (4) ability of the fabric to function properly at elevated temperatures in one time or in repeated use; and (5) ability of the fabric to function properly at room temperature (or some other lower temperature) after exposure at high temperature for a given period of time.

Table 17.10 shows the effect of heat on fiber properties of various fibers. Normally for a textile fiber to be industrially useful it should not become tacky or soften below about 300°F. Upper temperature limits depend upon end-use requirements, and upon the ability of the finishing plant to provide a temperature which can heat set the fabric in order to stabilize it and to remove wrinkles and distortions.

Table 13.2 (Chapter 13.0) lists the commercially available high temperature fibers and Table 13.3 gives their properties.

23. EFFECT OF HEAT ON THE TENSILE PROPERTIES OF FIBERS

Two subjects must clearly be separated for the influence of heat upon fiber properties:

(1) Tensile properties of fibers tested at elevated temperatures
(2) Tensile properties of fibers tested at room temperature after exposure to elevated temperatures for selected time periods

The former indicates the capability of the fiber to perform at the required elevated temperature. The latter is often used as a criterion of heat degradation resistance.

Fabric degradation by heat normally is a function of temperature, time, relative humidity, and air circulation. Since many heat degradation processes involve oxidation, the greater the air circulation the greater will be the amount of oxygen which comes in intimate contact with the fiber, and the more rapid will be the degradation. Of course, for those fibers which are insensitive to oxygen, this factor is of no consequence.

For those industrial textile uses where the item will be subjected to a tension at an elevated temperature, it is important that the fiber does not become soft and extensible at that temperature. Glass is generally used for heat insulation and heat resisting applications. While it does not begin to lose strength until 600°F, its abrasion resistance is poor, and it cannot be used where prolonged flexing or rubbing is required. Protective silicone finishes improve the abrasion resistance of glass fabrics, making them useful in certain applications, for example, high temperature resisting gas filtration fume bags. Nylon is strong and tough, but it degrades rather quickly at elevated temperatures in the presence of air, and this limits its high temperature use. For example, when exposed at 350°F for 6 hours, 210 denier type 6,6 nylon yarn loses

Skechers EX1062
Skechers v Nike

TABLE 17.10 Effect of Heat on Fiber Properties [2].

Fiber	Effect of Heat
Polyester	
A.C.E®	Softens at 464°F. Melts at 500°F.
Compet®	Melts at 488°F.
Dacron®	Sticks at 440 to 445°F. Melts at 482°F.
Fortrel®	Melts at 478 to 490°F.
Tairilin®	Sticks at 440–450°F. Melts at 485–495°F.
Trevira®	Softens at 445 to 465°F. Melts at 495°F.
Thornel® carbon	Does not melt. Oxidizes very slowly in air at temperatures above 600°F.
Nylon	
Nylon 6	Melts at 419 to 430°F. Slight discoloration at 300°F when held for 5 hr. Decomposes at 600 to 730°F.
Nylon 6,6	Sticks at 445°F. Melts at 480 to 500°F. Yellows slightly at 300°F when held for 5 hr.
Tencel® lyocell	Does not melt. Loses strength at about 300°F and begins to decompose at about 350°F under extended periods of exposure.
Rayon	
Fibro®	Does not melt. Loses strength at 300°F and decomposes at 350 to 464 under extended periods of exposure.
Cuprammonium	Does not soften, stick or melt. Decomposes at 350°F under extended exposure.
Rayon	Does not melt. Loses strength at 300°F and begins to decompose at about 325°F.
Saran	
Saran®	Melts at 240–280°F; will not support combustion; self extinguishing.
Acetate	Sticks at 350 to 375°F. Softens at 400 to 445°F. Melts at 500°F.
Sulfar	
Ryton®	Outstanding resistance to heat (melts at 285°C). Excellent resistance to aerial oxidation, most chemicals. Retains 70% + original strength to 400°F for 5,000 hr.
Acrylic	
Acrilan®,	Does not melt.
Creslan®	Sticks at 420 to 450°F. Safe ironing at 300°F.
MicroSupreme	Does not melt.
SEF® modacrylic	Does not melt. Boiling water shrinkage equals 1%. Excellent resistance to shrinkage in dry heat. At 390°F, 5% shrinkage.
Olefin	
Polyethylene	Low density softens at 225 to 230°F, melts at 230 to 250°F. High density softens at 240–260°F, melts at 225 to 280°F. Low density shrinks 5–8% at 165°F, 50–60% at 212°F. High density shrinks 3–5% at 165°F, 8–12% at 212°F.
Herculon®	Softens at 285 to 330°F. Melts at 320 to 350°F. Decomposes at 550°F. Zero to 5% shrinkage at 212°F; 5 to 12% at 265°F.
Marvess® and Alpha®	Fiber softens at 300–320°F. Melts at 320–340°F. Decomposes at 550°F.
Essera®, Marquesa Lana®, and Pation® III	Softens at 285–340°F. Melts at 325–340°F. 0–5% shrinkage at 212°F. 5–12% shrinkage at 265°F.
Spectra®	Melts about 300°F.
Fibrilon®	Fiber softens at 290–310°F, melts at 320°F, and decomposes at 550°F.

Skechers EX1062
Skechers v Nike

TABLE 17.10 (continued).

Fiber	Effect of Heat
Spandex	
Glospan®/Cleerspan, S-85	Good dimensional stability. Sticks at 420°F.
Lycra®	Good dimensional stability. Can be heat set. Sticks at 347–392°F. Melts at 446°F.
Glass	None burn. At 650°F, E holds 75% tensile strength; S 80%; multifilament 50%. E softens at 1,350 to 1,611°F; melts at 2,050 to 2,160°F. S softens at 1,560 to 1,778°F; melts at 2,720°F.
Aramid	
Kevlar®	Difficult to ignite. Does not propagate flame. Does not melt. Decomposes at about 900°F.
Nomex®	Does not melt. Decomposes at 700°F.
Fluorocarbon	
Gore-Tex®	Extremely heat resistant. Can be safely used from −350°F to +550°F. Melts at 620°F.
Teflon®	
TFE	Extremely heat resistant. Safely used at −350°F to +550°F. Melts at 620°F.
FEP,PFA	Extremely heat resistant. Continuous use temperature: FEP, 400°F, PFA 500°F.
PBI	Will not ignite. Does not melt. Decomposes in air at 860°F. Retains fiber integrity and suppleness upon flame exposure. High char yield.
Asbestos	Weight loss 0.5 to 1% after exposure at 1,400°F for 2 hours. Stable up to 1,490°F.
Cotton	Yellows at 250°F, decomposes at 300°F.
Silk	Decomposes at 300°F. Rapid disintegration above 340°F.
Wool	Decomposes at 275°F, chars at 570°F.

54% of its original strength. Dacron® polyester has better heat aging resistance, losing only 8% when exposed under the same conditions.

24. FIBER FLAMMABILITY

Several terms related to the burning behavior of textiles are defined by the ASTM as follows [9]:

- combustible textiles: "a textile that will ignite and burn or that will give off vapors that will ignite and burn when subjected to external sources of ignition"
- flame resistance: "the property of a material whereby flaming combustion is prevented, terminated, or inhibited following application of a flaming or nonflaming source of ignition, with or without subsequent removal of the ignition source"
- flammability: "those characteristics of a material that pertain to its relative ease of ignition and relative ability to sustain combustion"
- flammable textile: "any combustible textile that burns with a flame"
- heat resistance: "the extent to which a material retains useful properties as measured during exposure of the material to a specified temperature and environment for a specified time"
- inherent flame-resistance: "flame resistance that derives from an essential characteristic of the fiber from which the textile is made"
- non-combustible textile: "a textile that will neither ignite nor give off vapors that will ignite when subjected to external sources of ignition"
- non-flammable textile: "any combustible textile that burns without a flame"

Cotton and other cellulosics, as well as cellulose acetate, will ignite readily and are not self-extinguishing. Once they are ignited, they will continue to burn, even when the igniting flame is removed. Silk, wool, and all the other animal fibers will burn, but are self-extinguishing. Synthetic organic fibers have varying degrees of flammability depending upon their composi-

Skechers EX1062
Skechers v Nike

tions. Nylon 6,6 is stated to be moderately difficult to ignite and self-extinguishing. Glass does not burn. Carbon does not melt but oxidizes very slowly in air at temperatures above 600°F. Kevlar® aramid is difficult to ignite, does not propagate flame and does not melt. It decomposes at about 900°F. Nomex® aramid does not melt and decomposes at 700°F. Gore-Tex® and Teflon® are extremely heat resistant. They can be safely used from −350°F to +550°F. PBI will not ignite nor melt but decomposes in air at 860°F. It retains fiber integrity and suppleness upon flame exposure.

Because burning is an oxidation process, for those fibers which will burn, the type of yarns and fabrics into which they are manufactured will directly influence the burning rate. Dense, heavy fabrics will not burn as readily as will lofty, open, thin, or brushed pile fabrics. For these latter types, the oxygen in the air can surround each fiber and accelerate the burning rate. Here, if the fibers are combustible and finely dispersed, a rapid flash burning can develop. In addition to the intrinsic flammability of the fiber, and the textile into which it is manufactured, precaution must be taken to insure that a fabric finish or coating applied to impart a certain property do not produce a dangerously flammable fabric.

24.1 Flammable Fabrics Act

In 1953, the U.S. Congress passed the Flammable Fabrics Act to ban easily ignitable fabrics and wearing apparel from the market. The Act stated that "no article of wearing apparel or fabric subject to the Act and Regulations shall be marketed or handled if such article or fabric, when tested according to the procedures prescribed . . . is so highly flammable as to be dangerous when worn by 'individuals.' " These were mainly brushed or high pile cellulosic fabrics used occasionally in such garments as sweaters and children's costumes.

In 1967, the Act was amended to cover interior furnishings as well as fabrics and all wearing apparel which present an unreasonable risk from fire. In 1972, an Act of Congress established a new Consumer Product Safety Agency. In 1973, responsibility for both issuing and enforcing flammability regulations was transferred from the Commerce Department to the Agency.

The flammability standard described in the Act states, "Any fabric or article of wearing apparel shall be deemed so highly flammable within the mean . . . of this Act as to be dangerous when worn by individuals if such fabric or any uncovered or exposed part of such article of wearing apparel exhibits rapid and intense burning when tested under the conditions and in the manner prescribed in . . . 'Flammability of Clothing Textiles, Commercial Standard 191-53.' " This standard specified the methods for testing fabric flammability and classifies fabrics as follows.

Class 1. Normal Flammability

These textiles are generally accepted by the trade as having no unusual burning character.

- textiles that do not have a raised fiber surface, but have a time of flame spread in the test of 3.5 seconds or more
- textiles having a raised fiber surface that have a time of flame spread in the test of more than 7 seconds or that burn with a surface flash (time of flame spread less than 7 seconds) provided the intensity of the flame is insufficient to ignite or fuse the base fabric

Class 2. Intermediate Flammability

These textiles are recognized by the trade as having flammability characteristics between normal and intense burning. Textiles having a raised fiber surface that have a time of flame spread in the test of 4 to 7 seconds, inclusive, and the base fabric is ignited or fused.

Class 3. Rapid and Intense Burning

These textiles are considered dangerously flammable and are recognized by the trade as being unsuitable for clothing because of their rapid and intense burning.

Skechers EX1062
Skechers v Nike

- textiles that do not have a raised fiber surface, but that have a time of flame spread in the test of less than 3.5 seconds
- textiles having a raised fiber surface that have a time of flame spread in the test of less than 4 seconds, and the base fabric is ignited or fused

The chemical textile industries have expended large amounts of money and effort in developing flame resisting finishes for apparel, decorative and industrial fabrics. By law, curtains, draperies and other textiles in public buildings must be flameproof. Fire and flame resistance test methods are explained in Chapter 20.0, Textile Testing. Flame retardant finishes are included in Chapter 5.0, Section 5.1.

25. RESISTANCE OF FIBERS TO MILDEW, AGING, SUNLIGHT AND ABRASION

Table 17.11 lists mildew, aging, sunlight and abrasion properties of various fibers. Wool and cotton tend to turn yellow with age. Where necessary, bleaching the cotton with hypochlorite

TABLE 17.11 Resistance of Fibers to Mildew, Aging, Sunlight and Abrasion [2].

Fiber	Resistance to Mildew, Aging, Sunlight and Abrasion
Polyester	
A.C.E®	Excellent resistance to mildew; good to abrasion, aging and sunlight with some deterioration after prolonged exposure to sunlight.
Compet®	Excellent
Dacron®	Not weakened by mildew. Excellent resistance to aging and abrasion. Prolonged exposure to sunlight causes some strength loss.
Fortrel®	Excellent resistance to mildew, aging and abrasion. Prolonged exposure to sunlight causes some strength loss.
Tairilin®	Excellent resistance to mildew, aging, abrasion. Excellent resistance to sunlight, but prolonged exposure causes some strength loss.
Trevira®	Not attacked by mildew. Excellent resistance to aging and abrasion. Excellent resistance to sunlight, but prolonged exposure causes some strength loss.
Thornel® carbon	Excellent resistance to mildew, aging, and sunlight. Poor abrasion resistance.
Nylon	
Nylon 6	Excellent resistance to mildew, aging and abrasion. Prolonged exposure to sunlight causes some degradation.
Nylon 6,6	Excellent resistance to mildew, aging and abrasion. Prolonged exposure to sunlight causes some deterioration.
Tencel® lyocell	Attacked by mildew. Good resistance to aging, sunlight and abrasion.
Rayon	
Fibro®	Attacked by mildew. Resistance to aging, sunlight and abrasion is good. Long exposure to sun yellows some intermediate rayons; aging deteriorates them.
Cuprammonium	Attacked by mildew. Stable to aging. Not affected by sunlight. Good resistance to abrasion.
Rayon	Attacked by mildew. Good resistance to sunlight, abrasion and aging.
Saran	
Saran®	Not attacked by mildew. Good resistance to aging, sunlight and abrasion.
Acetate	Impervious to aging. Good resistance to mildew discoloration and sunlight (some lose strength from long exposure). Fair abrasion resistance.
Sulfar	
Ryton®	Excellent resistance to mildew, aging and sunlight. Fair abrasion resistance.
Acrylic	
Acrilan®	Excellent resistance to mildew, aging and sunlight. Good resistance to abrasion.
Creslan® and MicroSupreme	Excellent.
SEF® modacrylic	Excellent resistance to mildew, aging and sunlight. Good resistance to abrasion.

(continued)

Skechers EX1062
Skechers v Nike

TABLE 17.11 (continued).

Fiber	Resistance to Mildew, Aging, Sunlight and Abrasion
Olefin	
Polyethylene	Not attacked by mildew. Good resistance to aging, sunlight and abrasion.
Herculon®	Not attacked by mildew. Good resistance to aging, indirect sunlight and abrasion. Can be stabilized to give good resistance to direct sunlight.
Marvess® and Alpha®	Not attacked by mildew. Good resistance to aging and abrasion. Stabilizers provide good resistance to sunlight fading.
Spectra®	Excellent resistance to mildew, aging and abrasion. Some loss of strength with long exposure to sunlight.
Fibrilon®	Not attacked by mildew. Good resistance to aging and abrasion. Stabilizers provide good resistance to sunlight fading.
Spandex	
Glospan®/Cleerspan, S-85	Excellent resistance to aging and abrasion. Sunlight exposure causes mild discoloration but no loss of physical properties.
Lycra®	
Type 126,127	Mildew, aging: no effect. Strength loss from prolonged sunlight. Good abrasion resistance.
Type 128	Excellent abrasion and aging resistance.
Glass	Not attacked by mildew, although binder may be affected by it. Excellent resistance to aging and sunlight.
Aramid	
Kevlar®	Excellent resistance to mildew and aging. Prolonged exposure to sunlight causes deterioration, but fibers self-screening. Good abrasion resistance.
Nomex®	Excellent resistance to mildew and aging. Prolonged exposure to sunlight causes some strength loss. Good abrasion resistance.
Fluorocarbon	
Gore-Tex®	Excellent resistance to mildew, aging, sunlight and abrasion.
Teflon®	Not weakened by mildew. Excellent resistance to aging and sunlight. Good abrasion resistance.
PBI	Good resistance to mildew and aging. Prolonged exposure to sunlight will cause darkening and some loss of tensile strength. Good abrasion resistance.

or peroxide, and the wool with sulfur dioxide or peroxide will remove the yellow color. Exclusive of any microbial or mildew degradation, weathering and sunlight cause a slow but progressive loss in strength and serviceability for cotton and rayon. Acetate is probably more resistant than rayon. Wool generally has good resistance to sunlight, weathering, and aging. This appears quite logical when one considers the natural environment of sheep.

25.1 Mildew and Rot Damage

The terms mildew, rot, and decay are variously used to indicate growth upon or damage to textiles by microorganisms such as fungi and bacteria. The major types of fungi affecting textiles are the molds such as penicillium and aspergillus, and the soil molds such as actinomycetes. Bacteria which cause textile damage are most frequently of the bacillus or rod type. The terms *decay* and *mildew* are usually associated with damage by fungi, and *rot* with bacterial damage.

Since microorganisms require water and warmth to flourish and spread, all of the natural and regenerated hydrophilic vegetable and animal fibers are susceptible to microbial damage. Cotton, linen, viscose and cuprammonium rayons, and other cellulose based fibers, are subject to breakdown where, via a process called glycolysis, the cellulose is converted by the enzyme cellulase to cellobiose. This is then converted to glucose which serves as the food for the microorganism. Mildew is often manifested in cotton and other cellulosics by a musty odor, the formation of discolored and black areas, fabric tendering, and ultimately complete decay. Some mildews produce brightly colored spots, and often fluoresce strongly in ultraviolet

Skechers EX1062
Skechers v Nike

light. Therefore, an inexpensive ultraviolet or "black light" lamp is a useful tool for mildew identification.

Wool, other animal fibers, and regenerated proteins are usually not quite so sensitive but they, too, can be decomposed by specific bacteria, actinomycetes, and molds which attack keratin through the production of proteolytic enzymes by these organisms. The intact cuticle and epicuticle of the wool fiber are relatively inert to such enzymes, hence such attack is more rapid on wool which previously has been mechanically or chemically damaged.

Mildew most often develops when textiles are folded and stored for lengthy periods in a warm moist atmosphere. A relative humidity of about 82% for cotton and 85% for wool is required for mildew and mold growth. Bacterial requirements are higher. Wool must ordinarily be exposed to a relative humidity of approximately 95%, or must have a moisture content on the order of 20% to support active bacteria growth. Temperatures of 75 to 100°F are optimal for most microorganisms. Local condensation can start mildew growth, occasionally at a relative humidity which is lower than expected. Once started, mildew can absorb water hygroscopically from the air or from local condensation and continue its growth. This is why packaged or folded fabrics, without adequate ventilation, will sometimes mildew in relatively "dry" rooms.

Synthetic fibers have chemical structures not found in nature. Therefore, microorganisms do not attack them. Most synthetic fibers have little or no tendency to absorb water, a necessary component required by all microorganisms if they are to survive. Clearly, this is another reason why synthetic fibers are mildew resistant. Even a slight modification in the chemical structure of a natural or regenerated fiber may be sufficient to preclude microbial attack. The nylons, polyesters, acrylics, and all other completely synthetic fibers are completely impervious to mildew growth and attendant damage. A word of caution is necessary. Often synthetic yarns may be sized, or fabrics finished, with natural gums, starches, waxes or the like that are susceptible to mildew growth. This may make it appear that the fibers themselves are being attacked. Tests usually show that while the fiber may be stained, it suffers no actual deterioration and strength loss; only the finish is attacked.

25.2 Insect and Rodent Damage

Basically the same comments made above for mildew and rot damage hold for insect damage. The natural fibers are susceptible to damage by carpet beetles, cockroaches, ants, silverfish, and moth larvae. The synthetic fibers usually are not attacked. Many insects will eat natural fibers. They may cut through synthetic or other fibers which are not attractive as food in order to liberate themselves or reach an attractive food source, or they may eat an unattractive fiber which is coated or contaminated with an attractive material. Thus, while synthetic fibers normally are not subject to insect damage, they can be damaged under specific environmental conditions. Rodents, in cases of extreme hunger, may attempt to eat cellulose or keratin base fibers. They probably will not eat synthetic fibers, but might damage them by gnawing.

26. CHEMICAL RESISTANCE OF FIBERS

Table 17.12 lists the effect of acids, alkali solvents, and special chemicals on various fibers. Because of the many fibers and many chemicals, it is impractical to list all of the effects. The "state of aggregation" (i.e., position and orientation) of fibers in yarn, and yarn in fabric, the chemical concentration, temperature, and length of exposure time also influence reaction rates and extents of degradation.

Cotton and rayon have fairly good resistance to weak acids, for example, but are severely damaged by even dilute solutions of strong acids such as sulfuric and hydrochloric. These cellulosic fibers have good resistance to strong alkalis. Mercerizing strength caustic (20% sodium hydroxide) will swell the fibers and can ultimately degrade them.

Wool shows high resistance to weak and strong acids, but is disintegrated and dissolved by alkalis. Bleaching must be accomplished on

Skechers EX1062
Skechers v Nike

TABLE 17.12 Chemical Resistance of Fibers [2].

Fiber	Effects of Acids and Alkalis	Effects of Bleaches and Solvents
Polyester		
A.C.E®	Good resistance to organic acids. Good resistance to inorganic acids at room temperature; moderate resistance at 212°F. Disintegrates in concentrated hot alkalis.	Excellent resistance to bleaches and other oxidizing agents.
Compet®	Excellent resistance to acids.	
Dacron®	Good resistance to most mineral acids. Dissolves with partial decomposition in concentrated solution of sulfuric acids. Good resistance to weak alkalis. Moderate resistance to strong alkalis at room temperature. Disintegrates in strong alkalis at boil.	Excellent resistance to bleaches and other oxidizing agents. Generally insoluble except in some phenolic compounds.
Fortrel®	Good resistance to most mineral acids. Dissolves with partial decomposition by concentrated solutions of sulfuric acid. Good resistance to weak alkalis and moderate resistance to strong alkalis at room temperature. Disintegrates in strong alkalis at boil.	Excellent resistance to bleaches and other oxidizing agents. Generally insoluble except in some phenolic compounds.
Tairilin®	Good resistance to most mineral acids; fair resistance to concentrated sulfuric acid. Good resistance to weak alkalis; moderate resistance to strong alkalis at room temperature. Disintegrates in strong alkalis at boil.	Excellent resistance to bleaches and other oxidizing agents.
Trevira®	Excellent resistance to mineral and organic acids at room temperature. Good resistance to weak alkalis at room temperature. Good resistance to weak alkalis at room temperature. Moderate resistance to strong alkalis, depending on concentration, temperature and time.	Excellent resistance to bleaches and oxidizing agents.
Thornel® carbon	Excellent resistance to acids and alkalis, even at high concentrations and temperatures. Strong oxidizers will degrade fiber.	Inert to all known solvents. Poor resistance to hypochlorite.
Nylon		
Nylon 6	Strong oxidizing agents and mineral acids cause degradation. Others cause loss in tenacity and elongation. Resists weak acids. Soluble in formic and sulfuric acids. Hydrolyzed by strong acids at elevated temperatures. Substantially inert in alkalis.	Can be bleached in most bleaching solutions. Generally insoluble in organic solvents. Soluble in some phenolic compounds.
Nylon 6,6	Unaffected by most mineral acids, except hot mineral acids. Dissolves with partial decomposition in concentrated solutions of hydrochloric, sulfuric and nitric acids. Soluble in formic acid. Substantially inert in alkalis.	Can be bleached in most bleaching solutions. Generally insoluble in most organic solvents. Soluble in some phenolic compounds.

Skechers EX1062
Skechers v Nike

TABLE 17.12 (continued).

Fiber	Effects of Acids and Alkalis	Effects of Bleaches and Solvents
Tencel® lyocell	Similar to cotton. Hot dilute or cold concentrated acids disintegrate fiber. Strong alkaline solutions cause swelling and reduce strength. Can be mercerized.	Attacked by strong oxidizing agents. Not damaged by bleaches. Generally insoluble in common organic solvents.
Rayon		
Fibro®	Similar to cotton. Hot dilute or cold concentrated acids disintegrate fiber. Strong alkaline solutions cause swelling and reduce strength.	Attacked by strong oxidizing agents. Not damaged by hypochlorite or peroxide. Generally insoluble except in cuprammonium and a few complex compounds.
Cuprammonium	Hot acids or high concentrations tend to disintegrate fiber. Strong caustic solutions tend to swell fiber and reduce strength.	Not affected by solvents. Insoluble in common organic solvents. Damaged by normal concentrations of hypochlorite or peroxide bleaches.
Rayon	Similar to cotton. Hot dilute or cold concentrated acids disintegrate fibers. Strong alkaline solutions cause swelling and reduce fiber strength.	Attacked by strong oxidizing agents. Not damaged by bleaches. Generally insoluble in common organic solvents.
Saran		
Saran®	Generally good resistance to acids and most alkalis. Sodium hydroxide and ammonium derivatives, in conjunction with heat, cause discoloration.	Generally good resistance to bleaches and solvents. Esters and ethers may be detrimental in varying degrees.
Acetate	Deteriorates in concentrated solutions of strong acids. Unaffected by weak acids. Strong alkalis saponify into regenerated cellulose.	Attacked by strong oxidizing agents. Not damaged by mild hypochlorite or peroxide bleaching conditions. Soluble in phenol, acetone, concentrated and glacial acetic acid.
Sulfar		
Ryton®	Outstanding resistance to acids and alkalis except hot concentrated sulfuric acids and concentrated nitric acid.	Excellent resistance to all solvents at high temperatures.
Acrylic		
Acrilan®	Good to excellent resistance to mineral acids. Fair to good resistance to weak alkalis; moderate resistance to strong, cold solutions.	Good resistance to bleaches and common solvents.
Creslan® and MicroSupreme	Generally good resistance to mineral acids and weak alkalis. Moderate resistance to strong alkalis at room temperature.	Unaffected by dry cleaning solvents. Can be bleached with sodium chlorite.
SEF® modacrylic	Resistant to most acids. Good resistance to weak alkalis; moderate resistance to strong, cold alkalis.	Good resistance to bleaches, dry cleaning fluids and most common solvents.

(continued)

Skechers EX1062
Skechers v Nike

TABLE 17.12 (continued).

Fiber	Effects of Acids and Alkalis	Effects of Bleaches and Solvents
Olefin		
Polyethylene	Low density: excellent resistance to acids and alkalis, with the exception of oxidizing agents. High density: excellent resistance to acids and alkalis, with the exception of oxidizing agents.	Low density: resists well below 150°F. Swells in chlorinated hydrocarbons at room temperature. Soluble at 160 to 175°F. High density performs generally the same but not as pronounced.
Herculon®	Excellent resistance to most acids and alkalis with the exception of elevated temperature exposure to chlorosulfonic acid, concentrated nitric acid and certain oxidizing agents.	Resistant to bleaches and most solvents. Some swells in chlorinated hydrocarbons at room temperature and dissolves at 160°F and higher. Others swell only at elevated temperatures.
Marvess® and Alpha®	Excellent resistance to concentrated acids and alkalis.	Resistant to bleaches and most solvents. Chlorinated hydrocarbons cause swelling at room temperature and dissolve fibers at 160°F and higher.
Essera®, Marquesa Lana®, Patlon® III	Excellent resistance to most acids and alkalis with the exception of elevated temperature exposure to some acids.	Resistant to bleaches and most solvents. Some hydrocarbons will cause swelling at room temperature. Some solvents will dissolve above 200°F.
Spectra®	Excellent resistance to most acids and alkalis, with the exception of elevated temperature exposure to some acids.	Resistant to most solvents, good resistance to bleaches. Some hydrocarbons cause swelling, especially at elevated temperatures.
Fibrilon®	Excellent resistance to concentrated acids and alkalis.	Resistant to bleaches and most solvents. Chlorinated hydrocarbons cause swelling at room temperature and dissolve fiber at 160°F and higher.
Spandex		
Glospan®/ Cleerspan, S-85	Resistant to mild acids and alkalis. Is degraded by strong acids and alkalis at high temperatures.	Good resistance to deterioration by bleaches. Discolored slightly by hypochlorite bleach. Resistant to solvents and oils except glycols.
Lycra®		
Type 126,127	Good resistance to most acids. Slightly yellowed by dilute hydrochloric, sulfuric acids. Good resistance to most alkalis.	Hypochlorite bleaches discolor. Can use perborate. Good resistance to most solvents, oils.
Type 128	Resistant to mild acids and alkalis. Degraded by strong acids and alkalis at high temperatures.	Good resistance to discoloring. Strength loss by hypochlorite bleaches.

Skechers EX1062
Skechers v Nike

TABLE 17.12 (continued).

Fiber	Effects of Acids and Alkalis	Effects of Bleaches and Solvents
Glass	Resists most acids and alkalis.	Unaffected.
Aramid		
Kevlar®	Good resistance to dilute acids and bases. Degraded by strong mineral acids and, to lesser extent, by strong mineral bases. Best chemical resistance from Kevlar 149.	Should not be bleached. Excellent solvent resistance.
Nomex®	Unaffected by most acids, except some strength loss after long exposure to hydrochloric, nitric and sulfuric. Generally good resistance to alkalis.	Unaffected by most bleaches and solvents except for slight strength loss from exposure to sodium chlorite.
Fluorocarbon		
Gore-Tex®	Essentially inert to acids and alkalis.	Essentially inert to bleaches and solvents except for alkali metals at high temperature and/or pressure.
Teflon®	Essentially inert to acids and alkalis.	Most chemical-resistant fiber known. The only known solvents are alkali metals and certain perfluorinated organic liquids at temperatures about 570°F.
PBI	Excellent resistance to most acids and alkalis. Some strength loss with strong alkali at elevated temperatures. Excellent organic solvent resistance.	Unaffected by most bleaches and solvents.

the neutral or acid side. Certain reducing agents are employed to modify the wool by rupturing sulfur-sulfur bonds. The wool is then more "plastic" and can be set into a desired shape. Reoxidation then reforms the bonds and the fiber then maintains its new configuration.

All of the natural fibers are unaffected by the common hydrocarbon and aromatic solvents.

The polyesters have good resistance to most mineral acids and to weak alkalis, but are disintegrated by strong hot alkali. They have good resistance to oxidizing agents and to most organic solvents except phenols. Generally speaking, the polyesters are considered to have better chemical resistance than the polyamides. The acrylics and modacrylics generally have excellent chemical resistance. They have excellent acid resistance, fair alkali resistance and are impervious to many solvents. The modacrylics are softened or dissolved by certain ketones. Saran has excellent acid and alkali resistance although it is sensitive to ammonia. It is unaffected by most common solvents, but is degraded by certain esters and ethers. Polyethylene and polypropylene have excellent acid and alkali resistance, but are sensitive to alkaline oxidizing agents. Their general chemical and solvent resistance is high. They are normally soluble in hot chlorinated hydrocarbons.

27. ELECTROSTATIC PROPERTIES OF FIBERS

Both in processing and in use, the generation of static electricity on textile materials is at least a nuisance, and can be expensive or dangerous. During conversion of fiber to yarn and yarn to fabric, the large fiber surface areas are conducive to generating and holding electrostatic charges. These charges develop as the result of fiber to fiber, fiber to machinery, or even fiber to air friction. Most textile fibers are good or excellent electrical insulators; hence, electric charges cannot be conducted away. So the intensity of charge increases until fibers or yarns, all with the same charge, repel each other with accompanying "wildness" of fibers which then will not process properly. If the charge on the fibers is opposite to that on card clothing, drafting rolls, or other machinery parts, the fibers will stick to those parts of the machine oppo-

Skechers EX1062
Skechers v Nike

sitely charged, and processing may be slowed down or stopped. Static generation by conveyor belts and the like operating in areas where there are solvent fumes may be dangerous because a discharge spark may cause explosion and fire.

Truly distilled water is a relatively poor electrical conductor, but natural waters which contain even small quantities of soluble mineral salts are excellent conductors. Those fibers which have high moisture regains usually do not present quite as many static problems as do those which are impervious to water. If the relative humidity is sufficiently high, almost all textile fibers can be processed without electrostatic difficulty. As the humidity decreases, processing problems increase, usually geometrically with the synthetic hydrophobic fibers being the first to cause trouble. The polyesters, acrylics, olefins, and the polyamides having the lowest moisture regain are most likely to develop static charges. Rayon, silk, wool, and cotton can absorb water and hence can dissipate charges more easily. However, at low relative humidity all fibers may show processing difficulty. The textile industry, therefore, makes wide use of humidification during carding, combing, spinning, and weaving. Combing or spinning oils, warp sizes, and other processing chemicals usually contain anti-stats to eliminate the static problem. Static also may be eliminated by running the material over alpha particle radioactive sources which ionize the surrounding air.

Chemical anti-stats usually contain polar groups within their molecule. These act as conductors to prevent charge buildup or to conduct away any charges which do develop. Anti-stats also may be nothing more than humectants or water absorbing materials. The ionized water present on the textile will dissipate the static electricity. While generally an inverse relation exists between moisture regain and charge buildup, the intrinsic nature of the fiber polymer substance may also have a great bearing on static forming characteristics.

28. ELECTRICAL RESISTIVITY

Proper evaluation of the electrostatic properties of a fiber or fabric requires that all of the mechanisms for charge generation and dissipation be considered.

To pass a steady flow of electric charge, or current through any material requires a voltage. Ohm's law states that the ratio of applied voltage to current flow is called the electrical resistance. The lower the resistance, the more easily the current will flow. Flow can take place through either the volume of the material or along its surface, and the resulting resistances are called "volume resistance" and "surface resistance," respectively. Materials with high resistance will build up and hold electrostatic charges because the current cannot flow easily and allow the charge to leak off. Thus, a direct relationship normally exists between a fabric's surface or volume resistance and its tendency to build up a bothersome electrostatic charge.

Since water (other than distilled) is a good conductor, surface and volume resistances for all fibers are essentially inversely functional with moisture regain. Large changes in resistance result from small changes in regain. Many hydrophobic fibers may have high volume resistances because they are impervious to water. Their surface resistances may be proportionately lower, however, because they have thin or even molecular layers of water adhering to their surfaces. Methods for measuring resistivities are given in Chapter 20.0, Textile Testing.

Skechers EX1062
Skechers v Nike

17.2

References and Review Questions

1. REFERENCES

1. *ASTM D 276, Annual Book of ASTM Standards,* Vol. 7.01, 1993.
2. Textile Wold Manmade Fiber Chart 1994, McLean Hunter Publishing, Co.
3. *ASTM D 629, Annual Book of ASTM Standards,* Vol. 7.01, 1993.
4. *ASTM D 4848, Annual Book of ASTM Standards,* Vol. 7.02, 1993.
5. Backer, S., "The Relationship between the Structural Geometry of a Textile Fabric and Its Physical Properties. Part II: The Mechanics of Fabric Abrasion," *TRJ,* Vol. 21, 1951.
6. Hamburger, W. J., "Mechanics of Abrasion of Textile Materials," *TRJ,* Vol. 15, 1945.
7. Susich, G., "Abrasion Damage of Textile Fibers," *TRJ,* Vol. 24, 1954.
8. *ASTM D1909, Annual Book of ASTM Standards,* Vol. 7.01, 1993.
9. *ASTM D4391, Annual Book of ASTM Standards,* Vol. 7.02, 1993.

2. REVIEW QUESTIONS

1. Define refractive index. What is the significance of it?
2. What is tenacity? List all the fibers based on their tenacity values. Which fiber is the highest and which fiber is the lowest?
3. Is there any relation between fiber breaking elongation and its tenacity? Explain.
4. Explain viscoelasticity.
5. Define modulus. What are the different modulus definitions? Explain the significance of each. Give examples of fibers that should be tested with different modulus methods because of their properties.
6. What is toughness? Explain the significance of it for industrial textiles.
7. Discuss the significance of fiber elongation-recovery properties.
8. What methods are used to measure the loop and knot strength? How do loop and knot strength affect the performance of industrial textiles?
9. Does the fiber friction depend on fiber surface properties? Explain.
10. Why are abrasion and wear resistance critical for industrial textiles? Explain.
11. Explain how percent moisture content and percent moisture regain are determined. Which fiber has the highest moisture regain?
12. What is the effect of moisture and humidity on fiber strength?
13. Explain the effect of heat on tensile properties of fibers.
14. Why is resistance of fibers to mildew, aging and sunlight important? Explain.
15. What is the significance of electrical properties of fibers?

Skechers EX1062
Skechers v Nike

18.0

YARN NOMENCLATURE, PROPERTIES AND TECHNOLOGY

Skechers EX1062
Skechers v Nike

18.1

Yarn Nomenclature, Properties and Technology

S. ADANUR

Yarn nomenclature and the factors that influence yarn properties are discussed in this section. The textile industry has built a terminology that is dependent upon the nature of the fiber, yarn, or fabric, the country where the nomenclature developed, and the period in history during which common usage was established. Unfortunately the industry has not yet adopted one single standard terminology for defining yarn weight, twist and twist direction, number and direction of plies. The "Tex System" is a universal international system for establishing yarn weight per length and is explained below. The English system of length in inches, feet and yards, and weight in grains, ounces and pounds, is difficult and illogical not only for textile use, but in all industries. However, this system is still used by the textile industry, and so it is described in the following sections.

1. YARN NUMBER SYSTEMS

The yarn "number" or "count" defines the relationship between yarn weight and length. Two different systems are widely used in specific areas of the textile industry:

(1) The direct yarn number, or weight per unit length system, so called because the *heavier* the yarn the *greater* is the weight per unit length

(2) The indirect yarn number, or length per unit weight system, so called because the *lighter* (in weight) the yarn, the greater is the length per unit weight

The direct system is conducive to metric measure where the number of grams of weight for a given number of meters of yarn can be measured and recorded as a whole number. The indirect system is conducive to English measure where the number of yards per pound of yarn can be measured and recorded as a whole number.

"Yarn Number" by either system is a number of arbitrarily selected weights of yarn per unit length, or a number of arbitrarily selected lengths of yarn per unit weight. Examples of each system are as follows.

1.1 Direct Yarn Number

Tex: The tex is defined as the weight in grams of one kilometer (1,000 meters) of yarn. A kilotex equals 1,000 tex, a decitex equals 0.1 tex; and a millitex equals .001 tex. For example, a 300 tex yarn weighs 300 grams per kilometer.

Denier: The weight in grams of 9,000 meters of yarn. Commonly used in the man-made fiber industry, a 200 denier nylon yarn is one wherein 9,000 meters of yarn weigh 200 grams.

One tex equals one-ninth of the denier, and so these two systems are easily convertible.

1.2 Indirect Yarn Number

Cotton Hank: The number of 840 yard lengths in one pound of cotton yarn is called a 1s (ones) count yarn. A two hank cotton yarn contains $2 \times 840 = 1{,}680$ yards per pound and is called a 2s (twos) count yarn.

The 840 yards per pound nomenclature is used primarily for cotton. Yarns composed of other fibers use different yardages to describe their hanks. Thus a 1s worsted yarn count yarn

Skechers EX1062
Skechers v Nike

TABLE 18.1 Yarn Numbering and Count Systems (ASTM D 2260).

Direct or Weight per Unit Length Systems	
Tex	: the mass in grams of 1 km of yarn, filament, fiber or strand
Denier	: the mass in grams per 9,000 m of yarn, filament, fiber or other textile strand
American grain count	: the mass in grains per 120 yd of sliver or roving
Indirect or Length per Unit Weight Systems	
Cotton count	: the number of 840 yd lengths of yarn per lb
Cut (in glass yarns)	: the number of 100 yd lengths of yarn per lb
Cut (in wool yarns)	: the number of 300 yd lengths of yarn per lb
Linen lea	: the number of 300 yd lengths of yarn per lb
Metric count	: the number of meters of yarn per gram
American woolen run	: the number of 1,600 yd lengths of yarn per lb
Worsted count	: the number of 560 yd lengths of yarn per lb

contains 560 yards per pound, a 1s linen yarn contains 300 yards per pound.

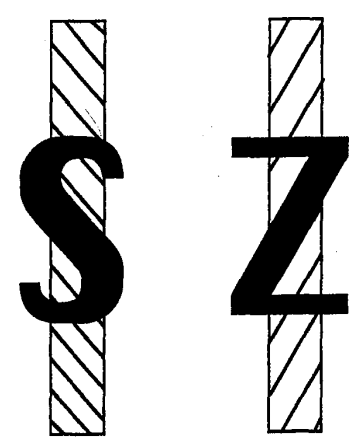
Table 18.1 lists yarn numbering or count systems as defined by the ASTM D 2260. Table 18.2 gives factors for converting yarn numbers from one system to another.

2. YARN TWIST DIRECTION

Twist is necessary in order to manufacture staple fiber yarns and to give integrity, compactness, snag and abrasion resistance to filament yarns as well as to cords and ropes, whether they be made from spun or continuous filament singles. Ideally, the twist path of a single element in the yarn is a perfect cylindrical helix. It is necessary to describe the nature of the helical path with respect to whether the twist is "left" or "right." Thus when the yarn is held in a vertical (north and south) position and the twist helix rises to the right, the yarn is stated to contain "right-hand" twist; when the helix rises to the left, the yarn contains "left-hand" twist. Methods for determining the number of turns per inch will be found in Chapter 20.0, Textile Testing. The letters S and Z are used as designating letters for left and right twist, respectively. Figure 18.1 gives the usual form of illustration that accompanies these definitions.

3. SINGLES AND PRODUCER'S YARN NOMENCLATURE

Trade practice uses a relatively simple code for identifying count, yarn twist, and twist direction. For spun cotton yarns, only the count and ply are usually given, e.g., 8s/10, meaning that ten plies of 8s singles are twisted together. Twist and twist direction are not normally listed. For continuous filament man-made producer's yarn the nomenclature on the package may read "nylon 210-34-1Z-300" which means that the yarn is 210 denier, contains 34 individual filaments, has 1 turn per inch Z twist, and the manufacturer's code type is 300. The letters B, D or SD may be given to identify bright, dull or semi-dull yarn. The fiber producer also identifies each lot of yarn with a "merge number." Since no two lots of yarn are exactly alike, in some uses care must be taken not to mix lots, otherwise streaks or bands may appear in the



'S' twist 'Z' twist

FIGURE 18.1 Yarn twist designations.

Skechers EX1062
Skechers v Nike

TABLE 18.2 Conversion Factors for Converting from One Yarn Numbering System to Another[a] (copyright ASTM).

System for Which Yarn Number Is Needed	System for Which Yarn Number Is Known: Tex[b]	Denier	American Grain Count	Cotton Count	English Worsted Count	American Woolen Run	Metric Count	Linen Lea	yd/lb
Tex[b] (g/km)	tex = · · ·	$\frac{\text{den}}{9}$	0.590 541 × gr	$\frac{590.541}{\text{cc}}$	$\frac{885.812}{\text{wc}}$	$\frac{310.034}{\text{wr}}$	$\frac{1\,000}{\text{mc}}$	$\frac{1\,653.52}{\text{lea}}$	$\frac{496\,055}{\text{y}}$
Denier (g/9,000 m)	den = 9 × tex	· ·	5.314 87 × gr	$\frac{5\,314.87}{\text{cc}}$	$\frac{7\,972.31}{\text{wc}}$	$\frac{2\,790.31}{\text{wr}}$	$\frac{9\,000}{\text{mc}}$	$\frac{14\,881.6}{\text{lea}}$	$\frac{4\,464\,492}{\text{y}}$
American grain count (grains/120 yd)	$\text{gr} = \frac{\text{tex}}{0.590\,541}$	$\frac{\text{den}}{5.314\,87}$	· · ·	$\frac{1\,000}{\text{cc}}$	$\frac{1\,500}{\text{wc}}$	$\frac{525}{\text{wr}}$	$\frac{1\,693.36}{\text{mc}}$	$\frac{2\,800}{\text{lea}}$	$\frac{840\,000}{\text{y}}$
Cotton count (840 yd lengths/lb)	$\text{cc} = \frac{590.541}{\text{tex}}$	$\frac{5\,314.87}{\text{den}}$	$\frac{1\,000}{\text{gr}}$	· · ·	$\frac{\text{wc}}{1.5}$	$\frac{\text{wr}}{0.525}$	0.590 541 × mc	$\frac{\text{lea}}{2.8}$	$\frac{\text{y}}{840}$
English worsted count (560 yd lengths/lb)	$\text{wc} = \frac{885.812}{\text{tex}}$	$\frac{7\,972.31}{\text{den}}$	$\frac{1\,500}{\text{gr}}$	1.5 × cc	· · ·	$\frac{\text{wr}}{0.35}$	0.885 812 × mc	$\frac{\text{lea}}{1.866\,67}$	$\frac{\text{y}}{560}$
American woolen run (1,600 yd lengths/lb)	$\text{wr} = \frac{310.034}{\text{tex}}$	$\frac{2\,790.31}{\text{den}}$	$\frac{525}{\text{gr}}$	0.525 × cc	0.35 × wc	· · ·	0.310 034 × mc	0.187 5 × lea	$\frac{\text{y}}{1\,600}$
Metric count (1,000 m/kg)	$\text{mc} = \frac{1\,000}{\text{tex}}$	$\frac{9\,000}{\text{den}}$	$\frac{1\,693.36}{\text{gr}}$	$\frac{\text{cc}}{0.590\,541}$	$\frac{\text{wc}}{0.885\,812}$	$\frac{\text{wr}}{0.310\,034}$	· · ·	$\frac{\text{lea}}{1.653\,52}$	$\frac{\text{y}}{496.055}$
Linen lea (300 yd lengths/lb)	$\text{lea} = \frac{1\,653.52}{\text{tex}}$	$\frac{14\,881.6}{\text{den}}$	$\frac{2\,800}{\text{gr}}$	2.8 × cc	1.866 67 × wc	0.187 5 × wr	1.653 52 × mc	· · ·	$\frac{\text{y}}{300}$
Yards per pound (yd/lb)	$y = \frac{496\,055}{\text{tex}}$	$\frac{4\,464\,492}{\text{den}}$	$\frac{840\,000}{\text{gr}}$	840 × cc	560 × wc	1600 × wr	496.055 × mc	300 × lea	· · ·

[a]The conversion factors are based on the following relationships given in Metric Practice E 380: 1 yard = 0.9144 m, exactly, and 1 lb (avoirdupois) = 0.453 592 37 kg, exactly. The conversion factors containing fewer than six significant digits are exact values.

[b]Multiples and submultiples of this basic unit may be used as a convenience to avoid large numbers or decimal fractions. For example, decitex (dtex) or tex × 10 is suitable for fine yarns and fibers; millitex (mtex) or tex × 1,000 is suitable for fibers; while kilotex (ktex) or tex/1,000 is often used for ropes, cords, rovings, tops, and slivers.

Examples of use:

1) The English worsted count equivalent to a cotton count of 10 is 1.5 times 10, or 15 English worsted count.
2) The cotton count equivalent to 30 tex is 590.54 divided by 30, or 19.7 cotton count.

Skechers EX1062
Skechers v Nike

dyed fabric. Yarns of differing merge numbers may have slightly different optical properties due to small differences in molecular weight, degree of crystallinity, orientation or amount of draw during manufacture. These differences can cause small but different degrees of dye acceptance, which will be manifested as streaks or bands.

4. PLIED YARN NOMENCLATURE

Because of the many singles yarn count systems used, in describing plied yarns care must be taken to properly list the construction and weight. However, once the singles yarn count system is known, the description of the number of plies is relatively straightforward.

4.1 Indirect Count

For indirect yarn numbers, the count of the singles yarn is given, followed by the number of singles combined to make the plied yarn, and the number of plied yarns combined to make the cord.

Example 1: A cotton 10s/2 (tens-2 ply) means that two cotton yarns, each of 10s count are plied together.

Example 2: If three such 10s/2 yarns are again plied to form a cord, the cord is identified as 10s/2/3. Note that in the first example the actual weight of the plied yarn, neglecting any contraction due to twist take-up (defined later in the chapter), is a 5s. This is called the "equivalent count" of the yarn. It is often necessary to know the equivalent count for purposes of calculating fabric weight or strength. For example, if a number 5 cotton duck is composed of 7s/3 warp yarns and 7s/4 filling yarns with 36 warp ends and 24 filling picks per inch, the fabric weight and strength can be reasonably estimated, predicated on the calculation of equivalent count.

4.2 Direct Count

Here the tex or denier of the singles yarn is given, followed by the number of singles making up the ply, and the number of plies making up the cord.

Example 1: A continuous filament nylon 210/3 plied yarn means that three singles yarns, each being 210 denier, are plied together. Excluding any contraction due to "twist take-up," the equivalent yarn count is 630 denier.

Example 2: If five such 210/3 plied yarns are again plied to form a cord, the cord is identified as 210/3/5, the equivalent yarn count being 3150 denier.

Sometimes the yarn is further described by giving the singles and ply twist and direction; for example, 210/3 – 8S – 6Z indicates three 210 denier singles yarns, each with 8 turns per inch S twist before plying, plied together with 6 turns per inch Z twist.

5. YARN TWIST MATHEMATICS

Ideally for a twisted perfectly symmetrical yarn composed of many (i.e., more than thirty) perfectly round continuous filaments of equal diameter, each filament will assume the form of a perfect cylindrical helix as shown in Figure 18.2.

If the cross sections are not round, or the symmetry is not perfect, deviations from the perfect helix will exist. In the case of plied yarns, each composed of twisted singles, a helix may be imposed upon a helix and the final path

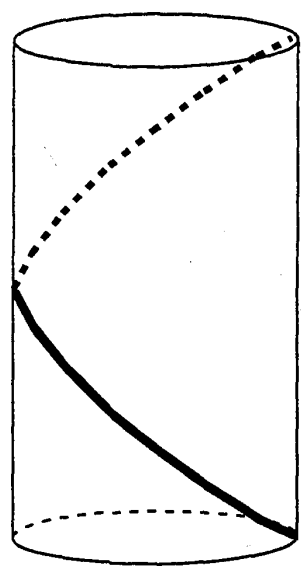


FIGURE 18.2 Ideal helix of a fiber in a yarn.

Skechers EX1062
Skechers v Nike

of a single filament becomes complicated. In the case of spun yarns, particularly for natural fibers, cross sections are not round, fiber diameters and lengths are not constant, and symmetry with respect to fiber position is minimum, largely because the individual fibers are not perfectly oriented longitudinally with the fiber axis but may "dart" from the center to the outer periphery of the yarn.

Certain classical mathematical relationships can be derived and are useful with respect to yarn manufacture. The relationships among filament size and shape, turns per inch, helix angle, yarn diameter and the spatial or geometric positioning of individual fibers can all theoretically be calculated. Deviations from the theoretical can be valuable in the practical phases of yarn manufacturing and in the evaluation of yarn properties. It will be apparent that in such geometrical mathematical analyses the same general principles which hold for filaments in yarns also pertain for yarns in plied yarns, and for plied yarns in cords. Several of the important factors that influence yarn properties are listed below, using the relationship of singles to plied yarns as a model. The same reasoning can be applied to the next lower (fibers into yarns), or next higher (plied yarns into cords) order of construction. A more thorough mathematical treatment is found in Appendix 5.

6. TWIST TAKE-UP

When two fixed lengths of singles yarns are twisted together to form a plied yarn, because of the helical path that each assumes with respect to the other, the resulting length of plied yarn must be less than that of each singles yarn from which the plied yarn is composed. The reduction in plied yarn length is called "twist take-up." It is defined as the change in length of a filament, yarn, or cord caused by twisting, expressed as a percent of the original untwisted length. Twist take-up is most easily determined by inserting a fixed length of yarn in a twist tester, untwisting, measuring the extended length, and calculating the percent extension as a function of the new extended length. Appendix 5 gives the mathematical analysis of twist take-up.

7. HELIX ANGLE VERSUS TURNS PER INCH

In the plied yarn the angle made by individual singles yarns with the axis of the plied yarn is called the helix angle (Appendix 5). It is a function of the turns per inch in the ply, the singles and plied yarn diameters, and a geometrical constant K, which is dependent upon the number and shape of the individual singles making up the ply.

8. YARN STABILITY

The value of the geometrical constant K, is dependent upon the shape and number of filaments making up the yarn, for these parameters will govern the manner in which the filaments pack together. Figure 18.3 shows filament packing configurations. The two and three filament (or ply) constructions are stable; four and five reasonably stable; the latter not in the form of a ring but in the flattened 2-3 form. The six develops as a central core of one, and an incomplete outer ring of five. Seven gives excellent symmetry and stability. Somewhat of a disadvantage in the seven unit construction is the problem of corkscrew (explained next) and elongation balance (Chapter 19.0, Fabric Properties and Technology). The single central filament may be slightly shorter than the peripheral filaments, and when a stress is applied the central filament may reach its limiting strain first and then break. The overall effect is somewhat lowered strength efficiency. The most stable constructions are made of 2, 3, 7 or 13 units. Of course most singles yarns, whether they be spun or continuous, usually contain more than, say, 15 filaments, and filament cross sections are not usually perfect circles. Therefore the number of filaments selected is not necessarily critical. In plied yarn or cord constructions, however, the number selected is of great importance because of the corkscrew influence.

9. CORKSCREW YARN

In plying yarns, one of the plies may run slack during the twisting while the remaining plies

Skechers EX1062
Skechers v Nike

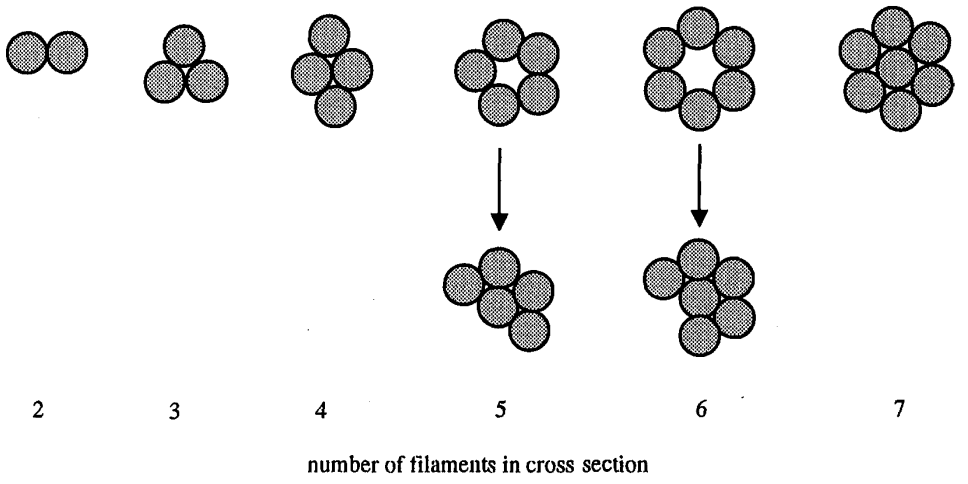


FIGURE 18.3 Filament packing.

are kept taut. This produces a "corkscrew" effect where the slack ply entwines about the remaining straight strands. While useful as a novelty effect, corkscrew yarns should be avoided in any industrial fabric where high strength-to-weight ratios are desired. Corkscrew yarns are weak because all plies do not break at the same time, and the yarn is stated to be "inefficient" because lack of rupture elongation balance. When tension is applied to such a yarn, the multi-yarn core, being shorter, will reach its limiting strain and will break first. Then the load is transferred to the corkscrewed yarn (or yarns). Depending upon their number, these may be too weak to support the load previously held by the straight core yarns, and so they, too, fail. Thus the strength of a corkscrew yarn must always be less than the theoretical attainable in a yarn devoid of corkscrew (see Appendix 5 for additional comments on corkscrew).

10. TWIST MULTIPLIER FOR SPUN YARNS

Because of the relationship between turns per inch and yarn size (diameter), the yarn manufacturer has found it necessary to establish a formula that will permit him to calculate the turns per inch necessary for a given size spun yarn. He uses a simple relationship between the turns per inch and the cotton count, calling the factor the "twist multiplier." This is a quantitative index of the relative steepness of the helix angle. Twist multiplier is defined as

$$\mathrm{TM} = \frac{T}{C^{1/2}} \tag{18.1}$$

where

T = turns per inch
C = cotton count

The twist multiplier is widely used as an empirical means for establishing proper twist in staple yarns. For cotton, for example, twist multipliers range from 2.5 for soft twisted yarns to six for very hard twisted yarns. Qualitatively, cotton singles yarns having a TM of about 4.5 have a surface helix angle of about 30°.

11. EFFECT OF YARN TWIST ON BREAKING STRENGTH

The twist that the manufacturer inserts in spun singles yarn depends upon the desired yarn character and intended use. In industrial fabrics a twist may normally be selected that will produce maximum breaking strength.

Figure 18.4 shows a graph of turns per inch versus breaking strength for a cotton yarn. The strength increases with twist until a maximum is

Skechers EX1062
Skechers v Nike

reached. For the example shown, this is at about 22 turns per inch. Then the strength starts to decrease. Two phenomena working opposite to each other produce this type of twist-strength relationship. As the twist increases, the individual fibers assume helical paths and wrap around each other. The normal pressure and total friction of the individual fibers pressing against each other progressively increase, with accompanying yarn strength increase, the theoretical maximum being that force which will rupture the fibers.

However, as the twist increases, the helix angle becomes more acute, and the force component along the yarn axis becomes less. This produces a progressive reduction in yarn strength. Furthermore, the randomness of the position of, and points of contact between, the individual fibers in the yarn produces a distribution of fiber lengths. When these varying fiber lengths are stressed, elongation unbalance results, the fibers break one at a time instead of as a group, and a lower yarn strength results. This elongation balance phenomenon is discussed in Chapter 19.0, Fabric Properties and Technology. Thus, the factors tending to produce increased yarn strength are more effective at low twist, while the factors tending to produce decreased yarn strength are more effective at higher twist, and so a rising and then falling twist versus strength curve results.

To explain the translation of staple fiber strength into spun yarn strength is an exercise in physics and mathematics of considerable complexity. Yarn strength is based upon such intrinsic fiber properties as strength, elongation, cross-sectional shape, length, friction coefficient, and upon such geometric factors involved in yarn formation, such as yarn diameter, turns per inch, degree of fiber packing (i.e., the ratio of fiber space to void space within the yarn), and the randomness of fiber position within the yarn.

12. YARN BREAKING STRENGTH AND ELONGATION TESTS

There are mainly two types of yarn breaking strength-elongation tests: single end and skein tests.

12.1 Single End Test

The single end test consists of inserting a length of yarn between the jaws of the testing

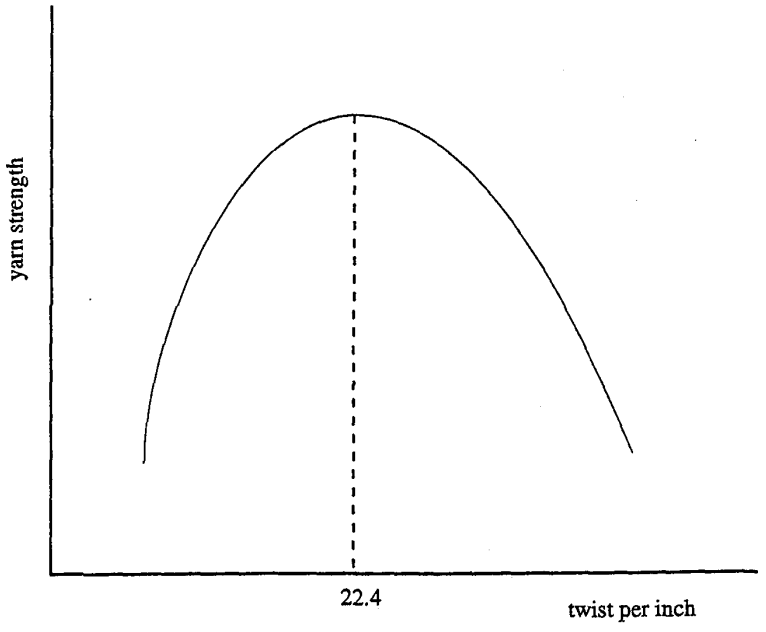


FIGURE 18.4 Effect of twist (turns per inch) on skein breaking strength of cotton yarn.

Skechers EX1062
Skechers v Nike

machine, separating the jaws, and recording the load-elongation curve using tensile testing machines. To avoid yarn cutting and "jaw breaks," capstan rather than flat jaws are often employed. The yarn is wound around the capstans with about ten inches of yarn in the "free gauge length," that is, the length between capstan tangent points. During the test, yarn elongation takes place not only in the free gauge area but also progressively around the capstans where the yarn is being snubbed. This snubbing elongation around the capstan must be taken into account in calculating true rupture elongation of the yarn (Chapter 20.0, Textile Testing).

12.2 Skein Test

Single end breaks give valid measures of strength and elongation under the selected test conditions, but are slow and time consuming for routine test purposes. At least five, and often fifteen or twenty tests are necessary to obtain a meaningful average. Therefore the skein test is widely used. Eighty 1.5 yard wraps of yarn are wound onto a reel, forming a skein which is then placed over two capstan jaws on the testing machine, and the breaking strength determined. ASTM D 1578 gives several options for number of turns and reel diameter. The strength per end may be calculated by dividing the recorded strength by 160 ends, or the skein strength itself may be used as an index of quality. In breaking a multiplicity of yarns in this type of test, all yarn ends do not break at the same instant of time. Because of weak spots, unequal rupture elongations and unequal tensions and lengths that develop in winding the skein, some yarns will break sooner than others. When one yarn is broken, the load that it supported is transferred to the others. This fractional additional load per yarn may exceed the capacity of another yarn, and it, in turn, will fail. The break is progressive through the skein, the phenomenon being called "serigraph effect" or lack of elongation balance (Chapter 19.0, Fabric Properties and Technology). Because of the serigraph effect, individual yarn strengths calculated from skein strength tests are lower than single end test values.

Fully automated modern yarn testing machines can test the strength of individual yarns very fast (a few seconds per yarn test), in a continuous manner, and may be used to replace skein tests.

13. COTTON YARN STRENGTH-COUNT FACTOR

For cotton yarns the higher the yarn number the lighter the yarn weight and (presumably) the lower the breaking strength. Because of this inverse relationship, the product of pounds breaking strength and yarn number tends to remain constant and it may be used as a criterion of breaking strength efficiency. The product is called the strength-count factor and is comparable to "tenacity," a term employed to describe the strength efficiency of man-made fibers, calculated as grams breaking strength per denier (or tex). The strength-count factor, of course, is not an absolute constant for singles cotton yarns, but is dependent upon fiber strength and staple length, yarn twist, whether the yarn is combed, etc. Empirical equations have been developed that relate skein strength and yarn count.

14. YARN TWIST BALANCE

Fibers in yarns assume an imposed helical shape that is not necessarily stable, there being a desire for each individual fiber to revert to its original configuration. The integrated effect sets up a torque in the yarn opposite to the direction of inserted twist, i.e., the yarn tends to untwist and therefore is stated to be "unbalanced" or "wild." Usually the greater the amount of twist, the greater is the tendency for unbalance. The term *balanced yarn* is applied to one exhibiting no tendency to double, twist or kink when held in a slack condition. To test for balance, a four or five foot length of yarn is held by the ends and allowed to hang freely in a loop while the ends are brought together. If this can be performed without the loops exhibiting any tendency to rotate or twist, the yarn is said to be balanced (Figure 18.5).

When testing for twist balance it is important

Skechers EX1062
Skechers v Nike

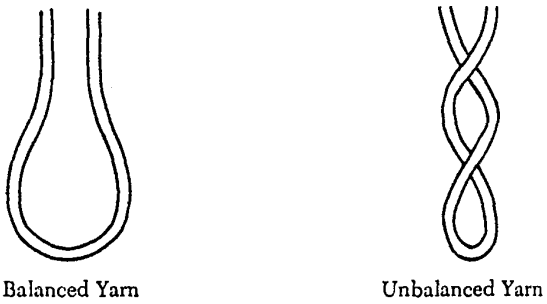


FIGURE 18.5 Twist balance.

to remove the yarn from the package without changing the twist in so doing. Upon cutting a length of yarn care must be taken not to permit one end of the yarn to rotate relative to the other. It should also be remembered that yarn twist can be changed by simply drawing the yarn over the top of the package. The yarn should always be removed from the package by the same method which is to be used for the end objective desired. Thus if the balance of a sewing thread is to be determined, and the yarn normally is paid off the spool by rotation rather than over the top of the spool, the same technique should be followed in selecting the sample for testing.

15. RELATIONSHIP OF SINGLES TO PLY TWIST

In manufacturing plied yarns or cords, the attainment of yarn balance may be desirable in order to obtain stability in the resulting fabric. If twist balance is not obtained, the yarn will be wild and difficult to manage, and the resulting fabric may pucker, curl or otherwise distort. Of course, it will be apparent that for some purposes unbalanced or wild yarns are desired—for example in the manufacture of "twist" broadloom carpets or seersucker fabrics. Presumably for most industrial uses, however, balanced yarns and cords are an advantage.

Balance can be obtained via two mechanisms. First, if the relationship of turns per inch and twist direction among singles, plies, and cords is correct, balance may result purely from the geometry of the structure. Second, independent of the geometry, balance, particularly in singles, can be obtained by relaxing the torques induced during spinning and twisting. Depending upon the nature of the fiber, this can be accomplished by immersion in water or steam for such hydrophilic fibers as cotton, rayon or wool; or by dry heat for such hydrophobic fibers as the polyesters or the polyacrylics. Aging of the yarn for prolonged periods also is useful in allowing torque stresses to decay until the yarn is "balanced." Chemical setting may also be used; in fact this is the basis of many of the so-called wash and wear finishes.

As a simple example of ply twist balance, consider an unstabilized singles yarn that contains eight turns of S twist. Referring to Figure 18.6 this would be accomplished by rotating the end of a 1 inch element through eight complete turns in a clockwise direction. If three such 8 tpi S twist singles are now plied together with eight (plus) Z turns, accomplished by rotating the three plies about the common axis in a counterclockwise direction, the original twist in the singles will be removed (approximately).

Thus, the plied structure will have eight

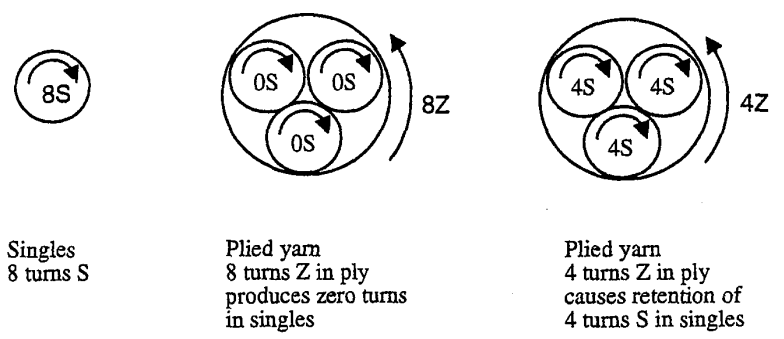
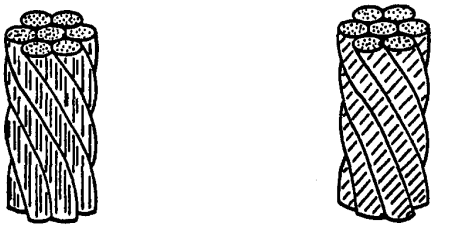


FIGURE 18.6 Singles-ply twist relations.

Skechers EX1062
Skechers v Nike

(plus) turns, while singles will theoretically be untwisted as they lie in the ply end and will possess little residual torque. The ply will contain eight turns and so a tendency for the ply to untwist will result because there is no offsetting twist in the singles. Now as a second example, if instead of eight turns Z ply twist, only four turns are inserted, the resulting structure will have approximately four turns S in singles and four Z turns in the ply, and balance is obtained. Of course this is an oversimplification of the problem. In theory, account must be taken of fiber torsional and bending rigidities, friction and stress relaxation time effects. In practice, because of these factors that cause deviations from the theoretical, the number of turns of twist in the singles and in the ply must be empirically determined in order to obtain balance. The main factor is the nature of the fiber itself. Fibers are not perfectly elastic; they do not obey Hooke's law which states that strain (elongation) is linearly proportional to applied stress (force). Fibers are said to be "viscoelastic" (Chapter 17.0, Fiber Properties and Technology); upon application of a load they initially deform approximately according to Hooke's law, but then may continue to "creep" or flow as long as a force is maintained. Upon load removal they tend to slowly "recover," i.e., revert back toward their original configuration and dimension. Therefore, when a single or plied yarn is manufactured, stresses that manifest themselves as torques result, and only by empirical means can one with certainty arrive at a balanced structure. Finally it will also be obvious that balance may occur at one relative humidity and temperature, but if the fibers are sensitive to heat or moisture, a different set of ambient conditions may result in a new unbalanced state. For heavy plied structures such as cords or ropes, balance is most easily obtained if the individual fibers in the singles yarn, or the individual yarns in the cord, are parallel to the axis of the next higher structure (Figure 18.7).



Balanced structure: fibers parallel to plied yarn axis.

Unbalanced structure: fibers are not parallel to plied yarn axis.

FIGURE 18.7 Plied yarn balance.

Skechers EX1062
Skechers v Nike

18.2

Review Questions

1. REVIEW QUESTIONS

1. What is the difference between the direct and indirect yarn number systems? Which one is more logical? Why?
2. Define the following terms:
   - twist direction
   - singles yarn
   - producer's yarn
   - merge number
   - S twist
   - Z twist
   - twist take-up
3. How is the twist multiplier for spun yarns calculated?
4. Explain the effect of yarn twist on breaking strength.
5. What is the significance of having twist balance in a yarn? Explain.

Skechers EX1062
Skechers v Nike

19.0

FABRIC PROPERTIES AND TECHNOLOGY

Skechers EX1062
Skechers v Nike

19.1

Fabric Properties and Technology

S. ADANUR

1. FABRIC GEOMETRY

The visual, tactile and engineering properties of a fabric are dependent upon many intrinsic as well as geometric fiber, yarn and fabric variables. A fiber's properties are governed by the character of the polymer substance from which it is made and by such geometric factors as cross-sectional area and shape, length, amount of crimp, stiffness, and surface characteristics. Yarn properties are governed by fiber properties and by such geometric factors as yarn diameter, twist, cross-sectional shape, and degree of fiber compactness. Fabric properties are governed by yarn properties and by such geometric criteria as the fabric weave, number of threads per inch, degree of thread packing within the structure, and yarn crimp.

Peirce [1] states that there are eleven structural factors that control fabric construction. The factors, for both warp and filling are (Figure 19.1):

- total length of yarn L between yarn intersections
- reciprocal p of the number of threads per inch, i.e., horizontal projection of L
- yarn crimp, c
- maximum perpendicular displacement h of the center line of a yarn out of the fabric plane
- angle of inclination ϕ of that length of yarn which is out of the fabric plane
- sum of warp and filling yarn diameters, D

Proper utilization of these eleven interdependent variables permits the engineering design of fabrics with the desired weave, number of threads per inch, yarn crimp, degree of fabric cover (i.e., ratio of fabric surface covered by the yarns to the theoretical maximum), fabric density and thickness. These factors in turn (in addition to intrinsic properties) influence such properties as breaking and tear strength, abrasion resistance, air permeability, etc. For example, the amount of air that can flow through a fabric at a given pressure differential across the fabric is a function of the fabric weave, the number of yarns per inch, yarn crimp, and yarn cross-sectional shape, the latter influenced by yarn twist. All of these variables control the shape and number of open area interstices within and between yarns through which air flow takes place.

2. YARN COUNT AND COVER FACTOR

The "yarn count," i.e., the number of warp and filling yarns per inch in a fabric is most easily determined by a direct count with the aid of a pick counter. For a given yarn number, the larger the number of threads per inch the more dense and opaque is the fabric. If for each set of yarns the product of the thread count (per inch) and the yarn diameter (inches) is less than one, then theoretically open spaces will exist between the yarns. The ratio of fabric surface occupied by yarn to the total fabric surface is called the fabric "cover factor," and can be shown, theoretically, to be (Appendix 5):

$$C = (w \cdot d_w + f \cdot d_f - w \cdot f \cdot d_w \cdot d_f) \tag{19.1}$$

Skechers EX1062
Skechers v Nike

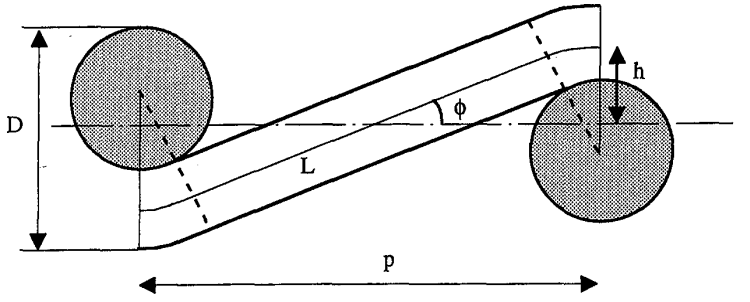


FIGURE 19.1 Schematic of a unit cell for a plain weave.

where

C = cover factor
w = warp threads per inch
f = filling threads per inch
d_w = warp yarn diameter in inches
d_f = filling yarn diameter in inches

When a condition is reached where, for either warp or filling yarns, the product of the number of yarns per inch and the diameter equals one, the yarns will touch each other, and the cover factor becomes one. When this condition exists for both sets of yarns the cover factor remains one. Often in this latter case the maximum number of warp and filling yarns possible has been woven into the fabric. Any further increase in picks or ends would result in yarns piling up on each other to give a double or multiple layer of yarns. Of course the yarns may be compressible and therefore more yarns than the theoretical maximum, calculated on the basis of uncompressed yarns, are often weavable into the fabric. Fabric cover factor is of obvious importance with respect to water, moisture vapor, or air permeability. In fabric coating the degree of openness will influence the penetration of coating into or through the fabric, and in part will affect adhesion.

3. FABRIC DENSITY, PACKING FACTOR, AND POROSITY

The density of a fabric is calculated by measuring its thickness and its weight per unit area:

$$\text{Density} = \frac{\text{weight}}{\text{unit volume}} = \frac{\text{weight}}{\text{unit area} \times \text{thickness}} \quad (19.2)$$

A fabric is composed of both fiber substance and air space, but only the fiber substance contributes to the weight. The theoretical maximum density achievable if all yarn and fabric voids are removed by compression is that of the fiber itself. The ratio of fabric density to fiber density is a measure of the degree to which the fibers are packed together and is called the "Packing Factor."

$$\text{Packing Factor (P.F.)} = \frac{\text{fabric density}}{\text{fiber density}} = \frac{W/V_t}{W/V_f} = \frac{V_f}{V_t} \quad (19.3)$$

where

W = fiber (as well as fabric) weight
V_t = total volume of fabric
V_f = volume of fiber

"Porosity" is the amount of open space within a fabric. Porosity may be defined as the ratio of the volume of air or void contained within the boundaries of a material to the total volume (solid material plus air or void) expressed as a percentage.

$$\text{Porosity } (P) = \frac{V_v}{V_t} \times 100 \quad (19.4)$$

where

P = porosity

Skechers EX1062
Skechers v Nike

V_v = volume of voids in the fabric
V_t = total volume of the fabric

Since both packing factor and porosity are measures of the ratio of fiber volume to total fabric volume, they are negatively correlated as follows:

$$\text{P.F.} = \frac{V_f}{V_t}$$

and

$$P = \frac{V_v}{V_t} = \frac{V_t - V_f}{V_t} = 1 - \frac{V_f}{V_t}$$

therefore

$$P = 1 - \text{P.F.} \qquad (19.5)$$

4. YARN CRIMP AND TAKE-UP

Since a woven fabric consists of sets of interlacing yarns, either the warp, the filling or both yarns must assume a wavy path in order to be accommodated within the fabric. This waviness is called yarn "crimp." Depending upon the tension applied to the yarns during weaving, most, or theoretically all, of the crimp can be inserted into the warp, with the filling being perfectly straight, or the crimp can be inserted into the filling, with the warp straight, or crimp can be present in both sets of yarns (Figure 19.2).

Fabric tensioning in either the warp or filling direction tends to remove the crimp and straighten the tensioned set of yarns. The straightening must inevitably produce increased crimp in the perpendicular set of yarns. This can be visualized by examining the top and middle portions of Figure 19.2. Tensioning the crimped filling produces a straight filling, but a crimped warp. This crimp transfer is called "crimp interchange." It can result in important changes in fabric gemoetry, which, in turn, can advantageously or negatively affect such properties as breaking strength and elongation, tear strength, energy absorption and crease resis-

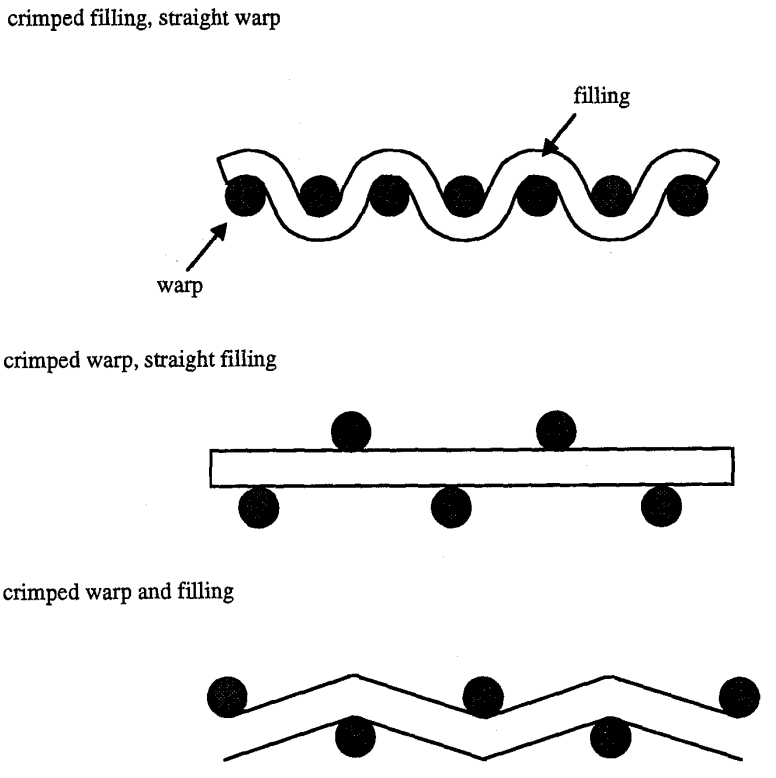


FIGURE 19.2 Fabric crimp.

Skechers EX1062
Skechers v Nike

tance. "Negative tension" via water or heat relaxation, with accompanying shrinkage, can also produce crimp interchange.

Fabric weave also influences the amount of yarn crimp. The greater the number of yarn intersections per unit area of fabric surface, the longer must be the path of warp over filling or filling over warp. Thus a plain weave fabric will have greater yarn crimp than a satin. In designing fabric constructions it is important that the crimp-elongation relationship be kept in mind. Thick bulky fabrics usually are designed with maximum yarn crimp. Double and triple fabrics contain high crimp yarns that travel from the face to the back of the fabric.

In addition to the crimp resulting from the passage of warp over filling, both the yarn itself and the fibers composing the yarn can also have different crimp frequencies as shown in Figure 19.3. Thus three different orders of crimp can exist within a fabric structure.

The percentage crimp which a yarn contains as it lies in a fabric is determined by placing gauge marks *on the fabric,* with crayon or ink, for example exactly ten inches apart, so that one or more of the yarns will contain the marks. Each marked yarn is then raveled out of the fabric, taking care not to strain it or disturb its twist. The flat jaws of a low capacity constant rate of extension tensile tester are adjusted to a gauge length of exactly ten inches, and the yarn inserted so that the original gauge marks on the yarn will exactly line up with the edge of each jaw. In this condition, because of the presence of yarn crimp, the yarn will be loose and floppy between the jaws. The lower jaw of the testing machine is slowly moved down, thus plotting an accurate load-elongation diagram, until the load required to straighten but not stretch, the yarn is achieved. The resulting elongation, as a percentage of the original length marked in the fabric is the percent crimp. Crimp is normally removed at very low loads and, therefore, meticulous techniques are required if accurate values are to be obtained.

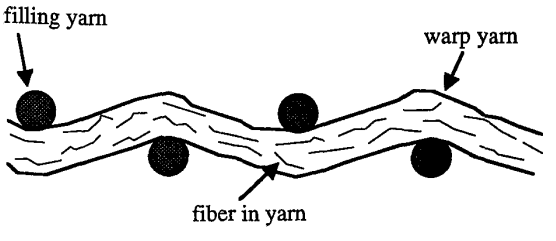


FIGURE 19.3 Three types of fiber and yarn crimp.

It is important to distinguish between the terms "percent yarn crimp" and "percent yarn take-up" or "contraction." The measurement is the same, but the former is calculated on the basis of the crimped length of yarn while the latter is calculated on the extended length. Thus according to ASTM [2]:

- *Percent crimp* is the difference in distance between two points on a yarn as it lies in a fabric, and the same two points when the yarn has been removed from the fabric and straightened under specified tension, expressed as a percentage of the distance between the two points as the yarn lies in the fabric.
- *Percent take-up* is the difference in distance between two points in a yarn as it lies in a fabric, and the same two points after the yarn has been removed from the fabric and straightened under specified tension, expressed as a percentage based on the straightened out-of-fabric distance.

The weaver uses percent take-up because it tells him the length of fabric he will obtain from a given length of yarn.

5. FABRIC SKEW AND BOW

The filling yarns in a fabric may not always lie perpendicular to the warp. Furthermore, because of tensions developed during weaving, the filling yarns may assume the shape of an arc or bow as they lie in the fabric. The former condition is known as skew; the latter as bow (Figure 19.4).

Skew is defined as the distance, measured parallel to and along the selvage, between the point at which a filling yarn meets one selvage, and perpendicular from the point at which the same filling yarn meets the other selvage. It is expressed as a direct distance (AB in

Skechers EX1062
Skechers v Nike

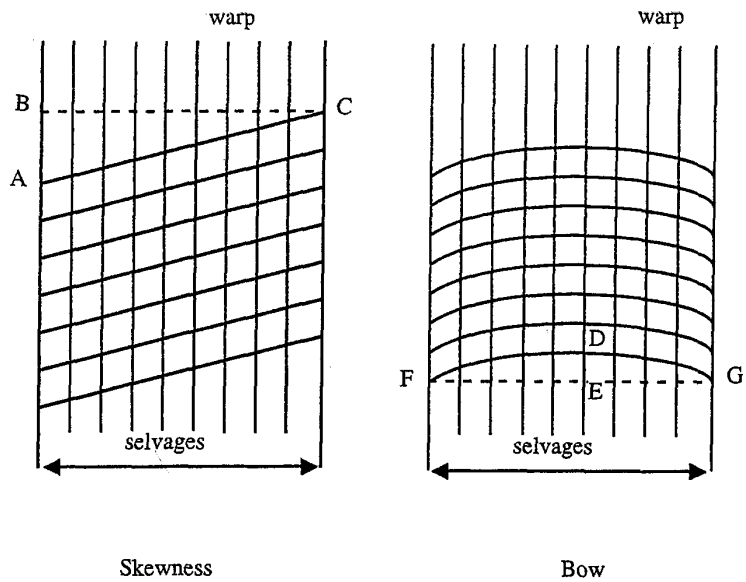


FIGURE 19.4 Fabric skew and bow.

Figure 19.4) or as a percentage of the fabric width:

$$\% \text{ Skew} = (AB/BC) \times 100 \quad (19.6)$$

Bow is defined as the greatest distance, measured parallel to the selvages, between a filling yarn and a straight line drawn between the points at which this yarn meets the two selvages. It is expressed as a direct measurement DE in Figure 19.4, or as a percentage of the fabric width:

$$\% \text{ Bow} = DE/FG \quad (19.7)$$

6. FABRIC WEIGHT

As in the case for yarns, there are both direct and indirect systems for describing fabric weights. The direct system indicates weight per area, or weight per running length for the full width of the fabric. It is unfortunate that many times when the fabric weight is given, the units are not recorded, so that one cannot know (except by experience) whether the weight per square yard or running yard is meant. Furthermore, the weight per running yard is meaningless (again except by experience) unless the width is given.

The indirect system indicates running length per weight, and is most often given as running yards per pound. Area per unit weight—for example, square yards per pound—is practically never used.

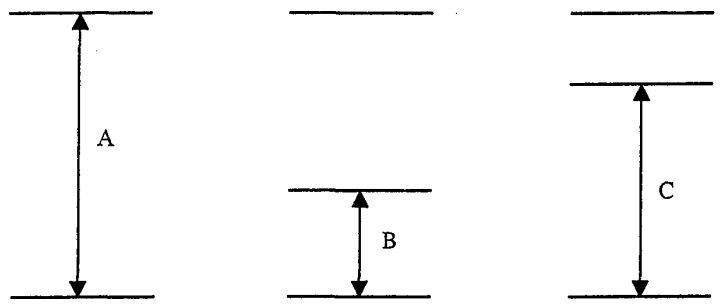
7. FABRIC THICKNESS

Because fabrics are compressible, the measurement of thickness should be made under controlled pressure of the thickness gauge. ASTM D 1777 specifies different pressures for different fabrics [3]. For dense compact fabrics, thickness is not critically influenced by pressures. For lofty, "soft," compressible fabrics it may be necessary to specify both the pressure and the area of the presser foot. Also, because the fabric might gradually compress and creep under the dead load, often the time, usually in seconds, that has elapsed between initial load application and the reading of the gauge, should be specified.

8. FABRIC COMPRESSIBILITY AND RESILIENCE

If a textile fabric is subjected to a progressively increasing compresssional load, there will be a progressive decrease in thickness.

Skechers EX1062
Skechers v Nike



A. Original fabric thickness at zero (or slight) compressional load

B. Compressed fabric thickness at selected load

C. Recovered fabric thickness after load removal

FIGURE 19.5 Fabric compression and resilience.

When the load is gradually removed, the thickness will revert toward, but may not ever return completely to its original thickness. The tensional creep-recovery phenomena and nomenclature described in Chapter 17.0, Fiber Properties and Technology, apply equally well to fabrics in compression. Therefore the amount of compression that is instantaneously recoverable upon load removal is called instantaneous elastic recovery, the delayed recovery is called primary creep, and the non-recovery portion is called secondary creep or permanent set.

The percent of fabric compression at any selected load level is called the "softness" of the fabric (Figure 19.5). The percent of compression recovered upon load removal is often, but not always, called the "resilience." A second concept of resilience is based upon the ability of the fabric to absorb and return energy, rather than upon linear compression and recovery. Thus, referring to Figure 19.5, resilience may be defined as the energy produced when the fabric recovers from thickness B to C as a percentage of the energy required to compress the fabric from A to B. The percent of thickness not recovered is called the permanent set.

$$\text{Percent Compression} = \frac{A - B}{A} \times 100 \tag{19.8}$$

$$\text{Percent Resilience (thickness basis)} = \frac{C - B}{A - B} \times 100 \tag{19.9}$$

$$\text{Percent Resilience (energy basis)} = \frac{\text{Energy absorbed A to B}}{\text{Energy released B to C}} \times 100 \tag{19.10}$$

$$\text{Percent Permanent Set} = \frac{A - C}{A} \times 100 \tag{19.11}$$

A thin, hard, dense fabric will have low compressibility or softness. It will not become appreciably reduced in thickness under load. Its resilience however may be high, for upon load removal the thickness that it did lose may become almost completely restored. A thick lofty fabric under load will compress significantly and is, therefore, soft. Its resilience may be high or low depending upon its capability of recovery to its original thickness.

A fabric may be called upon to withstand repeated cycles of compressional loading and load removal. This cycling often causes the thickness to become progressively lower, approaching a limiting minimum value under maximum load. Similarly the thickness after recovery approaches a minimum value under minimum load. The ability of the material repeatedly to become compressed and to recover to its original dimension will be important where retention of thickness for maintenance of thermal insulation is required. Also, the ability to absorb energy repeatedly is a function of the ability to maintain original thickness.

Skechers EX1062
Skechers v Nike

9. THERMAL CONDUCTIVITY

The amount of heat (in calories or British Thermal Units) that flows through an insulating material is given by:

$$Q = \frac{KA(T_2 - T_1)t}{d} \qquad (19.12)$$

where

Q = total quantity of heat transmitted through the material
K = thermal conductivity constant
A = area through which the heat is flowing
d = thickness
T_2, T_1 = temperatures of warm and cool surfaces
t = time of heat flow

By means of thermal conductivity test equipment and procedures, the coefficient of conductivity K can be determined. The above equation presumes that K *is* a true constant independent of insulation thickness, and this is true for relatively thick insulators such as brick or glass fiber batting. However, in comparing the insulation characteristics of different fabrics on a unit thickness basis, the use of K may not be justified because it is based upon the premise that the fabric thickness can be increased or decreased without causing a change in the basic heat insulation characteristics. This is not so. Textile fabrics are relatively thin, and because of the large surface effects on both sides of the fabric, the K may be meaningless. Therefore the coefficient of "conductance" C is usually calculated for fabrics. This is a measure of the heat flow through the fabric for the thickness of the fabric as it exists, the general equation being

$$Q = CA(T_2 - T_1)t \qquad (19.13)$$

where C is the conductance. Thus

$$C = K/d \qquad (19.14)$$

For textile fabrics, a linear relationship exists between thermal conductivity and thickness. Because all fibers have higher conductivities than air, the statement that thermal insulation is largely dependent upon the entrapment of still air within the fabric is true. If the fabric is lofty and open it may be an excellent insulator in still air, but may be poor where air velocity through the fabric is high. In this case the moving air will conduct heat away and thermal insulation will fail. Tightly woven fabrics of high cover factor will not permit as much air flow, and therefore thermal insulation at high air velocity will be maintained. On the basis of thermal insulation per unit weight, open lofty structures composed of fibers of low specific gravity will be the most efficient.

Three methods are normally employed to measure thermal conductivity.

(1) The fabric is placed between two plates (usually metal) at different temperatures, and the rate of heat flow is determined.
(2) A hot surface is wrapped with the fabric and its rate of cooling is measured.
(3) A hot surface is wrapped with the fabric and the amount of heat necessary to maintain temperature is measured.

Because conductance is dependent upon thickness, it is important that fabric thickness be accurately determined and maintained throughout the test. Conductance also may be a function of the temperature differential employed in the test. For example, the conductance at a differential between 500°F and 70°F might be entirely different from that between 32°F and −40°F.

10. AIR PERMEABILITY

Air flow through a textile fabric obeys the general rules for fluid flow through an orifice. However, fabric orifices that exist because of the interlacing of warp and filling yarns are small in size, odd in shape, and large in number. These seriously complicate air flow calculations. The classical expression for the flow of an incompressible fluid through an orifice states that the volume flow is directly proportional to the product of the orifice area and the square root of the pressure differential across the ori-

Skechers EX1062
Skechers v Nike

fice. The proportionality constant includes coefficients of contraction and velocity, the approach area, the fluid density and the gravitational constant. For a fabric, air flow at any selected pressure differential is directly proportional to the product of the amount of open area within the fabric through which the air can flow, and the square root of the pressure drop across the fabric:

$$Q = K(FA)(\Delta p)^{1/2} \qquad (19.15)$$

where

Q = volume flow rate per unit fabric area
FA = free area (fractional area of the total fabric surface not occupied by yarns)
K = proportionality constant dependent upon fabric geometry and other fluid flow factors
Δp = pressure differential across the fabric

For a hypothetical fabric composed of perfectly circular filaments that do not elongate under the applied pressure differential, the air flow can be calculated from the above formula, provided K is known. However, textile fibers are viscoelastic, and deform under the tensions that develop as a result of the applied pressure. The measurement of air permeability becomes further complicated because, as the pressure increases, the yarn elongations produce changes in the shape of the interstices and the total free area increases, thus producing a concomitant increase in air flow.

It is common practice in the laboratory to measure air flow in cubic feet of air per square foot of fabric per minute at a pressure differential across the fabric equivalent to 0.5 inches of water. In actual use of fabrics, much higher pressure differentials may develop. It has been established that at pressures up to about 50 inches of water, air flow takes place primarily between adjacent yarns, and only to a minor degree between fibers within a yarn. The effects of yarn twist on air permeability are twofold. In parachute fabrics composed of multi-filament yarns, as twist increases, both the circularity and the packing density of the yarn increase. Therefore, yarn diameters are reduced, the cover factor is lowered, and the pore space of free area between yarns increases. This produces an increase in air permeability.

Any construction factor or finishing technique that changes the area, shape or length of the air flow path can appreciably change air permeability. The effect of twist has been discussed above. Yarn crimp is important because it permits the yarns to extend easily, thus opening up the fabric and increasing the free area when a pressure differential is applied. In addition, yarn crimp and fabric weave will influence the shape and length of the free area orifice. Hot calendering is often used to reduce fabric air permeability by flattening the yarns so that their cross-sectional shapes are elliptical rather than circular, thus reducing free area.

11. MOISTURE VAPOR TRANSMISSION

Water vapor will pass through a fabric provided there is a relative humidity differential across the fabric, and provided that the vapor can transpire between yarns within the fabric, between fibers within the yarns, or through the fiber substance itself. For fabrics with low cover factor where free space exists between yarns, water vapor will pass through the yarn or fabric voids. For high cover factor fabrics composed of yarns containing densely packed fibers, water vapor cannot pass through the yarn or fabric interstices. If the fiber is hydrophobic, that is, has zero moisture regain and will not absorb or release water vapor, the fabric will act as an impervious membrane. However, if the fiber is hydrophilic and can easily absorb or release water vapor, significant although limited amounts of vapor can be transmitted through the fabric. For synthetic hydrophobic fibers, when the fiber volume in the fabric exceeds about 35% of theoretical maximum, moisture transmission resistance increases rapidly, while for hydrophilic fibers such as cotton and wool, the resistance increases slowly. If the fabric construction is proper, a fabric can have low air and liquid water permeability but nominal water vapor transmission.

Moisture vapor transmission is determined by the "absorption cup" or the "evaporation"

Skechers EX1062
Skechers v Nike

method. In the former the test fabric is placed horizontally over a cup of calcium chloride or other desiccant, the assembly is placed in a constant relative humidity atmosphere, and the absorption of water by the desiccant is measured by weighing the entire assembly at known time intervals. The second method consists of placing the test fabric horizontally over a cup of water, placing the assembly in a constant low relative humidity atmosphere, and plotting the loss in weight of water with time. For both tests transmission is calculated as grams of water transmitted per square meter of fabric per twenty-four-hour period. While these methods give valid results for impermeable materials such as plastic films, and may be useful for comparing fabrics, they do not give precise results for open fabrics of high moisture transmission. This is because as the water is absorbed into the desiccant (first method), or evaporates (second method), the relative humidity of the air adjacent to the fabric may not remain constant.

12. WATER REPELLENCY AND RESISTANCE

There are varying degrees of water repellency and resistance depending upon the nature of the fiber, the fabric construction, and whether the fabric is covered with an impermeable coating. The term *waterproof* is used to describe a fabric that is completely impermeable to the passage of water and moisture when water pressure is applied, and that will retain this property throughout its expected life under normal use.

In trade practice the canvas goods industry applies the term *waterproof* or *waterproofing* to knife coated finishes comprising such ingredients as paraffins, pigments, and resin binders with add-on weights of 50 to 90%. These types of treatments may not in fact produce fabrics that meet the strict waterproof definition. Rubber or vinyl coated fabrics that truly are waterproof are usually referred to as "coated fabrics."

The American Association of Textile Chemists and Colorists (AATCC) and the ASTM define "water resistance" as a general term denoting the ability of a fabric to resist wetting or penetration of water or both. "Water repellency" is defined as the ability of a textile fiber, yarn or fabric to resist wetting. Different tests for measuring the water resistance or repellency of fabrics are defined in Chapter 20.0, Textile Testing. The tests are of varying degrees of severity, but basically they measure (1) the resistance of the fabric to surface wetting and penetration by falling drops of water; (2) the amount of water that the fabric will absorb when immersed or manipulated under water; (3) the hydrostatic pressure required to cause fabric leakage, or the amount of water leakage at a given hydrostatic pressure; and (4) determination of fiber, yarn, or fabric wettability by contact angle measurement.

Gray unbleached cotton and linen fabrics have considerable natural water repellency because of the natural waxes present. Scoured and bleached cotton and linen fabrics, and also rayon fabrics are particularly hydrophilic unless water-repellent chemical finishes are subsequently applied. Thus they enjoy wide usage where large amounts of water are required to be absorbed. Wool initially has a fair degree of natural repellency, but when finally wet out, it has a large capacity to hold free water.

The tendency of a drop of water to spread out over a fiber, yarn, or fabric surface is dependent upon the angle of contact made by the water drop and the surface. If the fabric surface is water repellent, the drop will rest up on it and will not penetrate. The contact angle is stated to be high. If the water can easily wet the surface, spreading occurs with accompanying low contact angle. A synthetic fiber may be completely resistant to water absorption, and yet its surface may be thoroughly wetted by water. Therefore synthetic fabrics are often quickly and completely wet out, the water coating the surface of each fiber, as well as filling the voids between fibers. Because many synthetic fibers are hydrophobic, it does not follow that fabrics made from them will be water repellent. In fact, the voids that lie between fibers may act like capillaries and actually enhance the spreading and wicking of the water. Therefore many synthetic fibers must also be treated with special finishes if they are to be water repellent.

Fabric structure can play an important part in

Skechers EX1062
Skechers v Nike

water resistance. For example, a tightly woven cotton fabric with high cover factor that, when dry, has sufficient interstices between yarns to allow moisture vapor to dissipate, thus making the wearer comfortable. Upon wetting, the cotton fibers swell, making the fabric construction "jammed" so that water cannot get through the yarn and fabric interstices.

13. DRYING RATES AND DRYING TIME

The rate and time of drying for a textile material is a function of the state of aggregation (i.e., shape, position and distribution) of the fibers in the yarn and the yarns in the fabric, and depends as well upon the relative humidity, temperature and velocity of the air which is doing the drying via moisture absorption and subsequent dissipation. The moisture regain of the fiber itself has little influence on drying rate and time.

The drying mechanism consists of the water on the surface of the fibers evaporating into the surrounding air. Diffusion then causes water held within the fabric to come to the surface where it too can evaporate. The major part of the drying cycle from near saturation down to within 15% regain above 100% R.H. equilibrium moisture regain is characterized by a constancy in evaporation rate. This rate in grams per square centimeter of fabric per hour is equal for all fabrics of the same yarn and fabric construction, irrespective of fiber type, except that smooth-surfaced non-hairy fabrics exhibit somewhat higher rates. Total drying time under household drying conditions is dependent upon the ratio of total moisture uptake to peripheral surface area of fabric. It is generally known that identical textile structures will evaporate via identical mechanisms and at identical rates. An "Orlon" acrylic fabric and a wool fabric, both of the same yarn and fabric type, will have equal drying rates as measured by graphs of weight loss versus time. Drying times (i.e., the time required for the fabric to feel dry to the touch) will also be the same. These statements hold even though the "Orlon" has a moisture regain of 1.5% and the wool about 16%. The wool will feel dry when it has reached a regain somewhat lower than 29%, its 100% R.H. regain; but the "Orlon" must be brought below 2.5% regain, its 100% R.H. regain value before it feels dry. Thus the original regain of each fiber is of little consequence.

The general statement that synthetic fabrics are "quick drying" is fallacious. It is true that a thin, lightweight, low moisture regain synthetic filament fabric will dry more quickly than a thick, heavy, high moisture regain spun yarn fabric, but this is because the latter fabric must have a great deal more water evaporated from it before it becomes dry, not because it is made from hydrophilic fibers.

14. FABRIC BREAKING STRENGTH AND ELONGATION

The breaking strength of a fabric is popularly used both for quality control and as a performance standard. For industrial or other purposes where the fabric is in fact subjected to tension, it is proper that breaking strength be measured. In cases where the fabric is not called upon to withstand tensile forces, rightly or wrongly breaking strength is probably the most popular method for maintaining quality control. It is an easy test to make, and gives a quick and reliable indication that the fiber, yarn or fabric is up to standard. It should be remembered, however, that there are many textile applications where strength is of little consequence, and its use as a standard or quality index may be meaningless, improper, or far outweighed by other important criteria. In some cases the maximum or minimum elongation which is produced at a selected strength level below rupture is specified as a criterion.

Two types of fabric strength tests are commonly used: the "raveled strip" and "grab" methods.

14.1 Raveled Strip Strength Test

A specimen 6 inches long and 1.25 inches wide is cut in either the warp or filling direction. Edge yarns in the longer direction are raveled out and removed from the fabric until its width becomes one inch. A fringe 1/8 inch thick on each side of the fabric thus results (Figure

Skechers EX1062
Skechers v Nike

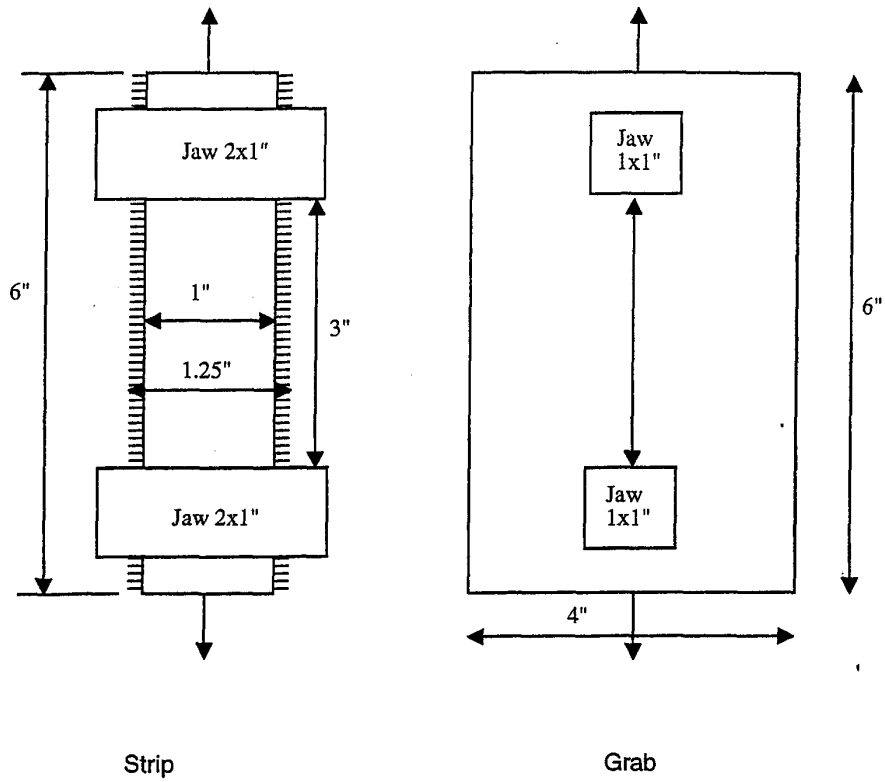


FIGURE 19.6 Raveled strip and grab breaking strength test specimens.

19.6). The test strip is clamped lengthwise in the flat jaws of the testing machine so that there are three inches between jaws. Each jaw is two inches wide so that all yarns within the fabric are held and broken during the test. If the fringe is not present, as the tensile force progressively increases, the edge yarns will pop out of the fabric, and while they are still held by both jaws, in effect a combination of yarn and fabric is tested, with the popped yarns not usually sharing their full burden of the load. The fringe prevents the yarns from popping out and hence the fabric is tested as a fabric.

Purely on a percentage basis, the need for accurately raveling coarse heavy fabrics where there may be fewer than thirty threads per inch is obviously much greater than for fine lightweight fabrics of eighty threads per inch or higher. If for any reason the yarn in the fabric is not easily raveled, it is then not necessary to ravel, for the edge yarns will not pop out during the test. In such cases the fabric is cut exactly one inch wide, and tested directly. Coated fabrics, resin impregnated fabrics where warp and filling yarns are bonded at yarn intersections, felts and nonwovens are cut to one inch, and are not raveled. Another advantage of raveling is that it permits the person conducting the tensile test to line up the yarns parallel with the direction of pull on the testing machine. There is less chance for a fabric to be tested slightly on the bias where yarns will not be through-going from top to bottom jaws.

The raveled or cut strip tensile test is an excellent method for studying the effects of chemical finishes, heat aging, weathering, microbial deterioration, and the like on tensile properties. Modern tensile testing machines produce a record of the load-elongation diagram from which strength elongation and energy absorption can be determined. Strip strength values are normally reported as pounds per inch. Breaking elongation is calculated as percent of original gauge length. Energy is given in inch-pounds per inch length and width of specimen or gram-cm per cm^2.

Skechers EX1062
Skechers v Nike

14.2 Grab Strength Test

The ravel strip test requires slow, careful and often tedious specimen preparation and therefore is considered uneconomical by many mills. In addition, it is criticized on the basis that it does not simulate the way fabrics are used. For both of these reasons the grab test is also popular, particularly in testing heavy industrial fabrics. A specimen 4 × 6 inches is cut so that the direction of test is in the longer direction (Figure 19.6). Flat jaws one inch on a side and three inches apart at the start of the test are used to clamp the fabric. When the jaws are separated, the through-going yarns clamped in both jaws are subjected to tension. In addition, because of the interaction of warp and filling yarns with attendant frictional forces a "fabric assistance" effect develops, and yarns adjacent to those actually clamped in the jaws will help to support the load. Thus grab strength tests usually produce higher strength values than strip tests.

Because of the fabric assistance effect and the lack of uniformity in elongation between the yarns fastened within the jaws and those adjacent yarns contributing strength and energy, grab test breaking elongation and energy values may not be meaningful. Repeated stress properties are not normally measured via the grab test.

14.3 Jaw Breaks

In conducting either strip or grab tests, care must be taken to insure that fabric failure does not occur at the jaw. Jaw breaks are almost always lower in strength than breaks that occur in the "free gauge" portion of the test specimen. Particularly in heavy goods, if the breaking strength is high, considerable pressure must be applied to the flat plates of the jaw so that fabric slippage will not develop. Sometimes if the jaw pressure is too great the yarns in the fabric are crushed, deformed or otherwise damaged with resulting strength loss. If the jaw pressure is too low, fabric slippage will occur and an improper test results. Sometimes masking tape or a coated fabric will be used to line the jaws, or rosin is applied to the fabric ends to prevent slippage. The ends of the fabric specimens may be impregnated with glue or resins such as vinyls or methacrylate dissolved in suitable solvents to permit application. In using such latter techniques care must be taken to insure that the resin or solvent does not damage the fiber.

14.4 Narrow Fabric and Ribbon Strength Tests

Fabrics, webbings, ribbons, etc., whose widths do not exceed about three inches are normally tested at full width. The test is identical with the strip test except that there is no raveling to form a fringe. Narrow fabrics usually have a woven, or resin bonded or heat fused edge so that raveling cannot develop. For heavy webbings jaw slippage or jaw breaks may occur, and so capstan jaws are often employed. The true determination of rupture elongation of a specimen tested with capstan jaws requires a correction factor because of progressive but diminishing elongation around the jaws.

14.5 Fabric Repeated Stress Properties

A raveled strip specimen can be repeatedly stressed and relaxed at load levels below rupture, and many properties can be determined similarly for the more structurally complex yarns and fabrics. However, in fibers (excluding natural or induced fiber crimp) all of the elongation, whether it be instantaneous elastic deflection, primary creep or secondary creep, is inherent in the fiber. In yarns and fabrics there can be additional elongation which is entirely geometrical, stemming from the straightening of yarn crimp. Often such geometric elongation is non-recoverable, since once the geometric deformation has occurred, there is no restoring force operating that can return the fabric to its original dimensions. Under such circumstances the fabric contains secondary creep. If, on the other hand, the geometric elongation is reversible, due to the desire of the fiber or yarn to return to its originally bent, coiled or crimped configuration, the fabric will contain primary creep. While it is not common practice in textile technology to identify them separately, there can be in fact six components of elongation in a fabric; inherent instantaneous elastic deforma-

Skechers EX1062
Skechers v Nike

tion, primary and secondary creep, and their geometric counterparts.

15. BIAXIAL STRESSING

The strip or grab tensile test is in general primarily concerned with the load-elongation characteristics of a specimen measured in a single direction for any given test. Tests may of course be performed in more than one fabric direction, most commonly in warp and filling directions, but each is evaluated without respect to any phenomena along any axis other than that of the test. Such tests are commonly classified as "uniaxial." That such a title is a misnomer can easily be seen by observing a simple strip tensile test, and noting the narrowing that takes place in the unrestrained region. Deformations are therefore occurring along more than one axial direction. What is really meant by a uniaxial test is not that loads or deformations take place along only one axis but that they are *applied* and *measured* along only one axis.

For many purposes a uniaxial test is adequate. It is an index of relative strength, of the degradation or improvement afforded by a treatment. Nonetheless, the practical applications of fabrics only rarely impose a truly uniaxial stress. Some examples of this are tapes and belts used for power transfer in machinery and ropes. In the more common cases stresses are simultaneously imposed in more than one direction. Obvious examples of this are the deformations at the knee or elbow of a garment, the fabric in a filter press, the walls of a fire hose, or the drying of a fabric on a tenter frame where warp and filling tensions are exerted at the same time.

Biaxial testers require control of the ratio of loading rates in the warp and filling directions and means for recording the resulting strains. Usually a cruciform specimen is employed, the two sets of jaws gripping opposite tails (Figure 19.7). In order to prevent the central portion of the fabric from skewing during the test, all four jaws must move at controlled rates. It is generally believed that the data obtained from the biaxial tests are usually not worth the effort applied. There are other empirical and easier ways of gaining an insight into the biaxial properties of fabrics, and these are the burst tests.

16. BURSTING STRENGTH

There are many industrial uses where textile fabrics are called upon to withstand bursting type forces that develop via air, fluid, or direct mechanical pressure. Pump diaphragms, screening, filter press fabrics, parachutes, hose, tarpaulins, and bags, are typical examples. The application of a pressure force perpendicular to the plane of the fabric is manifested as biaxial tensile forces along the warp and filling yarns within the fabric (Figure 19.8). The moduli of the yarns and the tensions that develop as the result of the pressure will influence the overall extension and shape of the fabric under pressure.

Two common textile structures that are called upon to withstand pressures, and that may be analyzed for resulting stresses by classical engineering methods are "thin membrane" materials in the form of (1) a hemisphere or diaphragm, and (2) a pipe. Assuming that each attains its proper respective shape upon application of pressure, the following relationships exist between the pressure applied and the tensional stresses that develop.

For a diaphragm (Figure 19.8):

$$S_1 = S_2 = \frac{PR}{2t} \qquad (19.16)$$

where

S_1 and S_2 = membrane stresses
P = pressure
R = radius of sphere
t = membrane thickness

For a pipe (Figure 19.8):

- longitudinal stress
  (lengthwise with the cylinder wall)

$$S_1 = \frac{PR}{2t} \qquad (19.17)$$

- hoop stress
  (along the wall circumference)

$$S_2 = \frac{PR}{t} \qquad (19.18)$$

Skechers EX1062
Skechers v Nike

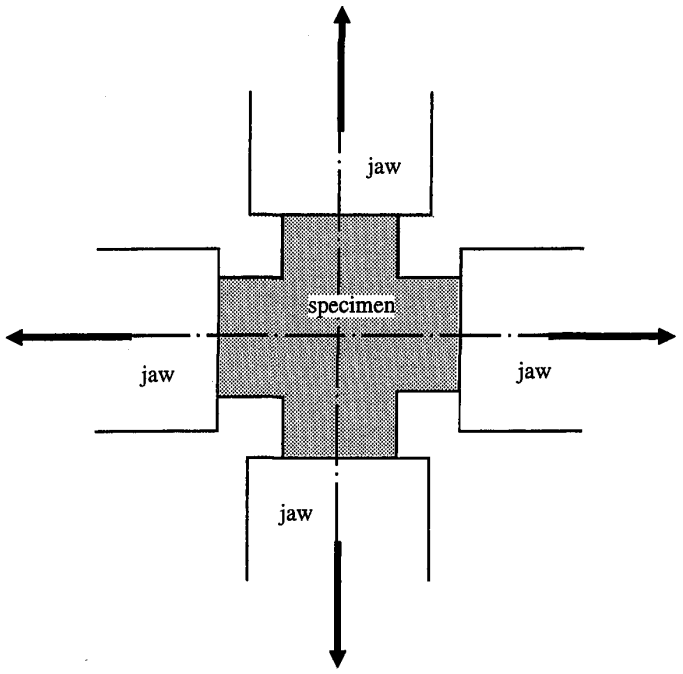


FIGURE 19.7 Biaxial stress specimen.

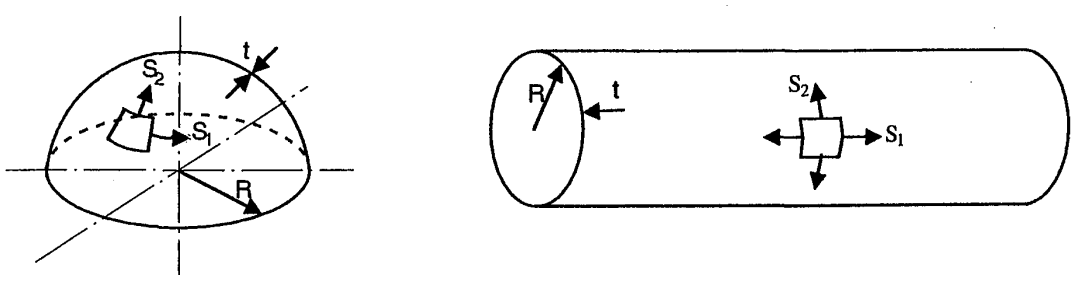
where

S_1 = longitudinal membrane stress
S_2 = hoop membrane stress
P = pressure
R = radius of pipe
t = membrane thickness

In the case of a pipe the longitudinal stress is always one-half the hoop stress. In manufacturing fire hose, for example, the most efficient design is one where the hoop breaking strength is twice the longitudinal breaking strength.

Maximum diaphragm bursting strength will occur when warp and filling rupture elongations are equal. Fabric manufacturers therefore attempt to produce fabrics that are "square," that is, they have equal crimps, strengths, and total rupture elongations in both warp and filling directions.

In such end uses as parachutes or filters where air or liquid passes through the fabric, the pressure causes both the warp and filling yarns to extend. Thus the fabric "opens up" and



Diaphragm stresses

Pipe stresses

FIGURE 19.8 Conversions of pressure into tensile forces.

Skechers EX1062
Skechers v Nike

the interstices between yarns increase, i.e., the "free area" unoccupied by yarn increases and the "cover factor" is reduced. This results in more air or liquid being capable of passing through the fabric. Because textiles are viscoelastic and will creep under the load, the air or liquid permeability of a fabric may increase with time because of the continuous application of a force upon warp and filling. It is important that the fabric modulus be high enough so that the fabric will not get out of shape, distort, and open up to the point that it passes excessive air, or no longer effectively filters. On the other hand, it is equally important that the fabric not be so inextensible that it cannot absorb energy, and fails because it reaches a limiting stress instead of deforming. For repeated use, the fabric should have a high degree of creep recovery.

Coated fabrics are often subjected to bursting-type forces and for proper continued functioning without cracking or delaminating, the elongation of the coating at any load must always be greater than that of the base fabric. To prevent such types of failure, rubber and elastomer coatings are normally made with rupture elongations considerably higher than those of the fabric to which the coating is applied.

Two types of bursting load measurements are made in the laboratory. The "ball burst" test determines the force necessary to drive a one inch diameter steel ball through a 1.75 inch diameter ring clamped fabric sample. In the "diaphragm test," also commonly called the Mullen burst test, a rubber diaphragm actuated by hydraulic oil is forced against a 1.2 inch diameter sample. The oil pressure necessary to rupture the fabric is recorded. The ball burst test records total force, i.e., pounds. The diaphragm test records pressure, i.e., pounds per square inch. There is no simple constant relationship between the two set values. The rubber diaphgram in the diaphragm test accommodates to the configuration of the fabric which in turn is distorting as a function of the applied load. The area of the specimen is not a constant with load and is unknown at the time of break. Therefore, the pressure recorded on the instrument dial is the oil pressure within the machine, and is not necessarily a measure of the true pressure upon the specimen.

17. YARN AND FABRIC ELONGATION BALANCE

In Chapter 17.0, Fiber Properties and Technology, it was pointed out that corkscrew, or the wrapping of one ply around the others in a plied yarn, is undesirable because it lowers yarn strength efficiency. When tension is applied, the multi-singles core, being shorter, will reach its limiting strain and will break first. Then the load is transferred to the corkscrewed singles yarn, but it is too weak to support alone the load previously held by several singles, and it too fails. Thus the theoretical maximum strength is not attained because all singles making up the ply yarn do not break at the same time.

It is equally desirable that all yarns in a fabric break at the same limiting elongation and at the same time.

Fabric elongation usually is composed of both geometric and intrinsic components, and it is necessary that total yarn elongations be equal for all yarns if high strength efficiency is to be achieved. For example, a warp yarn of proper elongation uniformity may be woven into a fabric with a weave such that some warp yarns will be longer than others because of crimp differences. When such a fabric is put under tension, the yarns with lower crimp will fail first, the load will then be transferred to the remaining yarns of higher crimp, and they in turn will fail, but the maximum strength potentially available in the cloth will not be achieved. In weaving it is very important that warp tensions in the loom be as uniform as possible in order that equal lengths of yarn be produced in the fabric. This is particularly necessary for low elongation yarns such as glass. With more extensible yarns such as nylon, total elongations have a chance to even out, and the strength translation efficiency is higher.

18. IMPACT PROPERTIES

In a great many applications, textile materials are often called upon to withstand "high speed" or "impact" loading. The cords in automobile and particularly airplane tires, auto and airplane seat belts, parachutes, aircraft carrier arresta-

Skechers EX1062
Skechers v Nike

tion cables, and body armor are typical examples of textile products that must have high impact strength. In textile processing, fibers or yarns may be impacted at low loads but at high frequencies in conjunction with picking, carding, combing, spinning, and weaving. A sewing machine causes thread to be impacted at velocities up to 180 ft/sec with short loading pulses of less than one millisecond duration.

In cases where textiles are subjected to impact forces it is required that they have the capacity to absorb large amounts of energy in an exceedingly small period of time. The area under the load-elongation diagram is a measure of the ability of the material to do work. The absorption of energy can be accomplished via various combinations of strengths and elongations. For example, the kinetic energy of a plane landing upon the deck of an aircraft carrier could be converted into strain energy by use of a solid concrete steel barrier, but the energy transfer would take place via the buildup of a high load in a very short time, and the plane would be demolished. If the deck length were no problem, the kinetic energy could be absorbed slowly by the friction of the brakes, or the reversal of the pitch of the propellers. In practice, of course, the plane is stopped by arrestation cables of both moderately high strength and elongation, thus absorbing the plane's energy over a time period sufficiently long to prevent excessive force buildup, but sufficiently short so that the plane stops within the length of the flight deck. Where impact forces are involved, the path of the load-elongation diagram, because it is a direct measure of energy absorption, must be considered with respect to the maximum stress and strain developed, and the time period during which the energy is being absorbed.

In the laboratory the load-elongation diagram of a fabric or cord is normally determined by separating the jaws of the testing machine at from about 1 to 12 inches per minute. The specimen length usually ranges from 3 to 20 inches. Therefore the maximum rate of extension of the specimen is about 12 inches per minute per 3 inches original gauge length, or 400% per minute—a relatively slow rate of deformation when compared with service conditions, where extension rates may be in the range of 500,000% per minute. It is well known that the strengths of most viscoelastic materials are greater, and rupture elongations are less, when tested under "impact" conditions as compared with "static" or low extension rate conditions.

There are several kinds of test instruments developed to measure impact properties. Among these are freely falling weights of various masses, dropping pendulums, high speed rotating flywheels, which at a selected time will engage a jaw and elongate the test specimen, and guns of various types that fire a projectile at the test specimen. Elongation or strain rates may range from 1 to 500,000% per minute. Since the time required to rupture a specimen is usually in the thousandths or millionths of a second range, extremely sophisticated and expensive electronic devices are necessary to record load, elongation and time.

At values below the critical velocity (described below) breaking strengths normally increase and elongations decrease as impact speed is increased. A simple explanation of this phenomenon is that at slow speeds the viscoelastic fibers have time to deform, and so plastic flow rather than immediate failure takes place with accompanying greater rupture elongation. Under impact conditions the viscous components of the fiber require higher stresses to cause deformations at high speeds. Therefore the breaking strength increases. At ballistic speeds, viscoelasticity has no opportunity to function at all, and primary or secondary creep elongation cannot contribute to energy absorption. Therefore the ability of a material to withstand ballistic impact loading is probably a function of the instantaneous elastic deflection portion of its conventional stress-strain diagram, the primary and secondary creep components not being considered. It has been found, however, that at the instant of impact, stress waves develop that travel through the fabric at a speed based primarily on the velocity of sound through the fibers. In effect this defines the length of specimen which is being placed under load. The greater the speed of sound through the material the greater is the specimen length, and the

Skechers EX1062
Skechers v Nike

greater is the total energy that can be absorbed. For each material there is a "critical velocity" at which the yarn ruptures immediately upon longitudinal impact and at the point of impact.

19. TEAR STRENGTH AND ENERGY

Tear resistance can be one of the most important properties of a fabric. For all flat sheet-like materials such as fabric, plastic films, paper and leather, the breaking strength of the material in tension is far greater than its tear resistance. While it may be difficult to induce a tear in any of these materials, usually the tear can be propagated at a relatively low load. We shall attempt briefly to analyze the stresses, and explain why tear strength is so much lower than tensile strength.

Three types of tear tests are widely, if not always properly used. The "tongue" and "trapezoid" methods employ a standard tensile testing machine for recording the force necessary to tear. The "Elmendorf" test utilizes a specially designed pendulum tester which measures tear energy.

19.1 Tongue Tear Test

In the tongue tear test a specimen 8 × 3 inches is cut so that the yarns to be ruptured during the tear lie in the shorter dimension (Figure 19.9). A cut 3.5 inches in length is made along the longer center line of the fabric (ASTM D 2261). This cut thus produces two 3 × 1.5 inch tongues which are placed in the upper and lower jaws of the testing machine. The nomenclature for identifying the direction of tear is important. A tongue sample cut so that the direction of tear is across the filling yarns, i.e., the filling yarns are ultimately broken, is called a filling tear specimen. As the jaws move apart the specimen assumes a configuration typified as shown in Figure 19.10. Each cross-yarn is subjected to progressively increasing tension that occurs in the triangular shaped distortion at the active region of tearing. The cross-yarns fail singly or often doubly, or even triply, depending upon the fabric weave, crimp distribution, yarn

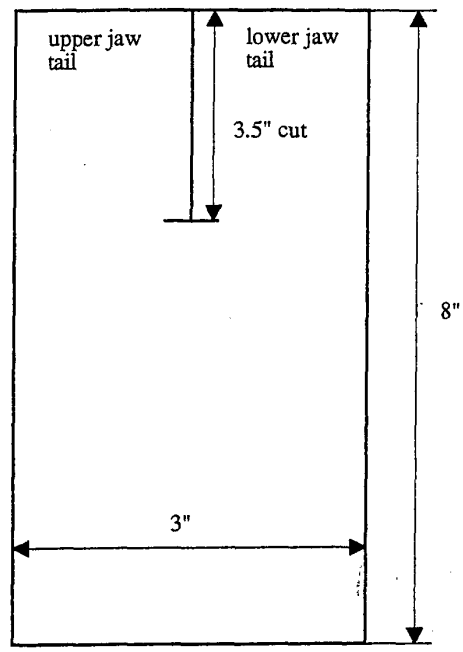


FIGURE 19.9 Tongue tear test specimen.

strength and elongation properties, and the like. It is important to note that the yarns fail individually in tension, and this is the reason that the fabric's tear strength is so much lower than its breaking strength, where all the yarns fail at the same time. The tearing action is manifested on the tensile tester recorder as a diagram of progressively increasing and then sharply decreasing loads.

The tension on a yarn (or yarns) builds up until rupture occurs at the upper peak (point P_u in Figure 19.10). Then the load drops off to P_m until the next yarn (or yarns) is brought into tension, and the procedure repeats. To obtain a proper tear diagram it is necessary to have a recorder which will respond quickly and accurately to changes in load. The electronic strain gauge tensile testers are excellent for this purpose. The average tear load may be calculated as the average of several high and low peaks.

As the tear progresses the tongues become progressively longer. They can absorb energy, which is a function of the stress-strain properties of the yarns. The yarn and tongue extensions contribute to the type of tear, and to the

Skechers EX1062
Skechers v Nike

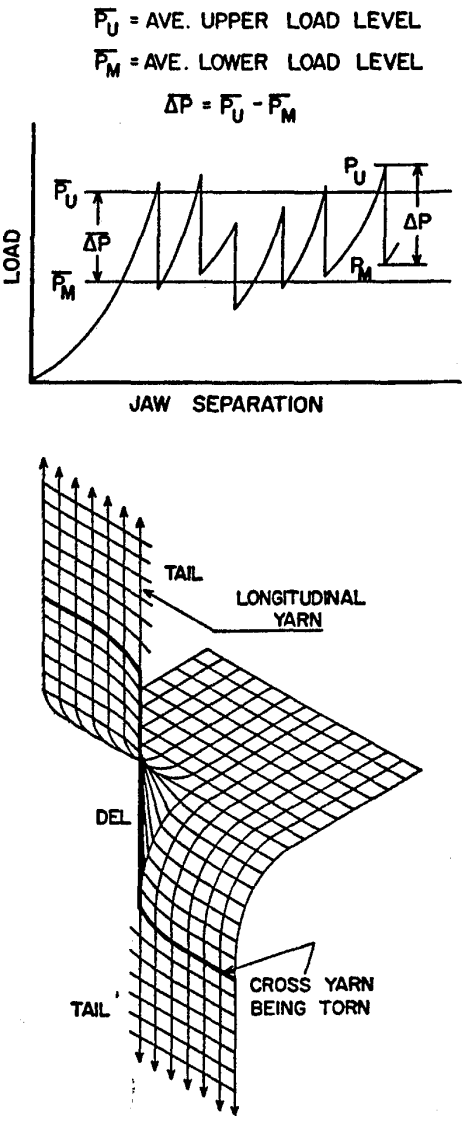


FIGURE 19.10 Failure mechanism and tear diagram in tongue tear test.

amount of tear energy or toughness. Low modulus extensible yarns have an opportunity to adjust in the tearing area. Two or more may have a chance to function together, and this produces a higher tear strength. For fabrics of the same construction at equal yarn strength levels, the higher the breaking elongation the higher will be the tear strength and energy. Often when resin finishes are applied to fabrics the tear strength is reduced severely, while the tensile strength is hardly altered or may even be increased. The answer lies with the embrittlement or increased modulus of the yarn, resulting from the resin applications and the binding of yarns so that they cannot shift to reinforce each other. Yarn extensions are lowered, the tear formation is changed, and instead of two or three yarns breaking at the same time, they may be breaking singly because they cannot bunch up. Thus the tear strength is appreciably reduced.

It will be apparent that fabric weave can have a great influence on tear strength. All other construction factors being equal, a 2 × 2 basket weave will have more than twice the tear strength of a 1 × 1 plain weave, the reason being that the two yarns act as one and they break at the same time. A 3 × 1 twill has about 1.5 times the strength of the plain weave. For the same yarns and the same weaves, tear strength diminishes as thread count increases. A high count plain weave cotton fabric will have a lower strength than a low count fabric. It is difficult to tear a cheesecloth or gauze because the construction is so open. The tear opening is very large, and the yarns bunch up to reinforce each other, so that tearing is difficult.

The higher original tear strength of a basket weave, as compared with a plain weave, may not be retained when such fabrics are coated. The increased openness (i.e., lower cover factor) of the basket weave causes greater resin coating "strike-through" into the fabric structure. Yarns may thus become immobile and be incapable of bunching together to reinforce each other. The yarns then break individually rather than in groups, and the tear strength is thus severely lowered.

Sometimes a fabric is constructed so completely unbalanced with respect to warp and filling strengths and elongation that it is impossible to tear the stronger, tougher set of yarns. When an attempt is made to tear across the stronger set, the weaker set of yarn fails, and the tongue is torn away from the specimen. It is impossible to determine the tongue tear strength of such a fabric in the stronger direction. When this occurs the "trapezoid test" is sometimes used, but its meaning is highly questionable.

19.2 Trapezoid Tear Test

The test specimen is 6 × 3 inches with a quarter inch cut placed midway along the longer

Skechers EX1062
Skechers v Nike

direction. The sample is inserted on the bias between the jaws of the testing machine so that the yarns are caused to fail progressively.

The increasing slack in the specimen from one side to the other causes individual yarns progressively to be brought into tension and fail. The test is entirely of a tension type, and has little meaning in terms of the practical tearing characteristics of a fabric. Therefore, this test is not used much.

19.3 Elmendorf Tear Test

The Elmendorf tester employs a pendulum to apply energy sufficient to tear through a fixed length of fabric. The tear is of the tongue type. The tester consists of a sector shaped pendulum, carrying a clamp that is in alignment with a fixed clamp when the pendulum is in the raised starting position with maximum potential energy. A rectangular specimen is fastened in the clamps and a slit is made to start the tear. The pendulum is released and the specimen is torn as the moving jaw separates from the fixed jaw. The energy required to tear is the potential energy difference at the beginning and end of the pendulum swing, as measured by the position of the pendulum at the end of the test. A graduated scale attached to the pendulum indicates the percentage of original potential energy available that was consumed in tearing the test specimen. Tear energy is recorded as inch-pounds per inch of fabric torn (or gram-centimeters per centimeter). The average tearing force may be calculated by dividing the energy by twice the length of tear, because during the test the jaws separate a distance equal to twice the length of tear.

The Elmendorf test is quick and easy to use, and gives a valid reading without the necessity of making even limited calculations. The actual tearing time is in the order of one second, so that the Elmendorf can almost be considered to be an impact tear test. It does not show maximum and minimum tear strength levels, however.

20. ABRASION RESISTANCE

The abrasion resistance of a yarn is a function of both the intrinsic abrasion resistance of the fiber composing the yarn and the geometry of the yarn structure. Textiles are flexible, and depending upon the end use, repeated flexing as well as pure abrasion can contribute to product failure. Therefore to simulate service conditions, in many abrasion test methods the yarn or fabric is repeatedly flexed and abraded.

Intrinsic abrasion resistance of fibers was discussed in Chapter 17.0, Fiber Properties and Technology. The geometric arrangements of fibers in yarns and yarns in fabric are equally important in designing fabrics with high abrasion resistance. Consider a yarn composed of, say, thirty continuous filaments. The turns per inch in the yarn, the yarn crimp and the fabric weave will all influence the frequency with which a particular filament will appear on the fabric surface, such that it will come in contact with the abradant. The relationships of yarn singles to ply twist will govern yarn shape, degree of fiber packing and these in turn will also influence the amount of fiber or yarn surface in contact with the abradant, and the frequency with which a particular filament or yarn ply will become abraded. Low twist yarns tend to flatten, and a greater surface may be exposed to abrasion, although by this arrangement the stress concentration may be lowered. In addition, individual fibers in low twist yarns may not be held together well, and they may be snagged and broken by the abradant. Higher twist yarns will retain roundness and cohesiveness, presenting a smaller total surface to be abraded. However, the stress concentration may be high, and the outer surface filaments may become more severely abraded. Higher yarn twist may also reduce individual fiber mobility, and so flex resistance can be significantly lowered. For heavy plied yarns, cables, and ropes, the number and diameter of filaments, and the singles-ply-cord twist relationships can be arranged so that certain fibers are buried within the structure and bear the requisite tensile load, while other surface fibers bear the abrasive action, but are not subject to high tensile forces.

Backer and Tanenhaus [4] list the following factors as having an influence on fabric abrasion: geometric area of contact between fabric

Skechers EX1062
Skechers v Nike

and abradant; local pressures or stress concentrations developing on specific yarn points or area; threads per inch; crown height, or the extent of yarn rise out of the fabric plane at warp and filling intersections; yarn size; fabric thickness; yarn crimp; float length; yarn cohesiveness; compressional resilience of fabric and backing; fabric tightness; and cover factor.

A number of laboratory abrasion testers are used. Independent of the design, they all probably fall into one of the following categories in terms of their actions.

(1) Plane unidirectional abrasion—The abradant travels back and forth in a straight line over the flat fabric surface.
(2) Plane multi-directional abrasion—The abradant rotates, producing a multi-directional abrasive action over the flat fabric surface. On some machines each point on the fabric surface is abraded in one direction only, although the direction may change from point to point. On other machines the directions, ideally, are entirely random.
(3) Unidirectional flex abrasion—The fabric is flexed and abraded back and forth over a cylindrical abrasive surface.
(4) Random flex abrasion—The fabric is randomly flexed and abraded in all directions.
(5) Flex without abrasion—An advantage of many flex-abrasion testers is that the abradant can be removed and replaced with a polished surface or minimum friction roller that will permit yarn or fabric flexing without surface abrasion.

Criteria of Abrasion Resistance

There are many variables that must be controlled in order to give meaning to abrasion resistance results. The abrasive surface should be uniform and not change during the test. For the planar abrasion tests, the weight of the abradant and hence the pressure on the fabric surface is significant. For the flex abrasion tests the tension on the fabric is also significant.

The three popular criteria of abrasion resistance are visual assessment, cycles to form a hole and strength loss. The fabric's end use should be known, and the type of laboratory abrasion test and performance criteria carefully selected in order to make the test meaningful. At best a laboratory abrasion test may be a hazardous way of predicting service performance.

When comparing two or more fabric samples, two basic approaches may be taken. The most direct method is to abrade all test specimens to exactly the same number of cycles, and then, evaluate their relative appearance, strength loss, thickness loss or the like. A second method is to abrade all specimens until they appear equally damaged or destroyed, and to record and then compare the number of cycles required.

The intensity of the abrasive action is of great significance. If the abrasion is too severe either inadvertently or in order to reduce testing time, so that fabric destruction occurs after a few cycles, the results may be meaningless. For example, if two lightweight fabrics are being evaluated and the abrasive action is so sharp, hard, or rough that both samples are destroyed in 25 or 30 rubs, no proper comparison can be made. If instead, a relatively mild abradant is used, requiring 1,000 or more rubs, then any differences which are observed become more meaningful. The direction of the abrasive action relative to the fabric construction can have a marked effect on abrasion resistance.

The problem of correlating laboratory abrasion tests and service performance exists because, in use, a textile may be subjected to wind, water, weather, heat, cold, bending, flexing, tension, punctures, tears, etc., all of which are grouped under the general heading of "wear." In the laboratory more idealized conditions prevail and usually only abrasion, with or without flexing, is permitted to act upon the test fabric.

21. STIFFNESS

The importance of proper fabric stiffness or flexibility should not be overlooked with respect to the proper functioning of an industrial textile fabric. Probably the prime reason textiles are useful is because of their flexibility. Two simple stiffness criteria are commonly used. The "cantilever bending length" is a measure of the

Skechers EX1062
Skechers v Nike

tendency of the fabric to bend under its own weight. It is simply measured by sliding a strip of the fabric over the edge of a horizontal surface until gravity causes the strip to bend to a prescribed angle. "Flexural rigidity" is the fabric's resistance to bending. It is the resistance that is evidenced when the fabric is bent back and forth between the fingers. Fabric stiffness is a function of both the intrinsic stiffness of the fibers and the geometry of the yarn and fabric structure. Two fabrics of different weights can have the same bending lengths because of their intrinsic and geometrical differences, but the heavier of the two will exert a greater resistance to bending and therefore will feel stiffer. Flexural rigidity takes into account the fabric weight.

The mathematics of the bending length test have been worked out so that the length of overhanging fabric that subtends an arc of 41.5° from the horizontal is twice the bending length (Figure 19.11). Flexural rigidity G is calculated according to the formula

$$G = wc^3 \qquad (19.19)$$

where

w = weight per unit area (mg/cm^2)
c = bending length (cm)

G values are expressed as gram-centimeters (or inch-pounds), and thus are units of torque. As an overall indication of fabric flexural rigidity ASTM uses the geometrical mean or square root of the product of warp and filling values [5].

$$G_o = (G_w \cdot G_f)^{1/2} \qquad (19.20)$$

where

G_o = overall flexural rigidity
G_w = warp flexural rigidity
G_f = filling flexural rigidity

22. DRAPE AND HAND

For industrial textiles neither fabric "drape" nor "hand" are normally important. Drape is generally considered to be a visual rather than tactile property observed as the tendency of the fabric to bend under its own weight into pleasing "folds." Both warp and filling bending lengths and their interactions will influence drape. Hand or "handle" is a tactile property most often described by subjective reaction rather than objective physical measurement. The Kawabata testing system has become popular in recent years in evaluating the hand properties of fabrics.

23. CREASE RETENTION AND WRINKLE RESISTANCE

In certain industrial applications, these properties may have aesthetic as well as functional importance. Heavier-weight industrial fabrics

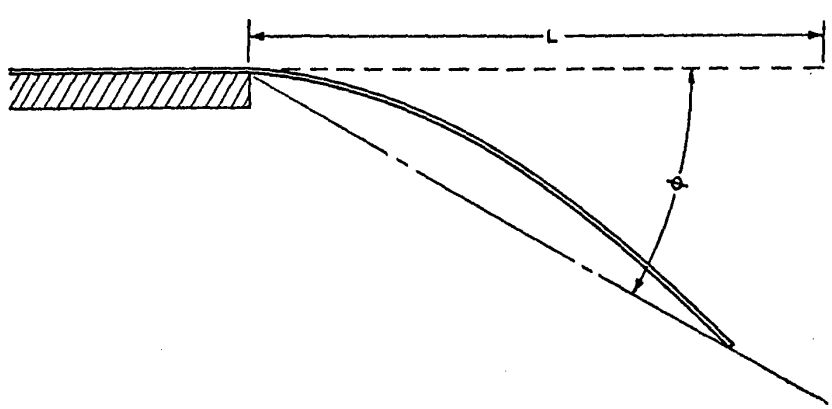


FIGURE 19.11 Cantilever bending length test.

Skechers EX1062
Skechers v Nike

are so thick that major permanent creases usually do not develop. However, lighter-weight goods may present more difficulty. If a fabric composed of continuous filament parallel yarns is creased so that the angle of bend approaches 180°, the fibers on the inner side of the bend are placed in compression and those on the outer side are placed in tension. There is a neutral plane where theoretically one fiber is neither compressed nor strained. If the intrinsic properties of the fibers, and the geometry of the yarn and fabric system are such that non-recoverable deformations result from the creasing action, a permanent crease will result. This can stem from two mechanisms. First, the outer fibers may be strained and the inner fibers compressed beyond their respective yield points, thus producing an objectionable crease which is called a wrinkle. Most often it is the tensional strain which is non-recoverable. Second, fibers in the yarn or yarns in the fabric may slide by each other as the result of the creasing force, but there is no restoring force which causes them to return to their original configuration.

Fibers with high extensibility coupled with high instantaneous elastic recovery and primary creep usually exhibit good-to-excellent wrinkle resistance. Fibers where high secondary creep occurs at low load and strain levels have poor wrinkle resistance. Low elongation fibers such as glass or linen have poor wrinkle resistance, since their yield points are quickly reached under the bending strain, and they cannot recover. In the case of glass fiber the creasing action often causes a strain in excess of the breaking elongation of the fiber, and so fiber failure occurs. The temperature and relative humidity of the air, as it influences the thermal or moisture sensitivity of the fiber, will also influence wrinkle resistance. Moisture sensitive fibers, particularly the rayons, have high wet secondary creep and this contributes to their poor wet wrinkle resistance. Crosslinked rayons with improved wet load elongation properties, and rayons resin-finished with "wrinkle resisting" finishes, exhibit better strain recovery properties and better wrinkle resistance. "Wash and wear" fabrics must have wet as well as dry wrinkle resistance and crease recovery.

Tightly woven fabrics generally will restrict fiber movement. When such fabrics are creased, the fibers in the yarns and the yarns in the fabric have insufficient space to enable them to move and slide relative to each other. Instead, the fibers become permanently strained or elongated beyond their yield points, consequently impairing the fabric's wrinkle recovery ability. Loosely woven fabrics allow more fiber redistribution and motion during creasing, and so less intrinsic fiber strain develops. However, the geometric movement of fibers in yarns and yarns in fabric may be large, with no inherent ability for the fabric to recover, and so any wrinkle which does develop may be more permanent.

For a given creasing force, a stiffer fabric will become creased to a lesser degree than a more flexible one. The resulting total strain will be less, and the amount of fabric creasing will be less. The crease recovery will depend upon the ability of the fibers and yarns to return to their original configuration. Thicker fabrics are generally stiffer than thin ones, and any crease which is imparted to the thicker ones is usually less permanent. For example, a crease in a tightly woven worsted fabric is more durable and permanent than an identical crease in a woolen fabric.

At equal degrees of creasing, a thicker fabric is more irrevocably deformed than a thin one, and a more permanent crease results. However, it is usually more difficult to produce equal degrees of creasing in a thick fabric, and this is why thin fabrics appear to be more easily wrinkled.

24. BLENDED AND COMBINATION FABRICS

In a strict sense, fabrics composed of more than one fiber are called blended fiber fabrics. Several types are common:

(1) Fabrics in which the spun yarns are composed of two or more types of staple fiber intimately mixed together, for example, a cotton-nylon blend. These are often called intimate blend fabrics.

(2) Combination yarn fabrics which contain plied yarns composed of two or more types of single yarns of different compositions.

Skechers EX1062
Skechers v Nike

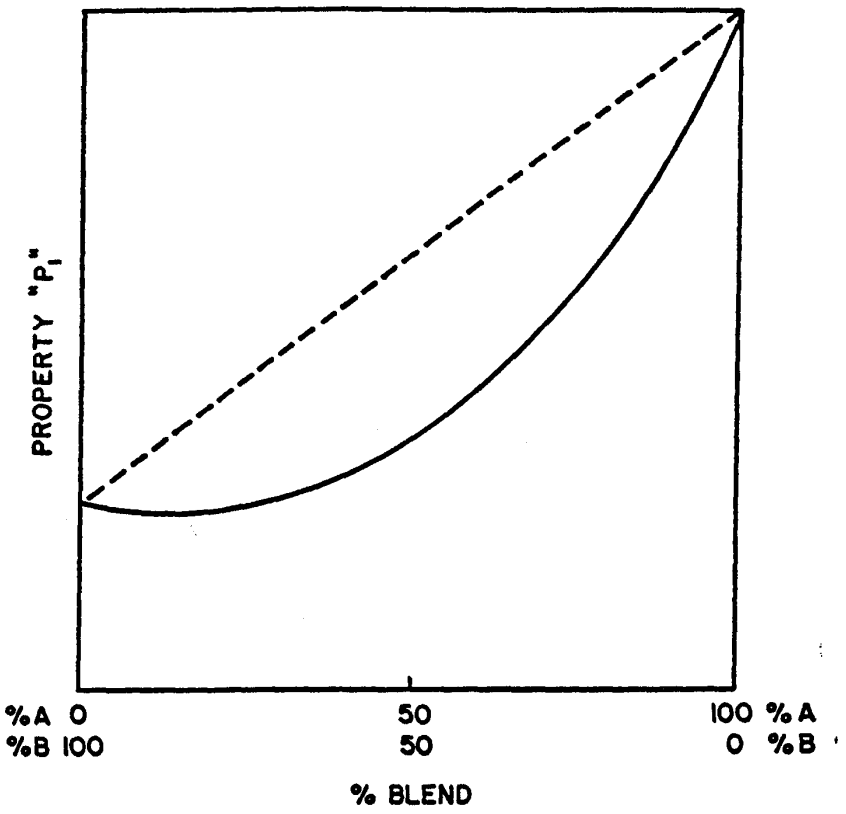


FIGURE 19.12 Effect of blend composition on yarn property *P*.

Examples are a rayon/nylon filament yarn, or spun and filament nylon yarns twisted together, or a glass core yarn wrapped with a cotton yarn cover.

(3) Combination fabrics composed of two or more types of yarns of different fiber compositions, for example, a cotton warp and a nylon filling

The objective of manufacturing a blend may stem from the utilization of a cheaper fiber as a diluent with a more expensive fiber or more properly, the attainment of certain yarn properties via the unique contribution that each component fiber gives to the blend.

It is well to consider, however, the influence of blend composition on yarn properties. Yarn strength and other properties do not necessarily follow a linear relationship with blend proportion. Figure 19.12 is a hypothetical graph that plots percent blend of a two-component mixture versus a selected property *P*.

The dotted line plots the linear relationship that would exist if each component fiber made its contribution on a direct percentage basis. This rarely happens, and the full curved line shows the kind of relationship that may develop. For example, when small amounts of a strong low-extension fiber are added to large amounts of a weaker high-extension fiber an initial reduction in yarn strength can develop so that the blended yarn is actually weaker. This phenomenon is again explained by differences in breaking elongation of the two fibers, i.e., elongation balance. The two fibers do not add the full components of their respective strengths when the less extensible one fails. Therefore the maximum strength theoretically attainable is not achieved.

In order to achieve the optimal blend at the most economical cost it is necessary that the property versus percentage composition curve be properly established. This may be done via theoretical calculation but usually experimental means are employed. Often two or more properties must be considered here, and obviously the selection of an optimum blend becomes more complicated.

Skechers EX1062
Skechers v Nike

19.2

References and Review Questions

1. REFERENCES

1. Peirce, F. T., "The Geometry of Cloth Structure," *JTI*, Vol. 28, T45, 1937.
2. ASTM D 3883, "Standard Test Method for Yarn Crimp or Yarn Take-Up in Woven Fabrics," *Annual Book of ASTM Standards*, Vol. 7.02, 1993.
3. ASTM D 1777, "Standard Method for Measuring Thickness of Textile Materials," *Annual Book of ASTM Standards*, Vol. 7.02, 1993.
4. Backer, S. and Tanenhaus, S. J., "The Relationship between the Structural Geometry of a Textile Fabric and Its Physical Properties," *TRJ*, Vol. 21, 1951.
5. ASTM D 1388, "Standard Test Methods for Stiffness of Fabrics," *Annual Book of ASTM Standards*, Vol. 7.01, 1993.

2. REVIEW QUESTIONS

1. Derive the fabric cover factor equation (19.1).
2. Define packing factor. How is it calculated?
3. Define fabric porosity. What is the significance of fabric porosity in industrial applications?
4. What is "crimp interchange"? Explain the effects of a typical heat setting process on warp and filling crimp.
5. Define "resilience." What is the physical meaning of it?
6. How can you control thermal conductivity of fabrics by altering fabric structure? Explain.
7. What are the industrial applications in which fabric air permeability plays an important role? Explain.
8. What are the advantages and disadvantages of waterproof functions in protective clothing?
9. What kind of information can one get from a biaxial stress test? What is the significance of this test?
10. Is bursting strength critical for geotextiles? Explain.
11. Explain the importance of impact properties in ballistic fabrics and textile composites.
12. How can you control fabric tear by fabric design? Explain.
13. What is the significance of abrasion resistance for industrial fabric applications?
14. What are the factors that affect fabric stiffness? Give application examples of industrial textiles where stiffness provides advantages and disadvantages.
15. Explain how one can improve the properties of fabrics by blended or combination structures.

Skechers EX1062
Skechers v Nike