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TECHNICAL REPORT

71-51-CE

The Mechanical Properties of Textile Materials as
Influenced by Structure and Strain Rate

by

Frank Figucia, Jr.
Louis I. Weiner
Roy C. Laible

April 1971

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U. S. ARMY NATICK LABORATORIES
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FOREWORD

The design of textile materials for the military requires consideration of a broad spectrum of uses and related performance requirements. Among the most severe of these are materials such as those used for high speed deceleration of aircraft, which undergo large tensile shock loadings, or body armor materials which must resist high energy transverse impacts. Continuous improvement in material properties is necessary to meet the constantly increasing performance demands in these areas. In consideration of these needs, advances in related technology must also keep pace.

This work was conducted under Project 1T062105A329, Organic Materials Research for Army Materiel. The bulk of the study however was conducted under Translation of Fiber Properties into Fabric Structures, which deals with the mechanical behavior of high performance textile systems, particularly from the point of view of the response of component substructures to impact forces. It aims at characterization of fiber and yarn elements by laboratory methods and combinations of these into higher structure at or near end-item levels. The ultimate objective is effective correlation between actual use and laboratory performance under simulated end use conditions.

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ABSTRACT

Fibrous structures of increasing complexity, as introduced by ply and twist, have been subjected to high and low speed tensile tests. The ratio of the strength at high speed to that at low speed is always greater than one but decreases with increasing complexity. The ratio of the elongation to break at high speed to that at low speed is always less than one and also decreases with increasing complexity of structure. The ability to absorb energy markedly increases with increasing complexity of geometry at the low strain rates characteristic of the Instron. The reasons for this additional energy absorption are discussed. Tests at high rates of straining point out the inability of many complex textile structures to translate their superior energy absorption characteristics to high strain rates. The results obtained and the principles demonstrated are applied to the development of improved materials for use in aerial delivery and ballistic applications.

THE MECHANICAL PROPERTIES OF TEXTILE MATERIALS AS INFLUENCED BY STRUCTURE AND STRAIN RATE

I. Introduction

Textile items used by industry, the military, and the individual consumer are subjected to various complex stresses. It has been recognized for some time that the speed at which stresses are applied must be considered in evaluating such textile items. Evaluation of a textile item under low conditions of 50-200 %/minute may not give accurate information concerning the breaking strength of an auto seat belt subjected to strain rates several decades greater. For this reason, scientific personnel in industrial, university and government laboratories have devised and utilized various instruments such as the falling weight, pneumatic or hydraulic piston devices, and even devices utilizing impact directly or indirectly with a missile to attain the higher strain rates characteristic of the end use applications. At the U. S. Army Natick Laboratories the strain rates used most frequently have been 100 %/minute and 288,000 %/minute.

Generalizations may be made concerning the changes in the mechanical properties of a textile yarn accompanying this three decade rise in strain rate. The breaking strength rises, the breaking elongation decreases, the modulus increases and the work to rupture may increase, decrease or stay the same with increased rate of testing. However, problems arise, some of which tend to invalidate this generally accepted behavior. For example, the strain rate of 288,000 %/minute may still be too low to duplicate the conditions operating at strain rates characteristic of ballistic impact. Or the strain history may not be at a simple constant rate as obtained with a pneumatic tester but may be a more complex strain history as is operating in the opening of a parachute. These two problems, although being addressed, are far from solved. This report is concerned with a third problem; that of complexity of structure as it interacts with strain rate.

Complexity itself has been studied in the past, notably by Treloar and Riding⁽¹⁾, who derived relationships for the stress-strain properties of yarns based on their structural geometry and the known stress-strain behavior of component filaments. Treloar⁽²⁾ also used a similar approach to predict plied yarn behavior, and Riding⁽³⁾ checked this theory experimentally, obtaining satisfactory agreement.

Platt⁽⁴⁾, Kilby⁽⁵⁾, Symes⁽⁶⁾, and others have also analyzed the many structural factors involved in yarn construction. In the present study, the influence of ply and twist are examined with the emphasis on commonly used amounts of these.

II. Experimental

A. Materials

A variety of yarns were used to make various comparisons in this study. The identification of these is as follows:

<u>Fiber</u>	<u>Designation</u>	<u>Denier</u>	<u>Producer</u>
High Modulus Polyamide	X-500, Type 1	1120	Monsanto
High Modulus Polyamide	X-500, Type 3	1125	Monsanto
Glass	E Glass	2400	United Merchants & Manufacturers
Polyamide	Nylon 6, Bal-10	1050	Allied
Polyamide	Nylon 66, Type 728	840	DuPont
Polyamide	Nylon 66, Type 330	210	DuPont
Polypeptide	Silk - Size F	1170	A. H. Rice
Polypeptide	JKS-1	156	Gulf South Research Institute
Polypeptide	JKS-2	157	Gulf South Research Institute

The nylon 66 yarns obtained from E. I. duPont deNemours & Co., were 210/34 single ply. They were plied to various levels (2, 3, 5 and 7), with various amounts of twist (2, 5 and 9 t.p.i.). This provided a yarn series with gradually increasing complexity which could be examined for effects of either plying, twisting or a combination of both. The processing for this series was performed at the Lowell Technological Institute, Lowell, Massachusetts.

The silk is a three-ply sewing yarn made from mulberry silk by the A. H. Rice Co. It was tested both in its final form and in unplied single strands.

The two polypeptides from Gulf South, the nylon 6 and the X-500 are experimental developments currently under investigation at the U. S. Army Natick Laboratories.

The fibrous glass yarn was extracted from 20,000 denier roving, which had been woven into an experimental fabric by United Merchants and Manufacturers.

X-500 is a high modulus aromatic polyamide available in three basic types, with variations of each type. Those used in this study were Type-1, which has the highest modulus, highest strength and lowest elongation, and Type-3, with the lowest modulus, lowest strength and highest elongation.

B. Methods

Tensile properties, (breaking strength, elongation, work-to-break, knot strength, and modulus), were measured at conventional test rates on an Instron Tester, and at impact rates with a FRITS* Impact Tester. The Instron Tester speed was 5 inches/minute which resulted in a strain rate on the test specimen of 100 %/minute. High speed tests were performed at 20 feet/second for a strain rate of 288,000 %/minute.

The FRITS Tester is a pneumatic piston type instrument which utilizes compressed nitrogen as a source of power. A piezoelectric crystal load cell transmits forces to an oscilloscope readout. A displacement-time signal is also provided by means of a pre-marked magnetic tape. Photographs of the oscilloscope screen are made to permanently record each test.

Twisting of X-500 and nylon 6 yarns was performed at NIABS with a Suter Twister under constant tension of 30 grams.

III. Results and Discussion

Translational effects in manufactured textile materials have been recognized for many years. The tensile strength of the finished item is rarely equal to the sum of its component yarn or fiber strengths. The elongation, on the other hand, is usually greater than that of the components due to additional plying, twisting, or weaving, which introduced additional "structural" elongation.

Though the efficiency with which an item translates mechanical properties may be dependent upon the type of fiber used, it is also dependent upon structural geometry. When a material is stressed, either axially or transversely, there is a natural tendency for the component members to orient in the direction of load, and to reinforce one another in resisting the load. The extent to which this reorientation takes

*Made by Fabric Research Laboratories, Dedham, Massachusetts

place determines the strength output of the total system. The amount of readjustment which can take place is controlled by two factors: (1) The limit allowed by the particular configuration, i.e., a woven fabric, with all its yarns oriented in the direction of load, will translate strength better than a braided cord, whose component yarns restrain each other from a perfectly axial orientation; and (2) The speed with which the load is applied. Internal readjustment is a time dependent process which can only reach the optimum point if loading takes place very slowly. As loads are applied more and more rapidly, there is less time for total adjustment to take place, and efficiency losses are noted.

These rate-dependent effects make the study of translational efficiency under rapid loading rates particularly important when characterizing materials for impact applications.

A. Complexity by Ply and Twist

Figure 1, shows generalized stress-strain curves for a typical fiber loaded at a conventional (slow) speed and a speed approximately 3000 times faster. Expressing the response of this material as the ratio of high speed to low speed output, it can be seen that the stress ratio is approximately one. Computing ratio in this manner gives an index of the percent output for a particular parameter at high speed compared to that at low. For convenience, in the following discussion these indices will be referred to as "impact performance ratios." Impact performance ratios were examined for the strength, elongation, and energy outputs of a series of nylon yarns. A gradual build-up in complexity of structure within the series was obtained through the addition of ply and twist. Thus, trends in impact performance could be observed and related to the various complexity levels. Figure 2, shows strength impact performance ratio plotted against twist for various plied yarns. It is seen that the ratios are all greater than one which reflects the inherent characteristics of the polymer to exhibit greater strength at high speed. However, the downward trends with both ply and twist indicate that strength translation at high speed becomes increasingly poor with additional complexity. The effect of twist is more severe than that of ply especially at the higher ply levels. The combined effects of ply and twist are illustrated in Figure 3, with the impact performance ratio plotted against $(\text{ply} \times \text{twist})^{\frac{1}{2}}$ as a complexity factor. This further depicts an overall downward trend in strength impact performance with increasing complexity.

The inherent tendency of the basic polymer to exhibit decreased elongation at high strain rate is observed in Figure 4 where impact performance ratios for elongation are all less than one. Here again, decreases are noted in impact performance with increases in both ply and twist. A downward trend with complexity is also noted in Figure 5. This indicates that although structural elongation is increasing with the

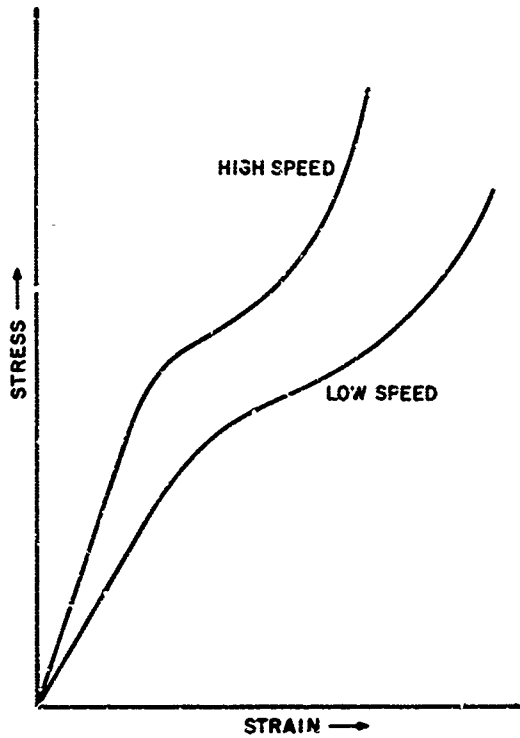


FIG. 1 GENERALIZED STRESS-STRAIN BEHAVIOR FOR MOST POLYMERIC MATERIALS AT HIGH AND LOW STRAIN RATES

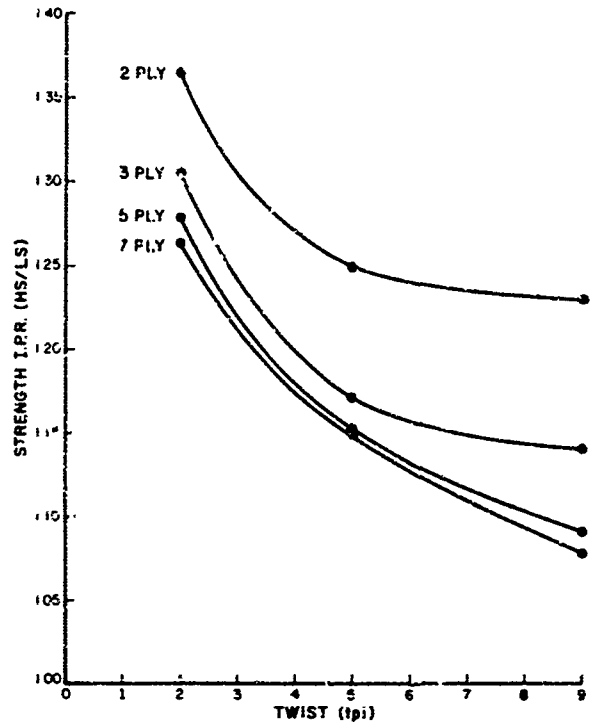


FIG. 2 IMPACT PERFORMANCE RATIO VS TWIST FOR BREAKING STRENGTH OF NYLON 66 YARNS AT HIGH AND LOW STRAIN RATES

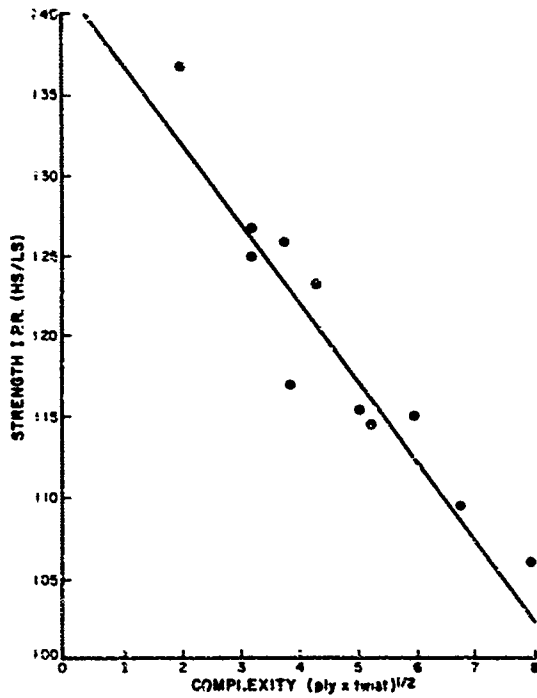


FIG. 3 IMPACT PERFORMANCE RATIO VS COMPLEXITY FOR BREAKING STRENGTH OF NYLON 66 YARNS AT HIGH AND LOW STRAIN RATES

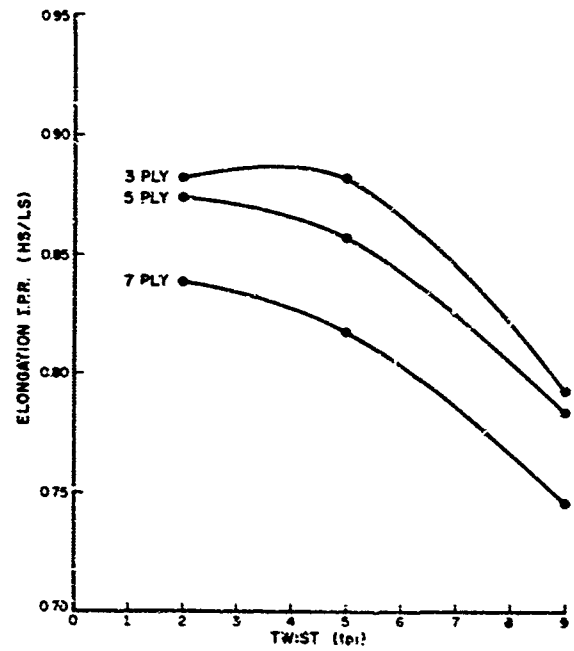


FIG. 4 IMPACT PERFORMANCE RATIO VS TWIST FOR ELONGATION OF NYLON 66 YARNS AT HIGH AND LOW STRAIN RATES

addition of ply and twist, it is not reflected in the ability of the yarns to elongate at high strain rate. Internal structural reinforcement when loads are applied instantaneously cannot progress to the same levels that can be attained at conventional speeds.

The combined losses for strength and elongation are shown in Figures 6 and 7 where energy impact performance ratios are plotted. It is seen that at the highest complexity level, the material at high speed translates just over 50% of the energy capacity exhibited at low speed (Figure 7).

These effects may apply to problems in the field of aerial delivery. Due to the complexity of suspension cords, tie down straps, knotted joints, and splices one gets an impression from low and quasi static test data of greater energy absorption, strength, and elongation than is actually available under actual use conditions. Thus, materials of this type furnish an excellent example of the interaction of complexity and speed of testing. Questions then arise as to the application of this complexity-rate of testing interaction to other areas. One of these areas, ballistic impact, has previously been investigated from the viewpoint of rate of testing, but never with the added consideration of complexity.

In general, it is known that textile yarns and fibers with good mechanical properties, namely high strength and high modulus and with sufficient ductility even under static testing conditions, are prime candidates for the preparation of felts and fabrics with optimum ballistic properties. However, occasionally a fiber or yarn with good static properties performs poorly ballistically, or one with fair or poor mechanical properties under static conditions performs better than expected. The simplest explanation would appear to be the rheological behavior of the material; the fact that processes of relaxation which can occur under a slow speed test are no longer able to occur at the very high speeds of test characteristic of a ballistic impact. In some cases, this explanation suffices and it may only be necessary to raise the testing rate a few decades to see the improved or degraded properties.

However, observation of the complexity of the structure governing the behavior of felted or woven fibers shows that a simple tensile test may be insufficient to predict or elucidate the ballistic performance of a new material. As a specific case, a new series of high modulus polyamide fibers with the designation X-500 became available from Monsanto Chemical Company. Two types examined had the following properties:

	<u>Breaking Stress (gpd)</u>	<u>Breaking Elongation (%)</u>	<u>Modulus (gpd)</u>
Type I	14	2.5-4.0	550
Type III	6.5	20	150

Type I had the high breaking stress and high modulus which should be useful for ballistic applications. Actually, this material was useless as a needle-punched felt and performed poorly in fabric, giving a V-50 ballistic limit value with the 17-grain fragment simulator of 1070 ft/sec as compared to greater than 1225 ft/sec for nylon 66 fabric plied to the same areal density. The ballistic limit value can be described as the velocity with which a missile would have a 50% chance of penetrating the target material. To further investigate this poor ballistic behavior, a yarn complexity analysis was performed on the X-500. Type I material in one and two ply yarns was tensile tested at various twist levels from "0" t.p.i. to "8" t.p.i. Figure 8 shows a marked decrease in the strength of the plied and unplied yarns as a function of twist even at the static rate of testing (100%/min). In contrast, a nylon 6 yarn shows a barely perceptible drop in strength with increasing twist. The nylon 6 in fabric form is known to give a higher ballistic resistance. Impact loading of the X-500 further reflects the complexity effect discussed earlier, where the losses due to increased twist are accentuated at the high speed. The loss observed (Figure 8), is particularly severe, with only 25% of its original strength retained at 8 turns per inch. This behavior illustrates the extreme sensitivity of this material to structural influences, which helps to explain its poor ballistic performance.

A material this structure-sensitive would most likely be very susceptible to failure at stress concentration points such as the yarn crossovers in a woven fabric. Observation of experimental ballistic panels supports this idea. The hole formed by penetration of the missile into the fabric is square in many cases for X-500, indicating that the yarns were cleanly sheared off along the crossovers on the outer edges of the failure. This is in contrast to more random failure patterns in nylon ballistic fabrics. Clearly the energy at the point of impact of the missile is not being translated beyond the nearest yarn crossovers.

3. Complexity by Knots

The distribution of stresses about the missile in a ballistic impact is a complex subject, not to be treated in depth in this report. Considering it briefly, however, examination of layered fabric panels which have been tested at their V-50 ballistic limit speed, indicates that a combination of fiber, yarn and weave properties contribute to the overall resistance of the complete layered assembly. It is not implied that the same effect to be discussed will occur at impact speeds considerably greater or less than the V-50 speed. Initial penetration of the first layer is normally a concentrated rupture with only very localized resistance from the contacted yarns. Failures at this point appear to be in shear, with the level of failure highly dependent upon modulus, or stiffness, as well as concentrations of bending stresses at crossover points. As the missile proceeds through the layered panel, a departure

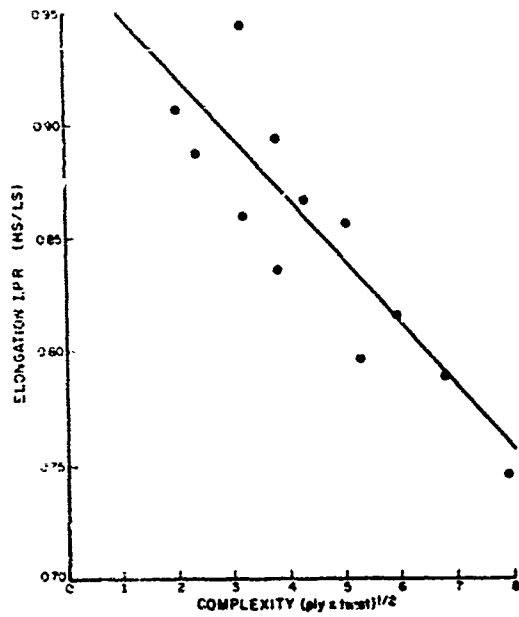


FIG 5 IMPACT PERFORMANCE RATIO VS COMPLEXITY FOR ELONGATION OF NYLON 66 YARNS AT HIGH AND LOW STRAIN RATES

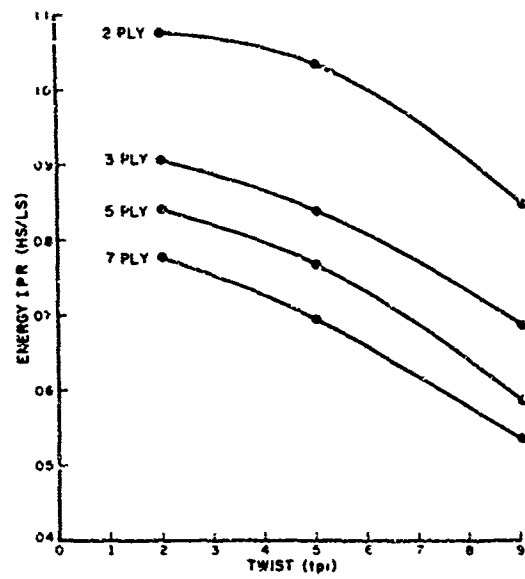


FIG 6 IMPACT PERFORMANCE RATIO VS TWIST FOR ENERGY CAPACITY OF NYLON 66 YARNS AT HIGH AND LOW STRAIN RATES

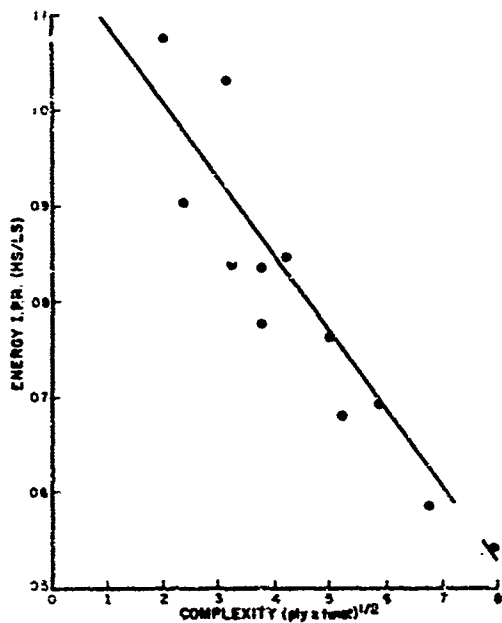


FIG 7 IMPACT PERFORMANCE RATIO VS COMPLEXITY FOR ENERGY CAPACITY OF NYLON 66 YARNS AT HIGH AND LOW STRAIN RATES

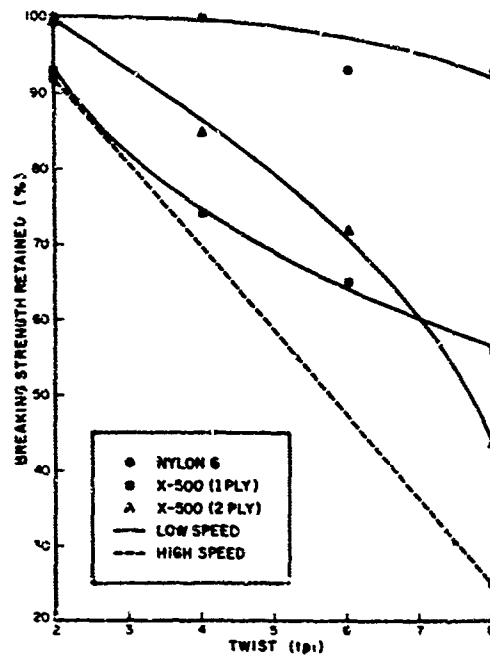


FIG 8 STRENGTH LOSSES WITH INCREASED TWIST FOR NYLON 6 AND X-500 YARNS

from this initial shattering effect takes place. In the last layer penetrated, a drawing of the yarns seems to take place, which indicates a more longitudinal or tensile yarn response to the applied load. Much of the resistance at this point is provided by the tenacity, elasticity, and toughness characteristics of the material. The stress is also dispersed over a wider area, allowing for fabric constructional features to contribute to the resistance of forces. At present, the combined effects of shear, elasticity, weave, etc., can only be evaluated by actual missile firings on layered panel specimens. However, the isolation of these and many other effects in the laboratory contributes greatly toward the evaluation of candidate materials for ballistic applications. Standard laboratory tensile tests at high speeds provide information related to the quasi-longitudinal responses in ballistic resistance. The shear-like responses related to the initial missile penetration, however, have been more difficult to assess in the laboratory. Methods based on the evaluation of tensile moduli or wave velocity, such as the Pulse Propagation Meter, have at times proved useful in understanding impact or ballistic behavior. In other instances (i.e., X-500) the high modulus and high wave velocity are inconsistent with the poor ballistic performance exhibited and one is inclined to search for another method of evaluation. One method which combines material stiffness characteristics, stress concentration, and complexity effects is the simple knot test. This test provides a means for evaluating a wide variety of materials easily and quickly. Figure 9 shows the percent of normal strength retained by knots under impact loading, as a function of high speed elongation. It is seen that the X-500 yarn, Type I, which displayed such poor ballistic resistance, had a strength retention of only 12% while nylon 6 and nylon 66 which possess relatively good ballistic resistance, retain

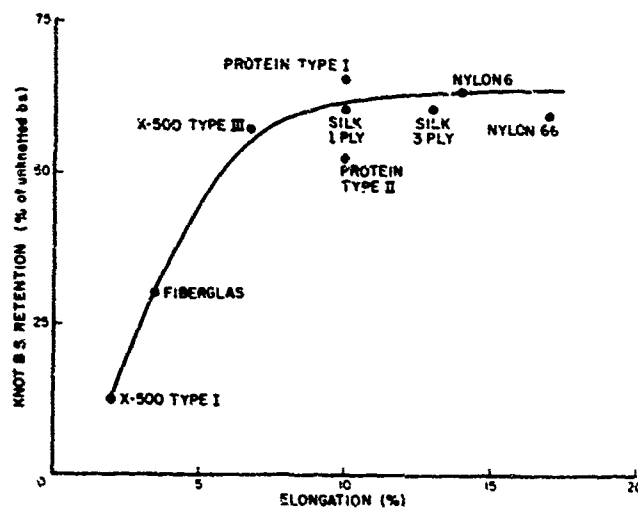


FIG 9 HIGH SPEED KNOT STRENGTH VS HIGH SPEED ELONGATION FOR A VARIETY OF YARN TYPES

62% of their strength when knotted. The silk, which also retains strength well in the knotted form, possesses good ballistic resistance. The protein fibers shown are experimental and have not been evaluated ballistically. Another example is that of glass. The knot strength retention was 30%. It is known that glass yarns in fabric form exhibit very low ballistic resistance and, therefore, glass with a reasonably high strength (10 g/d), and a high modulus (300 g/d), is limited by its lack of ductility. This plot suggests the simple expedient of determining elongation and forgetting the knot strength test. However, it is interesting to note that only 10-15% elongation is needed to insure good performance in the knot test, and that additional elongation to break is unnecessary. This feature of the curve may explain the good ballistic performance of a low elongation material (polyvinyl alcohol)⁽⁷⁾ and the relatively poor performance of a very high elongation material (polypropylene)⁽⁸⁾.

X-500 has a good potential for impact resistance because of its high modulus and accompanying high wave propagation velocity. It is the lack of ductility and translational ability that nullifies its usefulness in ballistic applications. In Figure 9, an X-500 yarn with greater ductility is represented. This yarn, Type III, was able to retain 57% of its breaking strength as compared to only 12% for Type I. Type III also exhibited much improved ballistic resistance (1244 ft/sec).

IV. Conclusions

Translational efficiency at high speed must be carefully considered in tensile or ballistic applications. The usual tensile strength and elongation changes with strain rate are altered in the case of complex structures. The strength Impact Performance Ratio, which is normally expected to be greater than one, is shown to steadily decrease with complexity. This trend can be carried to the point where complex braided cords used in parachutes actually have strength I.P.R.'s less than one, and energy I.P.R.'s as low as 0.5.

Increased stiffness and elasticity are advantageous only to certain limits in ballistic resistance. High modulus materials respond better ballistically, but only to the point where materials are too stiff to translate shear energy effectively. More extensible materials seem to translate more efficiently, but beyond a fairly low elongation level, extensibility has no further effect on translation. The proper balance of modulus, extensibility, and strength in a fiber seems to be the key to improved impact performance.

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