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The Tensile Properties of Textile Yarns at Very High Strain Rates

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Synopsis

Stress-strain curves have been determined at a very high rate (330 sec.$^{-1}$) and at a normal rate (8.3×10^{-3} sec.$^{-1}$) of straining for a range of lightly twisted yarns covering all commercially important fiber-forming polymers. From these curves breaking stress and extension, energy to rupture, initial modulus, and critical velocity have been obtained. Results are presented in detail to assist selection of fibers for applications where rapid extension is likely. At the high rate the breaking stress is always greater and, with one exception, the breaking extension less than at normal rates. The energy to rupture increases with rate for the wet-spun fibers and, with one exception, decreases for the thermoplastic. The variation in magnitude of these changes is considerable even among fibers from the same polymeric base, emphasizing the importance of testing at a rate comparable to that encountered in use. Similar experiments performed with three of the yarns highly twisted showed that the ranking of the yarns according to a particular property could be altered by the insertion of twist. The stress-strain curves of the material were used to predict the curves for the twisted yarn, following a theory of Treloar and Riding. At the normal rate agreement with experiment was fairly good, but it was much worse at the high rate.

INTRODUCTION

It is well known that the mechanical properties of polymeric materials depend significantly upon the rate at which they are deformed. The applications of these materials in situations where very high rates of strain are likely are increasing and so it is essential that data become available describing their properties in comparable conditions. The variation of modulus at very small strain with frequency of application of strain has been extensively studied, but information on the tensile properties at finite strain during rapid extension is scanty. This is true not only for polymeric materials in general but also for the particular case of textile fibers.

Such information is given in the present paper for a wide range of typical textile yarns extended at a strain rate of 330 sec.$^{-1}$. (This is the highest rate at which conventional stress-strain representation is likely to have any value, since at higher speeds of extension stress-pulse propagation phenom-

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ena predominate.) As a control, similar information is given for the material at a rate of strain of 8.3×10^{-3} sec.$^{-1}$, which is typical of normal testing rates.

Other studies of the effect of strain rate on the tensile properties of textile yarns have been published by Meredith,[1] Holden,[2] and Smith, Shouse, Blandford, and Towne.[3,4] The work of Meredith does not include the recently developed high strength fibers and the highest strain rate he used was about two decades slower than those available with modern instrumentation. Holden used the same apparatus as the present author but gave no accurate values for the energy to rupture. (In practice, extension at a high rate of strain is most likely to occur following ballistic impact and so the energy absorbed before breaking is one of the most important properties at these rates.) The method used by Smith et al. to obtain a high rate of strain is less direct than that used in this work. There are also other differences in experimental conditions. These will be discussed later in the paper and a comparison of the two sets of results will be given.

Since the prime interest of the present work is in the effect of rate on the properties of the material, and so that these properties should be unaffected by yarn structure, the yarns were tested with very low twist. It is possible however that the ranking of yarns according to any particular property could be altered by the insertion of twist as well as by the rate of extension at which the property was determined. This point has hitherto received little attention in experiments at high rates of strain. Smith, Blandford, Shouse and Towne[5] have reported on the properties of a 5-ply cord of high-tenacity deacetylated cellulose acetate with different singles and doubling twists at four strain rates up to 20 sec.$^{-1}$. However, an understanding of the problem is more likely to be achieved by studying first the simpler structure of single yarns. Treloar and Riding[6] have recently made progress in describing the stress-strain curve of these yarns in terms of the stress-strain curve of the material and geometrical factors, and have obtained a theory giving good agreement with experiment at normal strain rates.

In order to obtain some information on the tensile properties of twisted yarns at very high strain rates three of the yarns included in this series of experiments, standard rayon, nylon 100, and medium-tenacity Terylene, were twisted to a fairly high twist (the outside filament was inclined to the yarn axis at an angle of approximately 38°) and the stress-strain curves at rates of 8.3×10^{-3} sec.$^{-1}$ and 330 sec.$^{-1}$ are given here. The validity of the theory of Treloar and Riding is examined at both rates and the rate dependence of the change in breaking properties with twist is studied.

MATERIALS

Wherever possible the materials used were in commercial production at the time the study was commenced (April 1961) and were continuous

TABLE I. Details of materials Used

Yarn	No. of fil.	Tex	Manufacturer	Material	Linear density of test length, tex
Nylon 900	140	93.3	B.N.S.	Nylon 6.6	7.48[a]
Nylon 300	34	7.8	B.N.S.	Nylon 6.6	7.97
Nylon 100	34	7.8	B.N.S.	Nylon 6.6	7.91
Enkalon	24	6.7	A.K.U., N.V.	Nylon 6	6.66
High tenacity Enkalon	140	93.3	A.K.U., N.V.	Nylon 6	9.93
Tenasco 105	1000	122.2	Courtaulds Ltd.	Cellulose	7.00[a]
Textile Tenasco	80	22.2	Courtaulds Ltd.	Cellulose	21.8
Standard rayon	50	27.8	Courtaulds Ltd.	Cellulose	27.6
Polynosic S.C. 28	37	15.6	Courtaulds Ltd.	Cellulose	15.2
Tricel	70	31.1	Courtaulds Ltd.	Cellulose acetate	27.4
Ulstron	40	22.2	I.C.I.	Polypropylene	5.52[a]
Polypropylene Multifil	40	22.2	Courtaulds Ltd.	Polypropylene	6.26[a]
Polyethylene Multifil	45	22.2	Courtaulds Ltd.	Polyethylene	5.90[a]
Courlene X3	1		Courtaulds Ltd.	Polyethylene	13.0
Terylene Microdull H.T.	24	13.9	I.C.I.	Polyethylene terephthalate	6.04[a]
Terylene Dull M.T.	48	11.1	I.C.I.	Polyethylene terephthalate	11.1
Courtelle $4^1/_2$ den. tow			Courtaulds Ltd.	Polyacrylonitrile	9.81[a]
Acrilan-16	100	37.8	Chemstrand	Polyacrylonitrile	19.3[a]
Aeress	30	8.3	Union Carbide	Vinyl chloride/acrylonitrile copolymer	8.28
B.H.S.	40	8.3	Courtaulds Ltd.	Vinyl chloride/acrylonitrile copolymer	8.18
Human hair					33.6
Silk, degummed					13.4
Saran 3:1 draw ratio	12		B.X. Plastics	Polyvinylidene chloride	17.1[a]
Saran 3.6:1 draw ratio	1		B.X. Plastics	Polyvinylidene chloride	20.8
Vinal F.O.	36	26.7	Air Reduction Chemical Co.	Polyvinyl alcohol	10.4[a]

[a] Denotes a bundle of filaments split from the yarn for testing.

filament yarns containing only spinning twist and having a breaking strength in the range 200–500 g. In cases where only higher strength yarns were available a bundle of filaments of suitable strength was separated for testing. (500 g. was the upper limit of the capacity of the high speed testing apparatus.) Details of all the materials included in this series of tests are given in Table I.

Of those which were not available commercially the "Acrilan" was specially spun by Chemstrand Research Center Inc. and had very similar properties to commercial "Acrilan-16" staple. The "Courtelle" yarns were made from a length of $4^1/_2$ denier uncrimped tow with standard soft finish. Wool could not be obtained in sufficiently long staple lengths but human hair, which might be expected to have similar mechanical properties, was included. This was kindly supplied by a colleague of the author, Miss E. E. Clulow, and the only pre-treatment it had received was normal washing.

EXPERIMENTAL METHOD

Ten test pieces of each yarn were extended to break at a nominal extension speed of 20 metres/sec. The apparatus and experimental techniques used have already been fully described.[2,7] A gauge length of 5 cm. was used but previous experiments[7] have shown that an end correction (caused by slippage at the clamps) equivalent to an increase in gauge length of 0.78 cm. is necessary with this apparatus. This was added to the gauge length before calculating the strain and strain rate. Calculated in this manner the mean strain rate for the experiment was 330 sec.$^{-1}$.

As a control test on the material ten test pieces with a gauge length of 5 cm. were extended to break at a rate of 8.3×10^{-3} sec.$^{-1}$, using an Instron Tensile Tester. Previous experience with this machine has shown an end correction to be unnecessary. The purpose of this control test was twofold: to show how much the properties of the material are altered by the change in strain rate, and to show the difference between the properties of the particular sample tested and those normally quoted for the same material. However, this comparison must be made at low rates and it is not known to what extent any differences found will also exist at high rates.

All experiments were performed at a temperature of 21.6 ± 0.8°C. and a relative humidity of 65 ± 4%.

Most yarns were supplied with spinning twist and were tested in this condition; those which were originally twistless had a twist of 2 turns/cm. inserted manually prior to testing. This was to reduce premature breakage of the filaments in the yarn, which still happened in some cases. For these yarns the breaking strain was taken as that at which 50% of the filaments had broken and the breaking stress obtained by extrapolation from the point at which the first filament broke.

For the experiments on highly twisted yarns the standard rayon and nylon 100 were twisted on a small scale laboratory uptwister, and the

TABLE II
Details of Twisted Yarns

Material	Tex (nominal)	No. of filaments	No. of T/cm.	Tan θ[a]	Linear density of twisted yarn, tex
Standard rayon	27.8	50	12.1	0.866	31.4
Nylon 100	7.8	34	21.9	0.809	9.0
Medium-tenacity Terylene	11.1	48	18.0	0.718	12.1

[a] θ is angle between outside filament and yarn axis.

medium-tenacity Terylene on a laboratory twisting machine for twisting short lengths of yarn. Both machines have been shown to produce yarns having the same properties as those produced on commercial twisting machines. Details of the yarns are given in Table II.

From the mean stress-strain curve of each yarn at each rate, breaking stress and strain, energy to rupture, initial modulus, and critical velocity were determined.

Because of wave propagation effects, at high strain rates the stress-strain curve shows inflexions close to the origin. Therefore the values of initial moduli at high rate are likely to be inaccurate. To obtain the best possible estimate in these circumstances a smooth curve was fitted to the experimental values up to 4% strain using numerical analysis. The slope of this curve between 0 and 0.5% strain was taken as the initial modulus. Even so, uncertainties in the stress-strain curve near to the origin are still likely to cause considerable error in the values of initial moduli.

The energy to rupture was obtained by integrating the stress-strain curve from zero strain to the breaking point, using a planimeter. It is expressed in joules/g. (i.e., energy to rupture unit mass). This is easily converted to textile units. Dividing by 10^5 gives the energy required to break a 1 cm. length of 1 tex yarn.

When a filament is extended along its axis, strain is first experienced at the end being moved, and propagates from this point at a velocity which is a function of the slope of the stress-strain curve. If the velocity of extension is sufficiently large, strain at the end will increase more rapidly than it can be relieved by propagation along the filament, which will break with the absorption of very little energy. The velocity at which this happens is called the critical velocity. Under these conditions the length of filament suffering strain is theoretically zero, and the strain will rise instantaneously to the breaking value, the strain rate being infinite.

Calculations of critical velocity based on a stress-strain curve obtained at a finite rate of strain might therefore yield values liable to considerable error, even if the rate was as high as that used in these experiments. The

proximity of the velocity of extension to the critical value is unimportant, since any experiment in which a finite length is strained must yield a strain rate considerably below that obtained during extension at the critical velocity. However, to indicate the possible magnitude of this velocity, values have been calculated using the method given by Smith et al.[4] These must be interpreted with very great caution, intercomparison of the values for different fibers being possibly misleading.

Values have been calculated to indicate the sensitivity of the material to the change in strain rate. At a given strain the change in stress between the two rates has been expressed as a percentage of the stress at the low rate. This has been done for strains along the whole length of the stress-strain curve and the mean value determined. The quantity is strain dependent and so the mean must be regarded only as an indication of sensitivity to strain rate for intercomparison between materials, not a conversion factor between the two rates.

Other measures of sensitivity to rate which have been determined are the change in breaking strain expressed as a percentage of the strain at the low rate, and the change in energy to rupture, expressed as a percentage of the energy to rupture at the low rate.

RESULTS AND DISCUSSION

Lightly Twisted Yarns

The stress-strain curves which have been obtained are shown in Figures 1–7, and the breaking conditions, together with values indicating the sensitivity of the material to strain rate, are given in Table III. Except where otherwise stated the following discussion is confined to the properties at high rates.

Polyamide Fibers

The tenacity of nylon 900 was the greatest recorded in this series of experiments. Nylon 300 and high tenacity Enkalon are also very strong fibers. The extensibilities of nylon 6 were generally larger than for nylon 6.6, in particular that of Enkalon was exceptionally large. The values of energy to rupture of all fibers in this group were amongst the largest obtained in these experiments, even though each value was appreciably lower than the corresponding one at normal rates. The initial moduli were lower than those of other fibers of similar strength.

The energy to rupture nylon 6.6 increases with increasing tenacity, but the reverse is true for nylon 6. Similarly there is not any consistent pattern in the way the sensitivities to strain rate change with increasing tenacity. This group of fibers is unusual because of the wide variation in the sensitivity to strain rate as measured in column A of Table III.

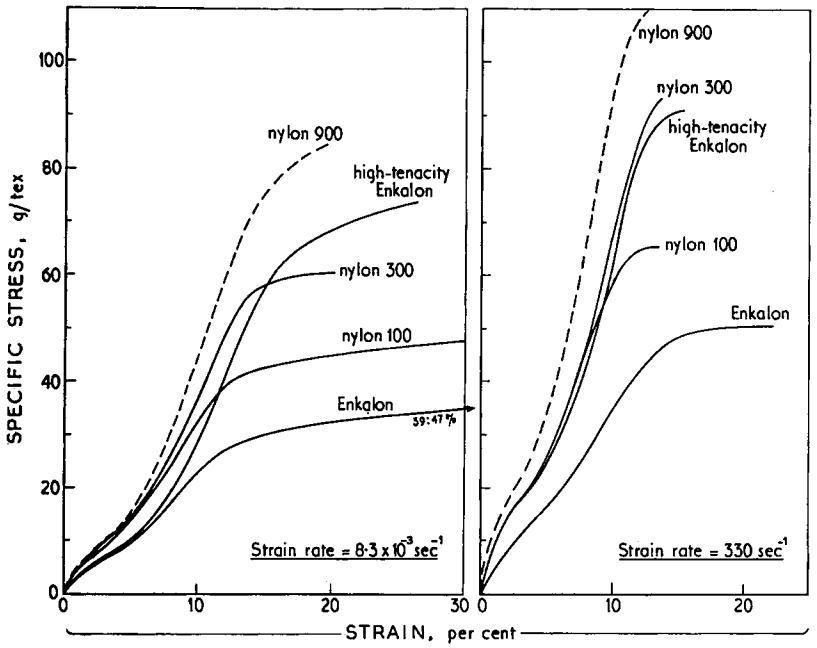

Fig. 1. Stress-strain curves of polyamide fibers.

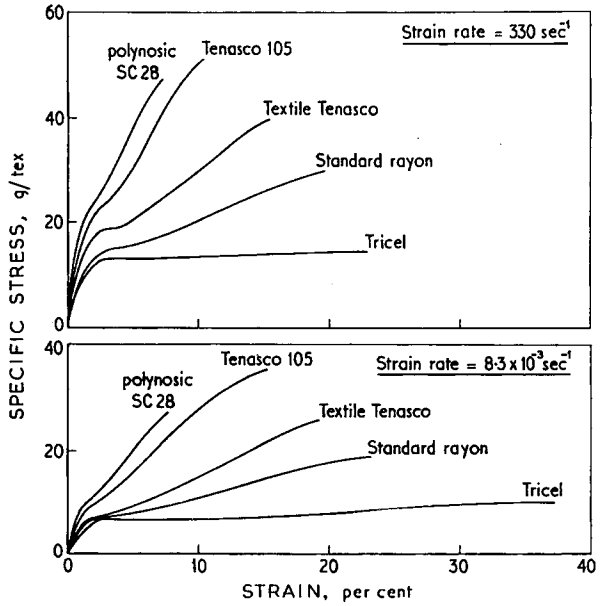

Fig. 2. Stress-strain curves of cellulosic fibers.

TABLE III
Summary of Experimental Results

Yarn	Breaking extension, %		Tenacity, g./tex		Initial modulus, g./tex		Energy to rupture, joule/g.		Critical velocity, m./sec	Sensitivity to strain rate[a]		
	8.3 × 10^{-3} sec.$^{-1}$	330 sec.$^{-1}$	8.3 × 10^{-3} sec.$^{-1}$	330 sec.$^{-1}$	8.3 × 10^{-3} sec.$^{-1}$	330 sec.$^{-1}$	8.3 × 10^{-3} sec.$^{-1}$	330 sec.$^{-1}$		A	B	C
Nylon 900	20.1	12.7	84.9	110.0	510	1900	87.1	67.5	360	142	37	−23
Nylon 300	20.5	13.8	60.6	93.1	360	700	71.7	59.7	350	89	33	−17
Nylon 100	30.4	13.7	48.2	65.4	350	1400	103.0	51.7	260	117	55	−50
H.T. Enkalon	26.8	15.3	73.9	90.8	320	1500	88.0	56.5	290	153	43	−36
Enkalon	46.8	22.1	38.9	50.4	240	500	132.0	71.7	350	69	53	−46
Tenasco 105	15.2	10.5	35.6	50.5	900	1800	29.8	32.8	190	99	31	+10
Textile Tenasco	19.2	15.5	26.1	39.5	730	1700	28.1	39.1	220	115	19	+39
Standard rayon	23.2	19.6	18.9	29.8	490	1200	27.8	38.9	210	90	16	+40
Polynosic S.C. 28	7.7	7.0	27.5	46.3	1040	2300	12.2	20.2	180	101	9	+66
Tricel	37.1	23.0	10.4	14.6	340	1200	29.4	29.8	110	99	16	+1.4
Ulstron	19.7	14.6	78.9	82.8	1080	1100	98.5	75.9	270	22	26	−23
Polypropylene Multifil	54.0	16.5	43.0	65.1	610	1100	193.0	69.8	300	76	70	−64
Polyethylene Multifil	23.8	7.4	39.9	69.8	770	1200	76.3	27.8	220	114	64	−64
Courlene X3	19.7	7.5	37.4	63.0	640	1300	57.6	25.7	210	121	62	−55
H.T. Terylene	12.8	7.3	60.8	77.7	1290	2000	54.5	34.4	220	57	75	−37
M.T. Terylene	31.0	17.6	41.4	43.9	900	1900	98.0	67.5	150	52	43	−31
Courtelle	33.9	22.1	25.0	27.4	530	1400	47.3	49.4	170	119	35	+4.4
Acrilan-16	40.9	29.2	20.9	28.6	490	900	57.5	65.6	210	85	19	+14
B.H.S.	17.8	15.7	39.6	54.8	570	1500	31.3	46.1	280	109	12	+47
Aeress	24.1	18.7	21.2	36.8	640	1300	31.5	48.1	210	127	22	+53
Human hair	50.4	41.9	17.1	20.9	380	600	52.2	60.4	250	61	17	+16
Silk	16.2	16.7	31.6	47.8	550	1500	35.1	61.8	230	80	−3.1	+76
Saran 3:1 draw ratio	66.9	18.4	9.6	16.8	70	500	50.3	20.9	170	226	73	−59
Saran 3.6:1 draw ratio	15.2	13.1	15.2	26.8	73	400	11.5	19.3	180	227	14	+68
Vinal F.O.	13.9	10.8	58.4	85.0	1440	4100	41.5	53.6	290	129	22	+29

[a] If t_h were the stress at a given strain at the high rate; t_n were the stress at the same strain at the normal rate; e_h were the breaking strain at the high rate; e_n were the breaking strain at the normal rate; E_h were the energy to rupture at the high rate; and E_n were the energy to rupture at the normal rate; then Column A = $100(t_h - t_n)/t_n$ averaged over the whole curve, Column B = $100(e_n - e_h)/e_n$, and Column C = $100(E_h - E_n)/E_n$.

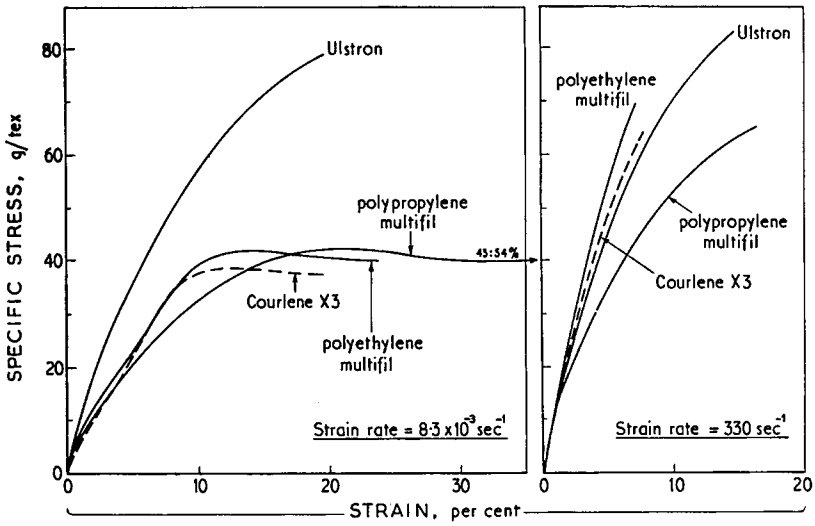

Fig. 3. Stress-strain curves of polyolefin fibers.

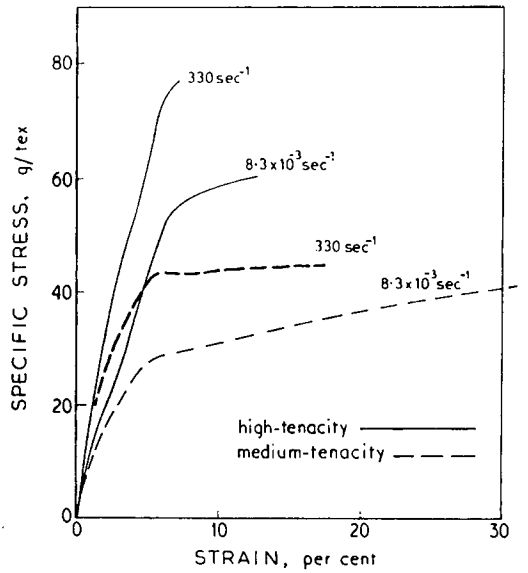

Fig. 4. Stress-strain curves of Terylene.

Cellulosic Fibers

The only noteworthy properties of this group are the high extensibilities of the Tricel and standard rayon and the high initial modulus of the polynosic and Tenasco yarns. Although the energy to rupture is in each case greater at the high rate than at the low, the highest value for this group is still lower than the lowest for the nylons. The sample of Tenasco 105

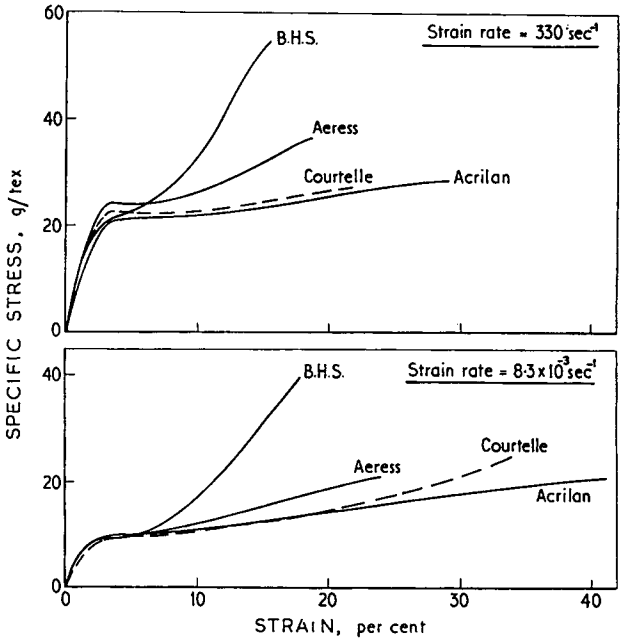

Fig. 5. Stress-strain curves of acrylic fibers.

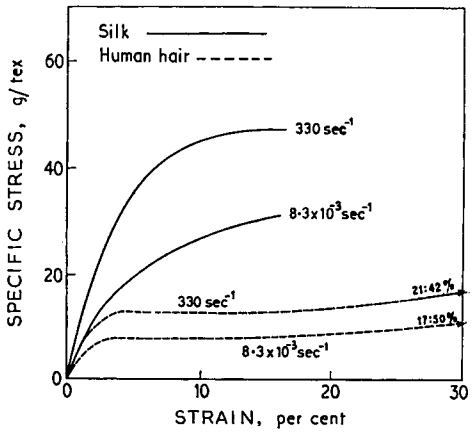

Fig. 6. Stress-strain curves of natural fibers.

which was tested had a rather lower tenacity at normal rates than the values which are usually quoted for this fiber. However, even if this is taken into account, the tenacity and energy to rupture are still inferior to those of the high tenacity nylons.

There is no consistent pattern in the way the sensitivities to strain rate change with increasing tenacity. The breaking strains of this group of fibers are less affected by the change in strain rate than most of those tested (Column B, Table III).

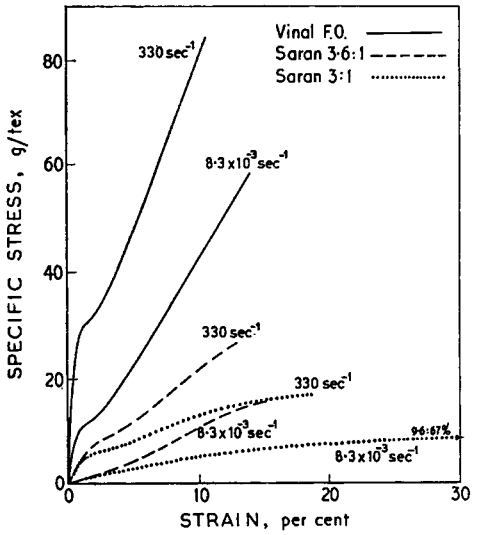

Fig. 7. Stress-strain curves of polyvinyl alcohol and polyvinylidine chloride fibers.

Polyolefin Fibers

Ulstron, at normal rates, is exceptionally strong, but because its sensitivity to strain rate, as measured in Column A of Table III, is extremely small it does not maintain this advantage at high rates. The extension at break of polyethylene is small, even though it is fairly large at normal rates. This might possibly be related to the low melting point of the polymer, for there is a rise in temperature during extension at high rates and while this is unlikely to cause melting[7] it might precipitate the fracture of a low melting point material. The energy to rupture of all the fibers in this group decreases with increasing rate, but even so the polypropylenes have some of the highest values obtained for this property.

Polyester Fibers

The value of energy to rupture for the medium tenacity Terylene is among the highest obtained for the fibers tested in this experiment, even though it is decreasing with increasing strain rate. The value for the high tenacity is, however, very low, a consequence of its low extension at break. Both fibers have high initial moduli.

Acrylic Fibers

The breaking extensions of both Courtelle and Acrilan, especially the latter, are larger than those of most of the fibers included in these experiments. The energy to rupture Acrilan is also fairly large.

Natural Fibers

Human hair has an extremely high extension at break, much higher than that of any other fiber tested in this series of experiments. The energy to

rupture is also fairly high. Silk is unusual in that it is the only material for which the breaking extension was found to be greater at high rates than at normal.

Polyvinylidene Chloride Fibers

These are low strength fibers, and at high rates are not very extensible. Initial modulus and energy to rupture are low. They are unusual in that the energy to rupture decreases with increasing strain rate for the 3:1 draw ratio sample but increases for the other. For all other materials tested in this series of experiments the change in the energy to rupture with change in rate has always been in the same direction for all members of a given group of fibers.

Polyvinyl Alcohol Fibers

The value of the initial modulus of this fiber was much greater than that found for any other material. The tenacity was also high.

Comparison with Results of Smith et al.[3,8]

As stated in the Introduction a comparable study has been made by Smith et al., and the results of this work will now be compared with those reported here. However, certain differences must be borne in mind in making this comparison in particular cases.

(*1*) The samples used in the work reported here were obtained from different manufacturers from those used by Smith et al. In no case is it possible to make a direct comparison between two nominally identical samples. In only one case (the textile Tenasco included in this paper and the rayon tire yarn tested by Smith et al.) were there two materials with similar properties at normal rates.

(*2*) The maximum strain rate used by Smith et al. was about a decade slower than the higher of the two rates used in the present experiments, and varied with strain. Thus, although experimental conditions are similar they are not identical.

(*3*) In the experiments of Smith et al. at high rates the temperature and relative humidity were not controlled, and at low rates they were controlled at values different from those used in this work.

In every case the change in properties of comparable samples with increasing rate was in the same direction in this work as in the experiments of Smith et al., but there were differences in magnitude. However, with the exception of initial moduli, these were not systematic and so most likely reflect differences in the materials being compared rather than in experimental technique. The initial moduli at high rates were very much greater in every case in the results reported here. These are however the least accurate measurements and stress pulse propagation effects might possibly cause over-estimation.

The only important differences in conclusions concern the relative merits of polyamide and cellulosic fibers, and the performance of polyester fibers at high rates. In this work the polyamides tested were in every case stronger than the cellulosics, with a higher energy to rupture, and this was true at both rates, whereas some of the cellulosics tested by Smith et al. had a higher value of energy to rupture at the highest rate than the one sample of nylon included in their experiments. The value of energy to rupture for the medium tenacity Terylene was among the highest obtained in the present experiments, whereas Smith et al. obtained a low value for a medium tenacity polyester. However, this could be caused by differences in the materials, since the results reported here show that the value of energy to rupture for Terylene decreases greatly with increase in tenacity.

Highly Twisted Yarns

The stress-strain curves which have been obtained for the highly twisted yarns are plotted in Figures 8–10, with the theoretical curves, calculated from the data for the lightly twisted yarn at the appropriate rate, shown in the same figure. The breaking properties are summarised in Table IV.

From Figures 8–10 it will be seen that for each yarn agreement between experiment and theory is poor at the high rate, the ordinates of the theoretical curve being greater than the experimental. Although for the nylon and viscose yarn agreement is much better at normal rates the theory still does not predict the exact shape of the stress-strain curve. In each case the theoretical curve rises more steeply than the experimental, and then falls to a lower slope so that the curves cross. This behavior confirms that

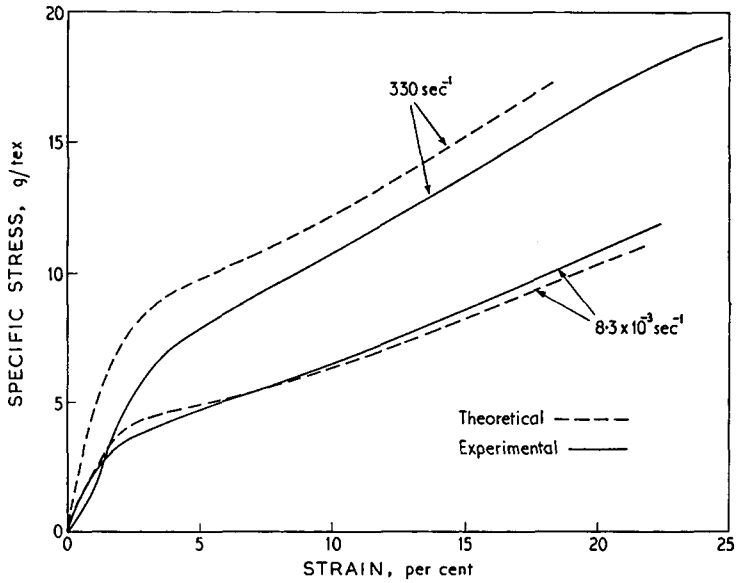

Fig. 8. Stress-strain curves of standard rayon twisted yarn.

TABLE IV
Summary of Breaking Properties of Twisted Yarns

Material	Tenacity g./tex		Breaking extension, %		Energy to rupture, joule/g.		Initial modulus, g./tex		Critical velocity, m./sec.
	330 sec.$^{-1}$	8.3×10^{-3} sec.$^{-1}$	330 sec.$^{-1}$	8.3×10^{-3} sec.$^{-1}$	330 sec.$^{-1}$	8.3×10^{-3} sec.$^{-1}$	330 sec.$^{-1}$	8.3×10^{-3} sec.$^{-1}$	
Standard rayon twisted	19.0	11.8	24.8	22.4	28.8	15.5	200	250	210
Standard rayon untwisted	29.8	18.9	19.6	23.2	38.9	27.8	1200	490	210
Nylon 100 twisted	42.1	39.1	21.1	38.0	48.4	90.0	300	160	300
Nylon 100 untwisted	65.4	48.2	13.7	30.4	51.7	103.0	1400	350	260
M.T. Terylene twisted	33.5	34.8	18.9	40.5	45.8	97.8	900	340	230
M.T. Terylene untwisted	55.4	41.4	17.6	31.0	83.4	98.0	2400	900	190

TABLE V
Percentage Change in Tensile Properties on Twisting

Material	Tenacity		Breaking extension		Energy to rupture		Initial modulus	
	330 sec.$^{-1}$	8.3×10^{-3} sec.$^{-1}$	330 sec.$^{-1}$	8.3×10^{-3} sec.$^{-1}$	330 sec.$^{-1}$	8.3×10^{-3} sec.$^{-1}$	330 sec.$^{-1}$	8.3×10^{-3} sec.$^{-1}$
Standard rayon	−36	−38	+27	−3	−26	−44	−80	−50
Nylon 100	−36	−19	+54	+25	−6	−13	−80	−27
M.T. Terylene	−26	−16	+7	+31	−32	0	−51	−62

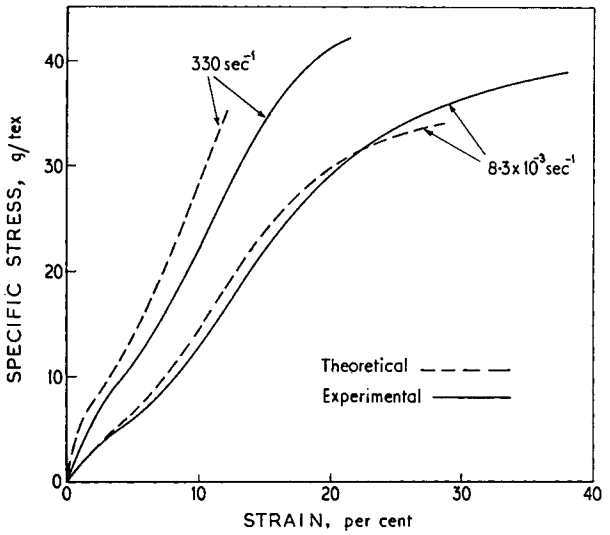

Fig. 9. Stress-strain curves of nylon 100 twisted yarn.

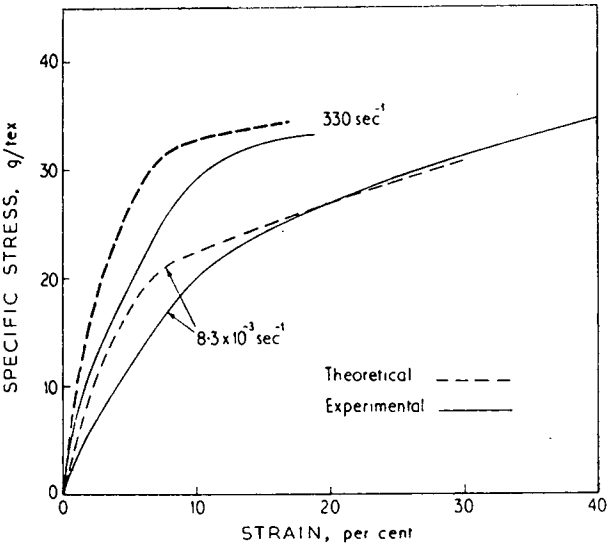

Fig. 10. Stress-strain curves of medium-tenacity Terylene twisted yarn.

already found by Treloar and Riding.[6,9] To look for similarities in the deviation between theory and experiment at both rates, in Figure 11 the difference between the theoretical and experimental curves, expressed as a percentage of the experimental stress at the same strain, has been plotted against the strain. This has been done for both strain rates for each material.

It will be seen that in each case, for strains above 3%, the deviation varies with strain in the same manner at both rates, the magnitude being

greater at the high rate. Figure 12, in which the deviation at normal rates is plotted against that at high rates, confirms this relationship between them. This would suggest that factors which might be expected to arise solely at high rates, such as heating of the yarn by inter-fiber friction or a

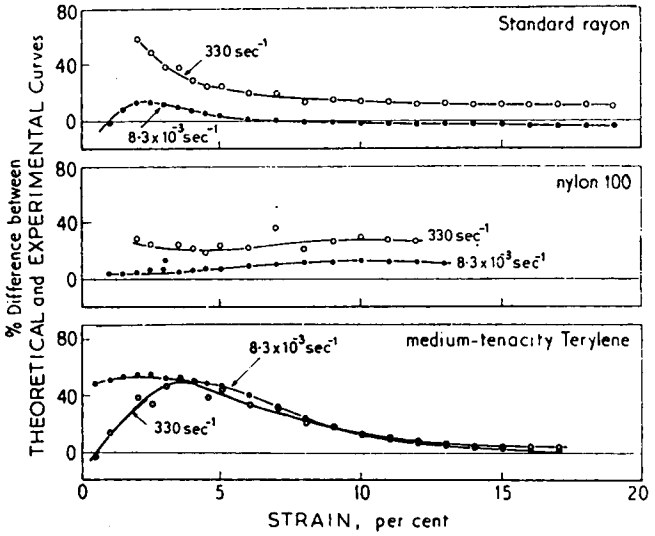

Fig. 11. Strain dependence of difference between theory and experiment.

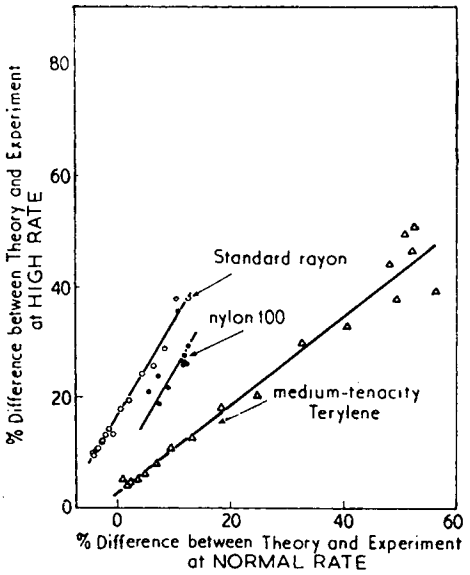

Fig. 12. Relationship between deviations of theory from experiment at normal and high rates.

different repacking of the filaments in the yarn during extension, are unlikely to be the cause of the discrepancy. It is far more likely that the cause of the disagreement at high rates is the same as that which causes the smaller, but systematic, difference at normal rates.

It would appear from the above that for reasons not understood at present the theory cannot be used at high rates without incurring considerable error, but even this conclusion should be treated with caution. In the theory the yarn is regarded as a continuum, the surface being cylindrical. The number of filaments (about 50) in the yarns used in these experiments is rather small for the strict application of this type of theory, and is a possible source of error. However, the results at low rates are confirmed by those of Treloar and Riding,[6,9] who used yarns containing many more filaments, and the relationship between the deviations at low and high rates has been demonstrated in Figures 11 and 12. This would not therefore seem to be a very likely explanation.

From Table IV it will be seen that, with the exception of standard rayon at the normal rate, the breaking extension is always greater in the twisted state, all the other properties being smaller. The magnitudes of the changes are considered in Table V and it will be seen that these vary with both rate and material, and are sufficiently large to alter the ranking of some of the properties. At high rates medium tenacity Terylene has the greatest energy to rupture of the three materials, but in the twisted state it is inferior in this respect to nylon 100. Terylene is also more extensible than nylon 100, but in the twisted state this situation is reversed.

CONCLUSIONS

For the lightly twisted yarns, in all cases the tenacity increases as strain rate is increased from normal to high rates, and with the exception of silk the extension at break decreases. The energy to rupture can either increase or decrease but with the exception of polyvinylidene chloride it has always been found to change in the same direction for all members of a given group of fibers. Apart from the above-mentioned exception it decreased with increasing rate for the thermoplastic fibers and increased for the wet-spun and natural fibers. It is not possible to put forward a reason for this at present but it might be related to the fact that the temperature of the test piece will rise during rapid extension and this is more likely to cause softening and precipitate fracture in a thermoplastic fiber. Despite this decrease the strong thermoplastic fibers had the highest energies to rupture at ballistic rates.

This is the most detailed pattern of behavior it is possible to fit to the results. The magnitudes by which the various properties of a fiber change as the strain rate is increased do not correlate with each other, or with the magnitudes of the changes in similar properties of different members of the same group of fibers. It is not possible therefore to predict the properties of a given fiber at high rates from a knowledge of the same

properties at normal rates and the way they change with increasing rate in other similar fibers. This also illustrates the difficulties of explaining the changes in terms of the physical and chemical structure of the fiber.

The choice of a fiber for a particular use will depend upon the important qualities required in that application. To assist selection, the five fibers having the maximum values of tenacity, energy to rupture, extension at break and initial modulus have been listed in Table VI. It will be seen from this table that the ranking of the fibers changes considerably between the different rates, and this emphasises the importance of testing at a comparable rate to that which will be encountered in use.

TABLE VI
The Five Fibers Having Maximum Values for Certain Properties

Properties	330 sec.$^{-1}$		8.3×10^{-3} sec.$^{-1}$	
Tenacity, g./tex	Nylon 900	110.0	Nylon 900	84.9
	Nylon 300	93.1	Ulstron	78.9
	H.T. Enkalon	90.8	H.T. Enkalon	73.9
	Vinal F.O.	85.0	H.T. Terylene	60.8
	Ulstron	82.8	Nylon 300	60.6
Extension at break, %	Human hair	41.9	Saran 3:1	66.9
	Acrilan-16	29.2	Polyprop. Mult.	54.0
	Tricel	23.0	Human hair	50.4
	Courtelle	22.1	Enkalon	46.8
	Enkalon	22.1	Acrilan-16	40.9
Energy to rupture, joules/g.	Ulstron	75.9	Polypropy. Mult.	193.0
	Enkalon	71.7	Enkalon	132.0
	Polypropy. Mult.	69.8	Nylon 100	103.0
	Nylon 900	67.5	Ulstron	98.5
	M.T. Terylene	67.5	M.T. Terylene	98.0
Initial modulus, g./tex.	Vinal F.O.	4100	Vinal F.O.	1440
	Polynosic S.C. 28	2300	H.T. Terylene	1290
	H.T. Terylene	2000	Ulstron	1080
	Nylon 900	1900	Polynosic S.C. 28	1040
	M.T. Terylene	1900	Tenasco 105	900

The results are in broad agreement with those reported by Smith et al.,[3,4] the most serious discrepancy being the change in the relative merits of nylon and cellulosic fibers between the two experiments. In no instance was an identical type of yarn from the same manufacturer used in each experiment, and so it is not possible to decide whether the differences which have been found arise from differences in material or experimental technique. In so far as differences are not systematic it would indicate the former to be the most likely explanation. The only systematic difference found is in the values of initial modulus which in every case are very much higher in the experiments reported here. There are however the least accurate measurements, and stress-pulse propagation effects at high speeds of extension might cause over-estimation.

The short study of highly twisted yarns was only intended as a preliminary survey to indicate whether conclusions from experiments on materials were a reliable guide to assist selection of the most suitable of these for use in twisted yarns. It has shown that they are not, and could be misleading.

The systematic deviation of the theory of Treloar and Riding[6] from experimental data is small enough to be unimportant at normal rates of testing for nylon and viscose yarn, but increases with rate to such an extent that there is appreciably larger disagreement at high rates. The cause of this is not understood at present.

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Résumé

Des courbes tension-élongation ont été déterminées à une vitesse d'élongation très élevée (330 sec^{-1}) et à une vitesse normale (8.3×10^{-3} sec^{-1}) pour une série de fibres légèrement tordues couvrant tous les polymères pouvant former des fibres et ayant une importance commerciale. A partir de ces courbes on a pu obtenir la force de rupture et d'extension, l'énergie de rupture, le module initial et la vitesse critique. On présente les résultats en détails en vue de faciliter la sélection des fibres pour des applications ou une extension rapide désirée. A vitesse élevée la force de rupture est toujours plus grande et, à une exception près, l'extension à la rupture moindre qu'aux vitesses normales. L'énergie à la rupture augmente avec la vitesse pour les fibres humides et, à une exception près, diminue pour le thermoplastique. La variation de grandeur de ces changements est considérable, même parmi les fibres provenant de la même base polymérique, ce qui met en évidence l'importance de l'essai à une vitesse comparable à celle rencontrée lors de l'emploi. Des expériences semblables effectuées sur trois des fibres fortement torsadées, montrent que l'arrangement des fibres conformément à une propriété particulière peut être altéré par l'insertion de torsade. Les courbes tension-élongation du matériau de base ont été utilisées pour prévoir les courbes pour la fibre torsadée, suivant une théorie de Treloar et Riding. A la vitesse normale, l'accord avec l'expérience est bon, mais il est beaucoup plus mauvais à la vitesse élevée.

Zusammenfassung

Spannungs-Dehnungskurven wurden bei sehr hoher (330 sec^{-1}) und bei normaler ($8{,}3.10^{-3}$ sec^{-1}) Dehnungsgeschwindigkeit an einer Reihe schwach gezwirnter, alle technisch wichtigen faserbildenden Polymeren umfassenden Garne bestimmt. Aus

diesen Kurven wurden Bruchspannung und -dehnung, Reissenergie, Anfangswert des Moduls und kritische Geschwindigkeit erhalten. Die Ergebnisse werden im einzelnen angeführt, um eine Auswahl von Fasern für Anwendungen, die zu rascher Dehnung führen können, zu erleichtern. Bei hoher Geschwindigkeit ist die Bruchspannung immer grösser und die Bruchdehnung, mit einer Ausnahme, geringer als bei normaler Geschwindigkeit. Die Reissenergie nimmt bei nassgesponnen Fasern mit der Geschwindigkeit zu und bei thermoplastischen, mit einer Ausnahme, ab. Die Unterschiede in der Grösse dieser Änderungen sind sogar bei Fasern auf gleicher Polymerbasis beträchtlich, was die Wichtigkeit einer Testung bei einer Geschwindigkeit, die der bei der Verwendung auftretenden entspricht, beweist. Ähnliche Versuche an drei stark gezwirnten Garnen zeigten, dass die Einstufung der Garne nach einer bestimmten Eigenschaft durch Einführung einer Verzwirnung geändert werden kann. Die Spannungs-Dehnungskurven eines Stoffes wurden gemäss einer Theorie von Treloar und Riding zur Voraussage der Kurve für das gezwirnte Garn benützt. Bei normaler Geschwindigkeit war die Uebereinstimmung mit dem Experiment recht gut, bei der hohen Geschwindigkeit jedoch bedeutend schlechter.