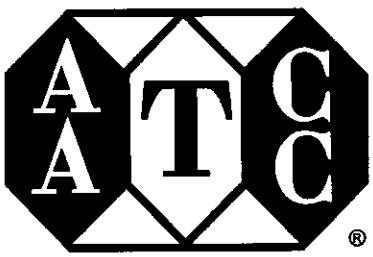

Textile Chemist and Colorist
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Olney Medal Address

Some Scientific and Technological Challenges in Textiles

BY LUDWIG REBENFELD, Textile Research Institute, Princeton, N. J.

I have heard it said on several occasions that there are no further scientific and technological challenges in the textile field; that the fiber and textile industries have matured to the point where only marketing, sales and promotion provide opportunities for future growth and business success.

I suppose that we must acknowledge that in the field of traditional textiles—i.e., the apparel and household sectors of the textile industry—we have provided just about everything in terms of quality and performance that the consumer can possibly expect. We can manufacture textile items that resist staining or soiling, that are easily cleaned or laundered when they do stain or soil, that are flame retardant, that do not crease, that are permanently pressed into all sorts of shapes, that can be maintained with minimum care, that can be colored and patterned without fading or discoloration under all sorts of conditions, that rarely if ever wear out, that provide protection under extreme climatic conditions, etc., etc. While some products occasionally find their way to the marketplace that do not meet quality standards and performance specifications, the fault invariably lies in some error or in some unwarranted cost cutting, rather than in any lack of scientific understanding or technological know-how. The consumer of traditional textiles has come to expect performance standards that could not have been imagined just a decade ago.

While there are several important technical issues that remain to be addressed and problems that remain to be solved, it is true that our industry is mature, and that the technological base upon which the textile industry now operates is solid and stable. It is not true, however, that there are no further scientific and technological challenges and opportunities in our field. Far from it, and as my Olney Medal Address I would like to explore with you the nature of some of these challenges, and describe some current work in our laboratories at TRI in several areas to exemplify my point.

What Are Textile Products?

First we must analyze what we mean by the term textile products. The meaning of that term has changed dramatically in recent years. It was not long ago that textile products meant only apparel items and household or domestic products, such as carpets, sheeting, toweling and the like, and a limited but quite diverse list of industrial products such as tents, awnings, filters, conveyor belts, etc. Textile products were associated with traditional markets that had existed for decades, if not centuries. But that has changed dramatically; we now have a much broader perspective of the term textile products, even if we do not always appreciate the full breadth of the modern textile picture. There has been an enormous diversification in the uses of textile materials. Engineers, and others who are concerned with the development and utilization of materials, increasingly recognize some of the unique and exceptional properties of textiles.

What are some of these properties that make textiles, and fiber materials generally, so exceptional? First of all, from the point of view of materials science and technology, textiles are exceptionally strong, with specific strengths or tenacities that rival and even exceed many alloys and metals. This potential for high strength of a textile product is due not only to the inherent high strength of fibers but also to the geometrical arrangement of the fibers in the product which allows the maximum fiber strength to be realized. The inherent high strength of fibers, which is based on the molecular structure and the three-dimensional architecture of the polymers which form fibers, coupled with the textile process, which aligns and twists the fibers together in a unique way to form yarns and fabrics, is responsible for the high strength of textile materials.

But textile materials are not only strong, in the sense of being able to bear high loads, they are also highly resilient; that is, they can absorb energy by a deformation process that is recoverable. Again this high resilience is due not only to the fibers themselves but to the way in which the fibers are combined and held together in the fabric network. Furthermore, textiles are highly flexible, and they can be produced into final products that have three-dimensional shapes. This is extremely important, and the relative ease with which complex shapes can be achieved clearly differentiates textile and fibrous materials from other materials such as wood, ceramics, metals and cements.

Apart from these mechanical properties, textile materials have remarkably high porosities that make them nearly ideal absorption substrates. The combination of mechanical integrity and exceptionally high specific surface areas is again unique to textile materials. These properties of textiles make them ideal in the wide range of traditional apparel, household and industrial applications, and also in a constantly widening range of nontraditional or innovative applications that include such things as fiber composites, geotextiles, catalyst supports, ultrafiltration products and chemisorption media, for example.

Maybe the best way to summarize the exceptional properties of textile products is to emphasize their diversity and flexibility; textile products can be almost anything that designers or fabricators want them to be. With this recognition and the widespread use of textiles in nontraditional applications have come a wide array of scientific and technological challenges that keep our field dynamic and that provide us with exciting opportunities.

Fiber Reinforced Composites

Probably no innovative use of fibers and textiles has captured the imagination of

materials scientists and engineers more than fiber reinforced composites. The use of thermosetting and thermoplastic resins reinforced with fibers and textiles to make them strong, tough and durable is growing at unprecedented rates. These lightweight composites are becoming the materials of choice in the automotive industry, in the aircraft and aerospace industries, in the construction industry, in sports and recreational equipment, in the furniture industry and in innumerable other applications where strength and durability combined with ease of fabrication are important criteria.

Many different types of fibers have found application as reinforcing elements in composites. In addition to the more common nylon, polyester and polypropylene fibers, there is a growing number of high performance fibers such as the aramids, liquid crystalline polyesters, graphitic carbon, specialty glass, ultra high density polyethylene, polybenzimidazole, a variety of specialty polyimides and others. Undoubtedly, this list will continue to grow in the years ahead. To this ever growing list of organic polymer fibers, we must now add many inorganic fibers, such as those based on aluminosilicates, alumina, silica, boron, boron carbide, boron nitride, silicon carbide and others. While we always focus on these new fibers, it is interesting that even natural cellulosic fibers, such as jute, hemp and sisal, are used as reinforcing elements in certain composites, particularly in reinforced cements and concrete.

Adhesion In Fiber Composites

Fiber scientists and textile chemists have enormous opportunities to contribute to the growing technology of fiber reinforced composites. Indeed, there are certain problems in this field where the textile chemist is uniquely qualified to make innovations and to solve problems. Take for example the critical area of fiber-matrix adhesion. The underlying concept of fiber reinforced composites is that stresses that are imposed on the resin matrix are transferred to the reinforcing fibers that are able to bear much higher loads than the resin. This stress transfer takes place at the fiber-matrix interface, and for this concept to work effectively, there must be good adhesion at that interface. Adhesion between two phases or two materials poses a very complex scientific problem.

The chemical and physical forces that are operative at a fiber-resin interface are specific to any particular composite system, but it is possible to identify several principal mechanisms through which adhesion can be achieved. These include:

(a) Adsorption and Wetting. It is generally necessary for the resin in its fluid form to wet the surface of the fibers. Thus the surface energy of the fibers must be greater than the surface energy or surface tension of the resin in order for effective wetting to occur.

(b) Interdiffusion. An effective bond may be formed if the molecules of one phase diffuse into the surface layers of the other phase, and vice-versa. Such interdiffusional processes will cause a localized molecular entanglement that will significantly contribute to interfacial adhesion. In most instances these interdiffusional processes are quite limited, but they can be significantly enhanced by increasing temperature and by various chemical additives, particularly those that can depress glass transition temperatures and enhance molecular mobility.

The 1987 Olney Medalist

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(c) Electrostatic Attraction. A difference in electrostatic charge between the fiber and the resin matrix at the interface would certainly contribute to the adhesion between them.

(d) Chemical Covalent Bonding. The formation of covalent chemical bonds between the fiber and the resin at the interface may be important in several systems. It is obvious that such direct chemical bonding would greatly enhance interfacial adhesion, but it is equally obvious that specific chemical functional groups are required at the fiber surface and in the resin matrix for reactions to occur.

(e) Chemical Secondary Bonding. Low energy intermolecular forces, such as those associated with hydrogen bonds, dipolar interactions, dispersion forces and van der Waals forces undoubtedly play an important mechanistic role in the development of interfacial adhesion between fiber and matrix.

(f) Mechanical Adhesion. Purely mechanical interlocking between the two phases can also contribute to adhesion. It is reasonable to expect that this mechanism would function most effectively with fibers with rough surfaces and with irregular or noncircular cross-sectional shapes.

In any given fiber-resin system all of the above adhesion mechanisms are probably operative to varying extents. In certain systems one or another of the mechanisms may play a greater role, but the complexities of adhesion are best understood in terms of these fundamental mechanisms.

Through this scientific approach to the adhesion problem, significant improvements in interfacial shear strengths have been achieved for many fiber-resin systems. One approach has involved the chemical treatment or modification of fiber surfaces to make them more compatible or even reactive with certain resins. For example, it is known that silane coupling agents enhance the adhesion between glass fibers and epoxy resins (*1*). The silane agent reacts with metal cations on the glass surface and also provides functional groups (amines or hydroxyls) that can react with the epoxy resin. The two phases are then coupled with covalent chemical bonds which should lead to high interfacial shear strengths. Indeed, it has been shown that the use of silane coupling agents can increase the durability and stability of glass reinforced epoxy and polyester composites (*2*).

Another example of interfacial shear strength enhancement is provided by the controlled surface medication of polyester fibers. Avny and Rebenfeld (*3*) were able to introduce reactive free amine groups on the surface of polyester fibers by controlled reactions with multifunctional amines. They were then able to show that a nearly two-fold increase in interfacial

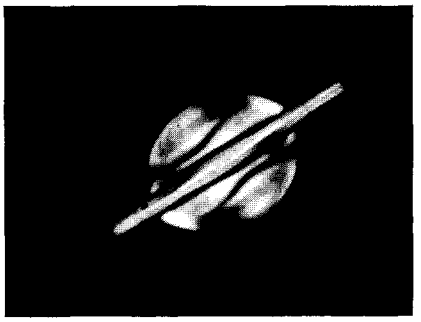

Fig. 1. A Kevlar aramid fiber-epoxy composite for the TRI microbond test. (Courtesy of Mrs. Sigrid B. Ruetsch, TRI.)

shear strength between such modified polyester fibers and an epoxy resin can be achieved. Similarly, controlled surface modification of Kevlar aramid fibers has been reported by Tesoro and associates (*4,5*), and improved adhesion with epoxy resins is achieved. Plasma modification of aramid fiber surfaces in the presence of ammonia and other reactive gases can also be used to increase bond strength (*6*). In certain cases the plasma treatment results in a decrease in fiber strength which must be balanced against the benefits derived from improved adhesion. This fact highlights the problems of chemical or any other modification of fibers to improve adhesion with resin matrices. It is important that the modification does not adversely affect strength, stiffness and other desirable and necessary physical properties of the fibers.

Another example of effective chemical modification of fiber surfaces is the controlled oxidative treatment of carbon fibers. Fitzer et al. (*7,8*) studied composites made with oxidized carbon fibers in phenolic and epoxy resins, and reported good correlations between the amount of surface oxides (carboxyl, carbonyl) and the improvement of mechanical properties of the composite. They postulated that the bonding is mainly controlled by the chemical reaction between the carboxyl groups on the fiber surface and the free hydroxyl groups of the resin. Ko et al. (*9*) compared epoxy resin composites made with oxidized and untreated carbon fibers, and found that the oxidized fibers gave composites with interlaminar shear strengths significantly higher than untreated fibers. They also found that the composites made with the oxidized fibers demonstrated better retention of strength when subjected to hydrothermal aging.

Table I. Interfacial Shear Strength Using the TRI Microbond Technique (*10*)

Fiber	Epoxy	Polyester
Kevlar 49	41.4 MPa	20.0 MPa
Carbon (Cellon)	65.3	26.3
E-glass	40.6	19.4

Measurement Of Interfacial Shear Strengths

One of the problems associated with research in this field has been the difficulty of making reliable interfacial shear strength measurements. An important contribution made by TRI has been the development of a technique that allows direct measurement of the interfacial shear strength between a resin matrix and the ultimate small diameter fiber. This technique, developed by Miller and his associates (*10*) and known as the microbond method, is based on the formation of a microcomposite consisting of a small resin droplet on an individual fiber, as is illustrated in Fig. 1. The force required to shear the resin droplet from the fiber is measured, and based on microscopic measurements of the fiber diameter and the droplet dimensions, the interfacial shear strength can be calculated. Typical values of the interfacial shear strengths for glass, aramid and carbon fibers, using two types of thermosetting resins, are shown in Table I. The microbond technique has made possible the quantitative evaluation of fiber surface modifications. For example, Tesoro and Benrashid (*5*) have recently explored various surface chemical modifications of aramid fibers involving nitration and subsequent reduction to amine groups. Utilizing the microbond technique, it has been possible to demonstrate the effectiveness of such modifications in increasing the interfacial shear strengths with an epoxy resin (*11*). Typical values are shown in Table II.

The TRI microbond technique can also be used with thermoplastic resins where there are some special opportunities to manipulate properties. With crystallizable thermoplastic resins it has been shown that there frequently exists a special crystalline morphology in the immediate region around the fiber that is distinctly different from that in the bulk resin. This zone has been referred to by various terms, but the term "interphase" seems most appropriate. Working with polyphenylene sulfide as the thermoplastic resin and several types of reinforcing fibers, Desio (*12*) at TRI has been able to produce some particularly striking examples of the interphase, as shown in Fig. 2.

Table II. Interfacial Shear Strength Epoxy Resin/Kevlar 49

Kevlar Fiber	ISS (MPa)
Control	42.6
Nitrated	40.0
Nitrated/Reduced	53.0

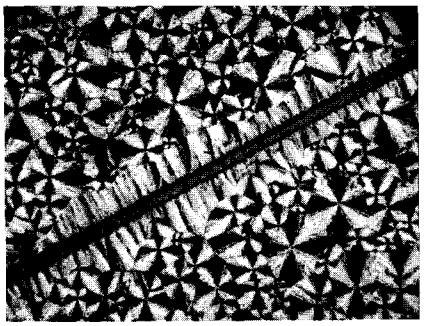

Fig. 2. Spherulitic and interphase structure of a Kevlar-polyphenylene sulfide composite (*12*).

We are now attempting to establish whether we can control the size and crystalline texture of the interphase by varying cooling rates during composite formation and by thermal aftertreatments. It is not known whether the interphase enhances the interfacial shear strength or whether it introduces a structural discontinuity that weakens the system. If we can learn to control the interphase region we should be able to answer this key question with the TRI microbond technique.

What more interesting and challenging problem for a textile chemist can one imagine than chemical modifications of fibers to improve their performance as reinforcing elements in composites. At the same time, we might be more qualified than a textile chemist to contribute to the solution of this problem. Textile chemists have worked on the chemical treatment and modification of fibers for decades and it is through this work that we now have minimum care, durable press, flame retardance, soil resistance, soil release, water repellency, etc., etc. Yes, the textile field is mature, but it does not lack scientific and technological challenges if we take a broad perspective of textile products.

Textile Processing

Let me explore another area that is of great importance in current textile technology, and that will undoubtedly continue to occupy a pre-eminent position for some time to come. This area involves the important question of spin finish distribution, which has become of importance, among other reasons, because of steadily increasing processing speeds both in fiber formation and in subsequent downstream textile operations.

By the way of introduction of this topic, we should note that American manufacturing industries are going through a revolutionary period as they seek to posture themselves to be fully competitive with their counterparts in other regions of the world. Computer controlled processing, CAD-CAM, robotics, automation, etc. are the key words of the future as all industries seek to increase their underly-

ing productivities. The textile industry has done well in this regard; its productivity has grown by more than 30% since 1977, well ahead of the productivity increase for the entire American manufacturing enterprise, as is shown in Fig. 3. Currently, the U.S. textile industry is able to process about 7,000 kg of fiber per employee compared to about half that amount as we entered the 1970's (*13*).

This major increase in textile productivity reflects the many innovations in production technologies that have been introduced in recent years. High speed spinning and texturing operations, automated doffing and materials handling, shuttleless weaving and vastly improved computer controlled dyeing and finishing procedures have come to characterize the textile industry of today. For example, with traditional shuttle looms, one was able to achieve weft insertion rates of approximately 400 meters per minute. Air and water jet looms now allow weft insertion rates of up to 2000 meters per minute, and multiphase looms promise weft insertion rates of 3000 meters per minute and higher. Similarly in yarn spinning, production rates for ring spun yarns are in the order of 10 to 20 meters per minute, open-end rotor spun yarns range from 50 to 100 meters per minute, and open-end friction spun yarns and air jet spun yarns range from 100 to 250 meters per minute.

In melt extrusion spinning of nylon, polyester and polypropylene filaments, take-up speeds of less than 2000 meters per minute were used for yarns which were subsequently and separately drawn to fully develop fiber orientation and crystallinity. In contrast, modern high speed melt spinning involved take-up speeds of anywhere between 4000 and 8000 meters per minute, with fiber structure development taking place on the spinline without subsequent and separate drawing.

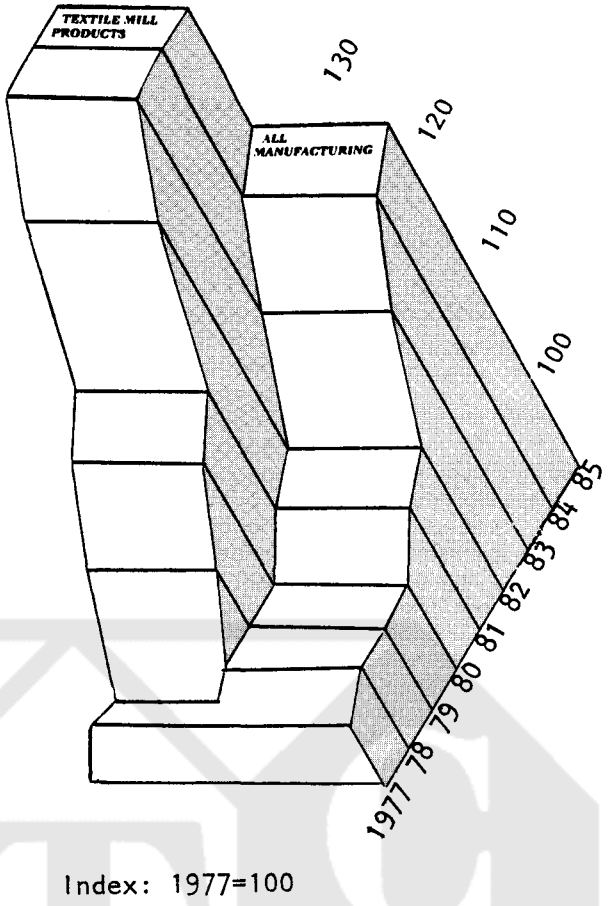

Fig. 3. U.S. productivity growth. (Courtesy of American Textile Manufacturers Institute.)

Spin Finish Distribution Studies

In the production of man-made fibers by one of several types of extrusion processes, the first step after filament formation is finish application. The spin finish serves to protect the newly formed fiber by coating it with a multicomponent formulation that invariably includes lubricants, antistatic agents, soil release agents, surfactants and other additives. An important function of the spin finish is to prepare the fiber for subsequent processing steps, such as crimping, spinning, texturing and weaving.

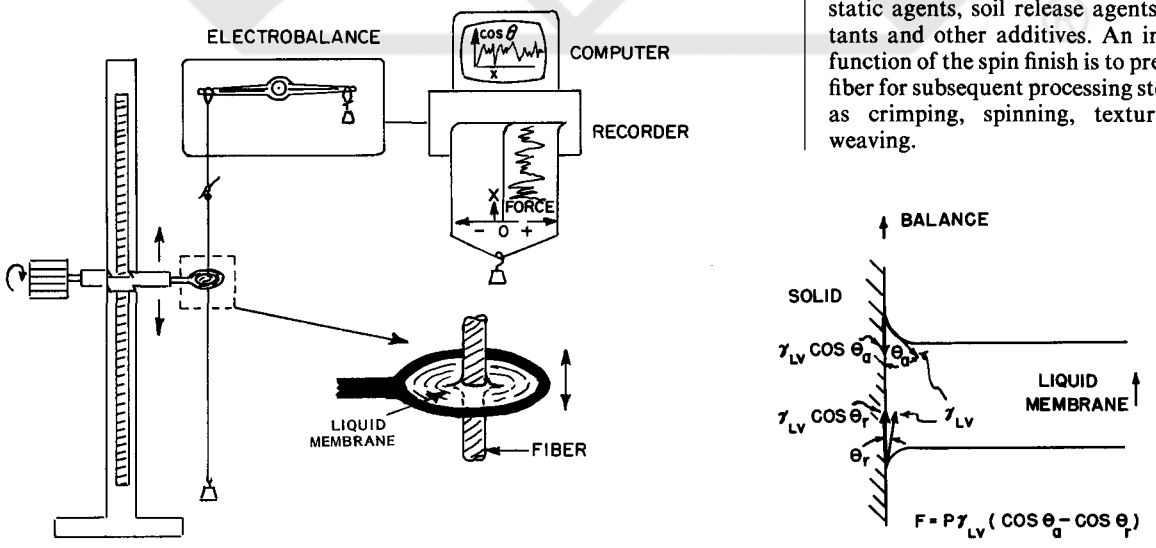

Fig. 4. Experimental arrangement for monitoring fiber wettability using a liquid membrane, and force diagram for the interaction between the liquid membrane and the fiber surface (*14*).

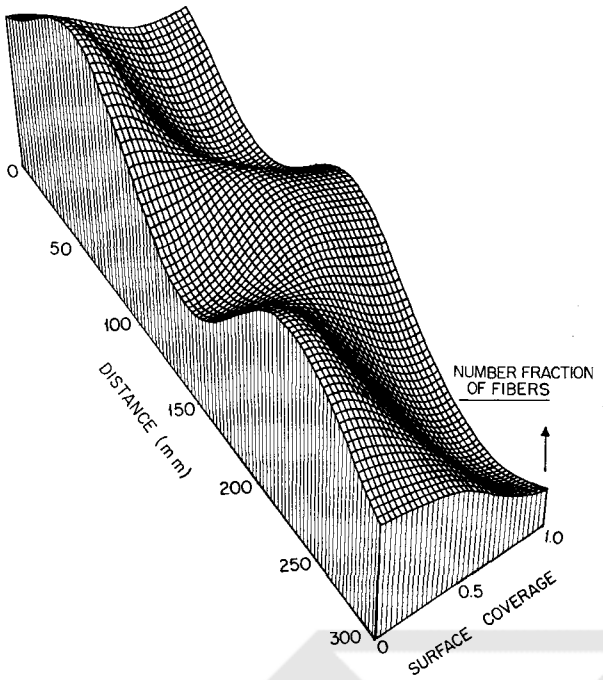

Fig. 5. Computer-generated three-dimensional surface coverage distribution plot for 70-filament nylon 6 yarn treated discontinuously with EO/PO 80/20.

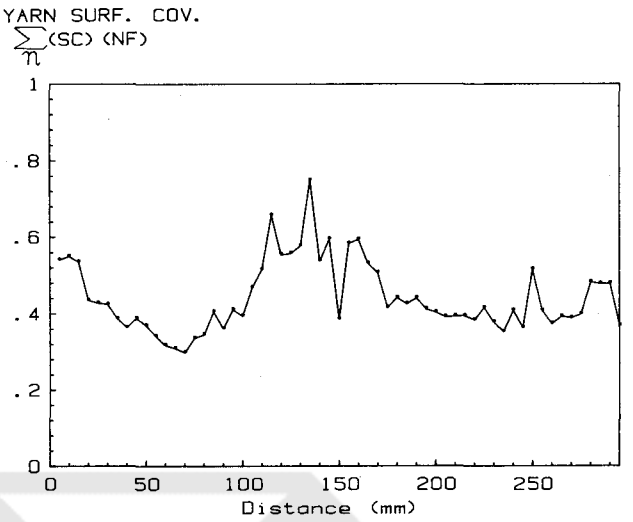

Fig. 6. Two-dimensional cumulative surface coverage distribution plot calculated for the data shown in Fig. 5.

The increased speed of processing has placed new demands on spin finish formulations. The finish must coat each filament, and penetrate a multifilament bundle by wicking. The role of surfactants and wetting agents in this process is obvious. One of the important areas of fiber technology today concerns the question of spin finish distribution. For the spin finish to be effective in its function, it must be uniformly distributed on the filament surface. It is no longer adequate to know the spin finish add-on; i.e., the relative weight of spin finish on the filaments. Typical spin finish add-ons may range from 0.5 to 2.0%, but such add-on values do not tell us anything about the uniformity of the spin finish, uniformity among filaments as well as uniformity along a single filament. This important question of spin finish distribution has been addressed by Weigmann and Kamath at TRI (*14*). First it was necessary to develop methods to evaluate and quantify the spin finish distribution along a filament. We are now able to do this by a technique that we refer to as wettability scanning. It involves measuring the surface energy or wettability of a filament as the filament is drawn through a liquid membrane, in an apparatus that is schematically shown in Fig. 4. This measurement provides us with an estimate of how the filament surface energy varies along its length, and by knowing the surface energy of an uncoated or unfinished filament and the surface energy of a coated or finished filament, we can calculate what we call the surface coverage; i.e., the fraction of the filament surface that is coated with the spin finish. This kind of measurement then allows us to construct three-dimensional representations of how the spin finish is distributed in multifilament yarns. This is shown in Fig. 5 where we have a computer generated three-dimensional surface coverage distribution for about 30 cm of a multifilament nylon yarn that was purposely treated with a spin finish to provide a nonuniform distribution (by a disrupted kiss-roll method). A high surface coverage region in the center of the specimen is flanked by two low surface coverage regions approximately 10 cm away on either side. The three-dimensional surface coverage distribution plot can be transformed into a two-dimensional cumulative surface coverage distribution shown in Fig. 6. It displays the same distribution pattern seen in Fig. 5. Each point on this plot represents the fraction of the total perimeter of the filaments of the yarn at a given location covered by the finish. The way the spin finish was applied to the yarn, it should have had a central region with a nearly complete surface coverage flanked on both sides by regions with no surface coverage. Yet, the center of the yarn specimen, which made contact with the kiss roll during spin finish application, is not completely covered by the finish, while the

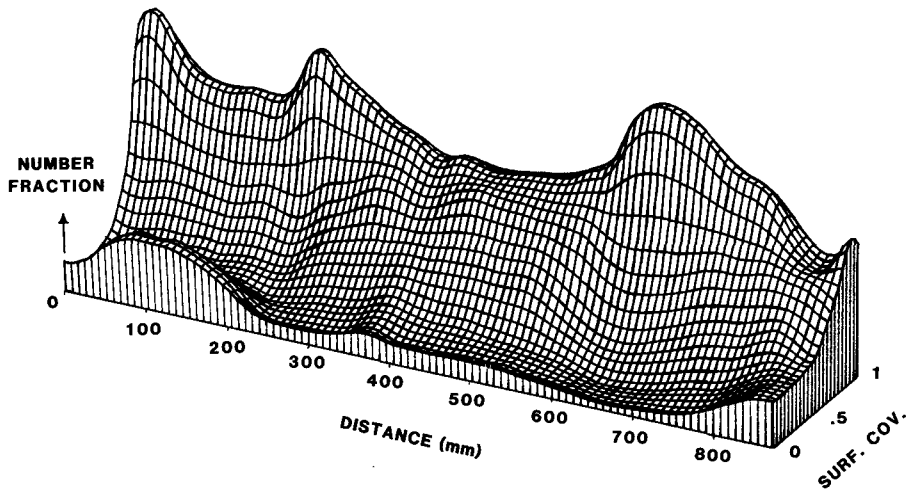

Fig. 7. Combined surface coverage distribution plot for a polyester yarn with 0.1% spin finish.

low surface coverage regions on either side of the central maximum show a finite surface coverage, even though the yarn was detached from the kiss roll at these locations. This lack of definition between contact and no-contact areas indicates that the finish tends to redistribute through wicking along the yarn axis during and after kiss roll application.

Another example of this type analysis is shown in Figs. 7 and 8 for a commercially finished 90 cm section of a multifilament polyester yarn. This yarn has a very low spin finish add-on, approximately 0.1%, yet the distribution over the 90 cm section is remarkably uniform, with an average surface coverage of about 70%. This was quite unexpected because of the very low finish add-on. Surface coverage is improved even further with higher add-ons. We have seen other spin finished yarns where surface coverage and uniformity were quite poor at low add-on levels. We are now using this exciting analytical tool extensively to quantify the distribution of finishes on filaments and yarns, and to establish how spin finish distribution can be controlled to allow more efficient processing.

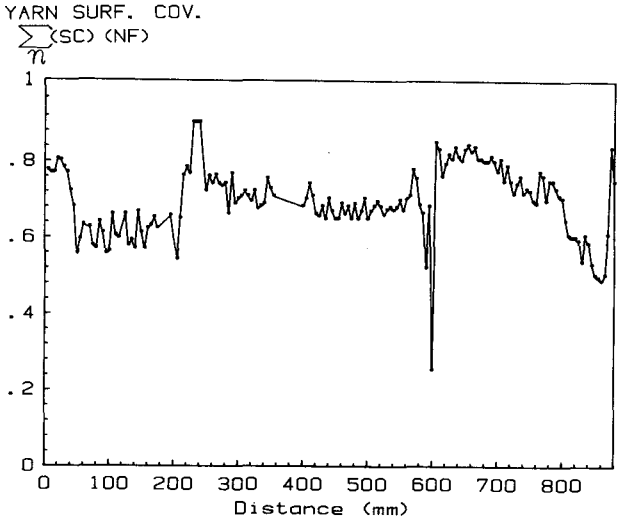

Fig. 8. Cumulative surface coverage distribution plot for the data in Fig. 7.

Absorption And Reaction Media

Finally, I would like to examine a rapidly growing field in the world of textiles, which is the use of fibrous materials as sorption and reaction media. Applications here range from such traditional products as diapers and wiping cloths to innovative uses such as catalyst support systems, oil spill recovery systems, controlled release chemotherapy, medical prosthetic devices, fertilizer delivery systems and many others. Particularly exciting is the use of fibrous materials as reaction media. A rapidly growing area of chemical research in recent years has been the use of polymers as functional chemical reagents. Polymeric reagents have been developed as bound catalysts, absorbents for biologically active compounds, and as transfer agents and carriers for complex organic syntheses. The work of Nobel Laureate R. Bruce Merrifield demonstrated beyond doubt the advantages that can be derived in polypeptide syntheses by anchoring reagents or reaction products on polymeric substrates. Immobilization of enzymes on polymer supports has also proven itself most useful in designing and operating enzyme controlled conversions. As a further advantage, it has been shown that the stability of many enzymes can be markedly increased by immobilization on polymeric substrates. Ion exchange resins and petroleum cracking catalysts are other examples where polymers are used as chemical reagents. When the polymeric reagent is used in the form of a fibrous network, we have the advantage of a substrate with a high specific surface area, and the added benefit of mechanical integrity that could not be achieved with any other form of polymeric reagents, such as granular materials. The fibrous network could be used not only as the polymeric reagent but also as a means of achieving separation. Because of its mechanical strength, the fibrous polymeric reagent could itself serve as a filter or it could be pulled or otherwise made to move to transport either the reagent or the desired product from one stage of the operation to another. Using fibrous networks as chemical reagents or as chemisorption substrates would broaden significantly the design opportunities for chemical processes.

Fluid Flow Behavior

In the use of fibrous materials as sorption and reaction media, there are a number of important scientific and technological

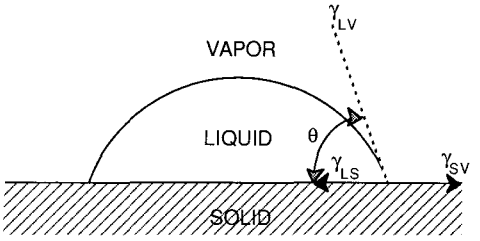

Fig. 9. Balance of interfacial forces defining the contact angle.

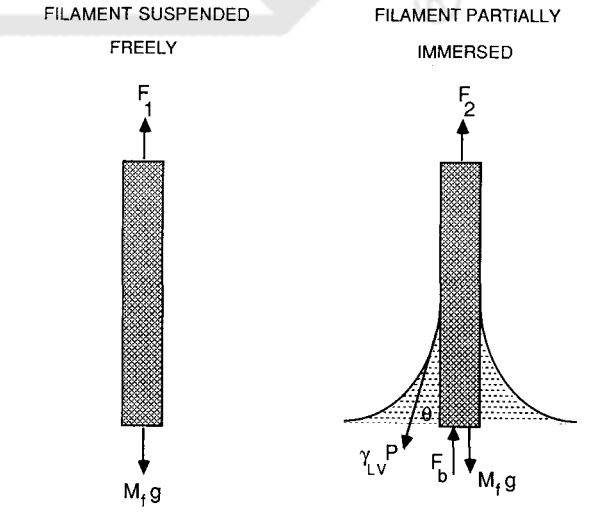

Fig. 10. Vertical forces on a suspended filament. If the buoyancy force F_b is negligible, $F_2 - F_1 = \gamma_{LV} P \cos\theta$ (M_{fg} = gravitational force).

challenges to which textile chemists and technologists are ideally suited to respond. For example, we need to have a good understanding of how the structure of the fiber network influences fluid flow characteristics. Both liquids and vapors must be able to permeate the network in a controlled and predictable manner. Miller and his associates at TRI have devoted a great deal of attention to the development of methods to characterize and quantify the interactions of liquids with fiber networks under a wide variety of conditions (*15*). There are two major factors that control fluid flow behavior: the wettability of the fiber surface and the dimensions of the pore spaces in the fiber network. Let us look at these two factors separately.

Table III. Work of Adhesion for Several Fiber-Liquid Combinations (*18*)

Liquid[a]	Work of Adhesion (ergs/cm²) Nylon	Polyester	Glass	Teflon	PP
Water (72.4)	93.1	84.2	131.4	45.0	54.6
Ethylene Glycol (47.5)	75.8	80.4	92.0	46.5	56.1
Methylene Iodide (48.6)	83.4	86.4	81.6	37.9	69.8
Hexadecane (28.4)	53.5	55.0	54.3	46.3	55.9
Surfactant Solution SDS (26-30)	48.2	45.0	44.7		38.4

[a]Values in parentheses are the liquid surface tensions (γ_{LV}) in dynes per cm.

Fiber Wettability

Wettability reflects the chemical structures of the two phases; i.e., the solid fiber and the liquid. There are several possible ways of formulating the thermodynamic quantities that describe wettability, but one of the most effective is through the work of adhesion (W), which is a measure of the attraction between the liquid and the solid, and which can be defined as

$$W = \gamma_{LV}(1 + \cos\theta)$$

Here γ_{LV} is the liquid surface tension, and θ is known as the contact angle. The contact angle is defined geometrically, as shown in Fig. 9, as the resultant of a balance of interfacial forces at the three-phase intersection. The experimental evaluation of the contact angle (θ) poses its own problems. It can be accomplished by direct microscopic observation of liquid drops that are carefully deposited on fiber surfaces. This is experimentally quite difficult, and the irregular shape and rugosity of typical textile fibers lead to considerable uncertainty. Miller, Hedvat, Kamath and others at TRI have used wetting force measurements as a means of quantifying the contact angle (*16,17*). Based on a balance of forces as shown in Fig. 10, the following relationship can be formulated:

$$F = P\gamma_{LV}\cos\theta$$

where F is the force (positive or negative) exerted on a fiber that is suspended or partially submerged in a liquid with a surface tension γ_{LV}. It is necessary to know the perimeter of the fiber, P, from some independent measurement. This method of contact angle evaluation is far superior to direct observation and is now extensively used to characterize fiber wettability. In fact, it is this measurement that forms the basis of the wettability scanning technique to characterize spin finish distribution as shown in Fig. 4.

The important point to note is that wettability, as quantified by the work of adhesion W in the equation above, is dependent on both the nature of the fiber (through the quantity cos θ) and the nature of the liquid (through the quantity γ_{LV}). Thus it is wrong to say that certain fibers are wettable while others are not; it depends on what liquid we are referring to. When using the term wettable we usually think of water as the liquid, which has a very high surface tension of 72 dynes/cm. However, there are innumerable other liquids, not to speak of surfactant solutions, that have much lower surface tension values. In Table III are shown work of adhesion data for several fiber-liquid combinations. One can see clearly here that whether or not a liquid has a strong interaction or adhesion to a fiber—that is, whether the fiber is wettable—depends not only on the fiber but also on the liquid.

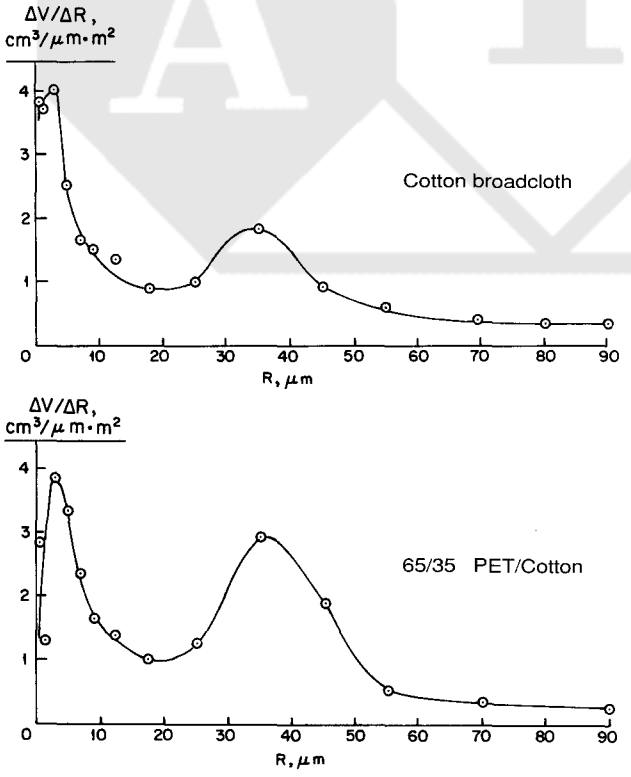

Fig. 11. Pore volume distribution curves for woven fabrics (*19*).

Pore Structure In Fabrics

The other important factor that controls flow behavior concerns the dimensions of the pore spaces in the network. Most fiber networks, whether woven, knitted or nonwoven materials, are highly porous. Typical porosity values range from 0.6 to 0.9 or even higher. The pores to which I refer are the spaces between yarns and the spaces between the fibers within individual yarns. In most fabrics these spaces are not uniform in size and shape. Quite to the contrary, in most materials there is a rather broad distribution of pore sizes and shapes. It is only recently that methods have been developed to quantify the pore size distributions of fiber networks. Miller and Tyomkin at TRI (*19*) have done this by a liquid extrusion technique that has important advantages over the well known

mercury intrusion method which is satisfactory for rigid porous materials, such as rocks and sand beds, but not for compressible materials such as textiles. With the Miller and Tyomkin method it is possible to determine pore size distribution quite easily for just about any fiber network.

In Fig. 11 are shown the pore size distribution curves for typical woven fabrics as determined by the TRI liquid extrusion method. There is a bimodal distribution of pore sizes which is invariably observed for woven fabrics. The larger pores are the spaces between the yarns while the smaller pores are the spaces between the fibers within the yarns. The exact shape of such distribution curves is dependent on the weave pattern, the fabric sett, and the yarn size and twist. Even fiber properties themselves affect the pore dimensions. For example, fiber fineness or diameter and fiber cross-sectional shape will influence the dimensions of the small pores within the yarn.

Pore size distribution curves for a typical nonwoven fabric as a function of compression or mat thickness are shown in Fig. 12. Note the decrease in pore size with decreasing mat thickness, and the fact that we do not see a bimodal distribution but rather a broad unimodal distribution of pore sizes which is typical of nonwovens (*20*). Indeed this difference in the pore size distribution between woven and nonwoven fabrics is one of the most important differences between these two fabric types. Of course there are other differences between woven and nonwoven fabrics, but the distinction in terms of pore dimensions cannot be over-emphasized. It is obvious that a knowledge of the structural factors that govern sorption and flow behavior under a wide variety of conditions is necessary in order that we be able to design products with optimal performance characteristics. It is for this reason that the techniques that we have developed at TRI to evaluate pore size distributions have been of such immense importance in many product development programs. For example, from some recent studies we have indications that it is not the average pore size that determines the permeability, but rather that the presence of a few large interconnected pores governs flow behavior.

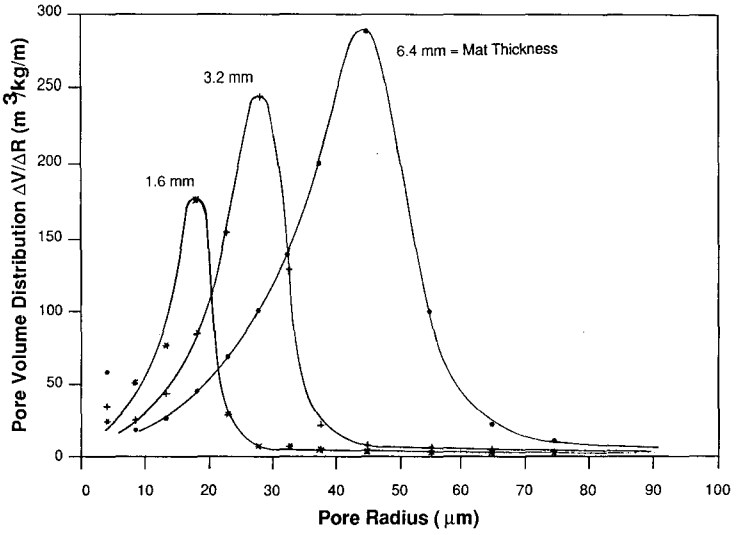

Fig. 12. Pore volume distribution curves for a glass fiber nonwoven mat at various compressed thicknesses (*20*).

Conclusion

I have touched on three different areas of technology to exemplify some of the scientific and technological challenges that exist today in the field of textiles. These topics currently command a great deal of attention at TRI and also in other research laboratories concerned with fibrous materials. Fiber reinforced composites, high speed processing and spin finish distribution, and the use of fibrous materials as sorption and reaction media may not, at first sight, appear to have any relationship to each other. Yet there is a relationship or at least a common link among them. In all three areas we are looking at technologies and innovations that go beyond traditional uses of fiber materials and traditional methods of processing. As such they represent the wave of the future; they exemplify that our field has many exciting challenges and many rewarding opportunities. The world has come to recognize that textiles, and fibrous materials in general, offer a unique combination of physical properties and other characteristics that make them ideally suited to many applications in addition to those associated with the traditional apparel, household and industrial markets. This places textiles at the forefront of innovations and developments in such exciting fields as materials engineering, space exploration, bioengineering and medical technology, to name just a few. The world of fibers and textiles today is as exciting and challenging as it has ever been.

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