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Bulk Resistance to Compression as a Measure of the Crimp of Staple Synthetic Fibres

by

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BULK RESISTANCE TO COMPRESSION AS A MEASURE OF THE CRIMP OF STAPLE SYNTHETIC FIBRES

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ABSTRACT

The use of the bulk resistance to compression of a randomised fibrous assembly, determined on a SAWTRI Compressibility Tester, as a measure of the crimp of staple synthetic fibres (mainly polyester), has been investigated. It was found that the bulk resistance to compression values were highly correlated ($r \approx 0,87$) with the single fibre uncrimping force and uncrimping energy as measured on an Instron Tensile tester. As in the case of wool, bulk resistance to compression was fairly highly correlated with the product of staple crimp and fibre linear density. When the results obtained on the different types of synthetic fibre were pooled, it was found that bulk resistance to compression was a function of fibre crimp, linear density and initial (pre-yield) modulus, the latter representing a measure of fibre bending stiffness. It is concluded that bulk resistance to compression provides a useful measure of polyester fibre crimp and possibly also of other synthetic fibres, provided possible variations in fibre fineness and bending stiffness are taken into consideration.

INTRODUCTION

It is generally accepted[1-30] that fibre crimp plays an important role in determining the processing performance of the fibre and the properties of the subsequent yarn and end product, whether the latter be fabric, carpet or filler. In many instances, some degree of fibre crimp adds to the textile performance of the fibre and to the aesthetic, comfort and even certain technical attributes of a textile product and this is the reason for synthetic fibre manufacturers imparting crimp, in one form or another, to their fibres[5, 8, 15]. Having accepted the importance of fibre crimp, the question arises as to the best way of measuring it quickly and accurately on a routine basis in a quality control or research laboratory.

Although various methods exist for determining fibre crimp, most of these involve tests on the single fibres which generally tend to be cumbersome and time consuming. In one proposed method drafting force is used as an indirect measure of crimp[30]. In the case of wool, considerable research effort has been directed towards both the measurement of fibre crimp and the establishment of its importance from a textile point of view. From these studies it was concluded[14] that the bulk or resistance to compression (sometimes referred to as compressibility or bulk resistance to compression) of a randomised fibrous mass provides a fairly accurate measure of fibre crimp and is far simpler and quicker than other methods of determining fibre crimp, particularly on scoured wool and tops. It has also been suggested that, for wool, the bulk/diameter ratio[31] is another fairly good measure of the overall fibre crimp. Van Wyk[32, 33] in 1946 well laid the theoretical foundation for understanding the behaviour of a randomised mass of fibre subjected to bulk compression. Although certain refinements to his work have been proposed[34−39] it is not intended to discuss here the theoretical aspects of bulk resistance to compression.

In the light of the potential use of resistance to compression as a quick and easy measure of fibre crimp, it was decided to investigate the application of the SAWTRI Compressibility Tester, developed for the routine measurement of wool bulk resistance to compression[40−42], to the measurement of the bulk resistance to compression of synthetic fibres with a view to using the results as a measure of fibre crimp.

EXPERIMENTAL

A total of 45 polyester (7 high tenacity, 27 medium tenacity and 11 low tenacity), 12 nylon, 12 acrylic and 3 polypropylene staple fibre samples were tested. Most of the samples were still in staple (i.e. unprocessed) form, the others being in top form.

The following tests were carried out on the samples, all tests being carried out under standard (20 ± 2°C and 65 ± 2% RH) atmoshperic conditions.

Diameter

Fibre diameter was measured on a projection microscope, two operators each reading more than 50 fibre snippets on each of three slides (i.e. a total of at least 300 readings per sample).

Vibroscope Fineness

Fibre linear density was measured on a vibroscope (Zweigle Vibroskop S151/2) according to a method similar to ASTM D1577-79, using the *maximum* tension at which a reading could be obtained. This ensured the smallest error in the measurement of the fibre linear density due to any crimp remaining in the fibre.

Staple Crimp

Thirty staples were selected at random from each sample and the crimp frequency determined over 25 mm on the unrestrained (relaxed) staples, by each of three operators using a counting glass.

Single Fibre Crimp Frequency

The crimp frequency (%) was determined on single fibres according to the ASTM-D3937-80 method, the crimp frequency being the number of crimp units divided by the extended length. The number of crimps per unit length was measured on ten fibres, in a slightly stretched state, each of the fibres being drawn from a different staple.

Percentage Crimped Length

Another measure of fibre crimp, termed crimped length (%), was obtained by measuring the unstretched length of ten staples and then the straightened length of two fibres from each staple. The percentage crimped length was calculated as follows:

$$\text{Crimped Length (\%)} = 100 \times \frac{(\text{Straightened Fibre Length} - \text{Staple Length})}{\text{Straightened Fibre Length}}$$

Single Fibre Uncrimping Force and Energy

Uncrimping force and uncrimping energy were measured, on an Instron Tensile Tester, on single fibres. Because these tests are time consuming only a selected number of samples were tested.

A number of staples were randomly selected from each sample, hand carded and left to condition overnight at 65% RH/20° C. This procedure was required so as to obtain fibres for testing which were in a state similar to that on which the bulk resistance to compression was obtained. From each of these prepared samples, twenty fibres were taken and tested on an Instron tensile tester by two operators (10 fibres each)[43].

The fibres were mounted between plug type jaws, under a pre-tension of 0,03 cN/tex, so that the *uncrimped* fibre length between the jaws would be approximately 20 mm . The starting position on the chart was marked and the fibre extended at a rate of 20 mm/min, using a sensitive load scale (1, 2 or 5cN full scale depending on the fibre linear density) and a high chart speed, until the fibre had been extended to just beyond the estimated uncrimping force. Both the crosshead and recorder pen were then immediately returned to their original positions (i.e. fibre slack) and thereafter the fibre was immediately extended at the same rate, using the same chart speed as before and an appropriate full scale, until the fibre broke. The method is illustrated in Fig. 1. The fibre length at the *uncrimping load* (the uncrimping load being that force reading on the load-extension curve which lies perpendicularly above the intercept of the "pre-yield" slope and the extension axis) was determined. This was required to calculate the extension at break (in %), the initial (pre-yield) modulus, the crimp (in %) and the uncrimping energy at both one fifth and one tenth of the uncrimping force (it being *assumed* that at the uncrimping force the fibre is fully straightened). The breaking strength was read from the graph and the tenacity calculated.

Bulk Resistance to Compression

The bulk resistance to compression of a randomised 2,5 g fibre sample was measured on a SAWTRI Compressibility Tester (see Figs 2 and 3), following the procedure adopted for wool[40-42] except that the fibres were not steamed or otherwise relaxed or oven dried prior to conditioning and testing.

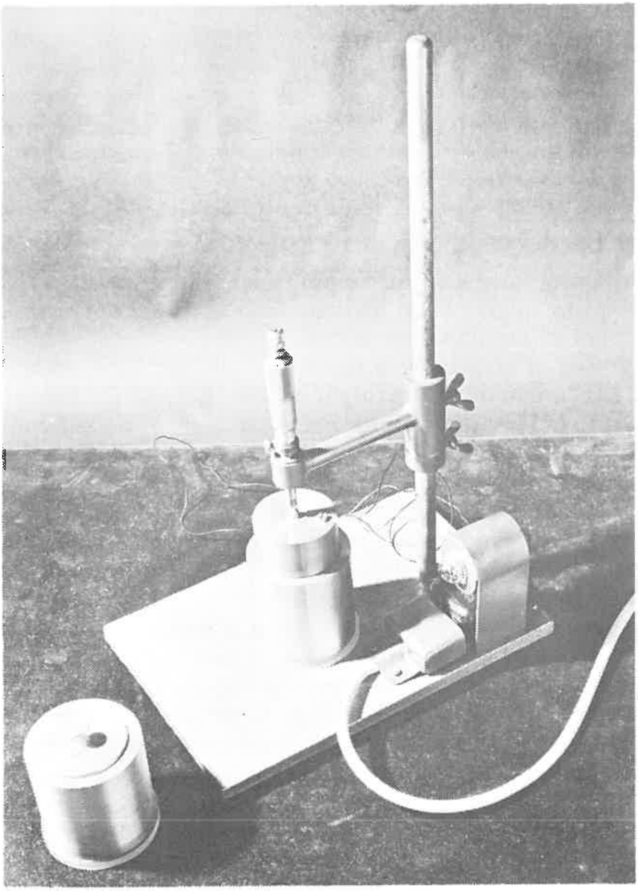


Fig. 2 – Photograph of SAWTRI Compressibility Tester.

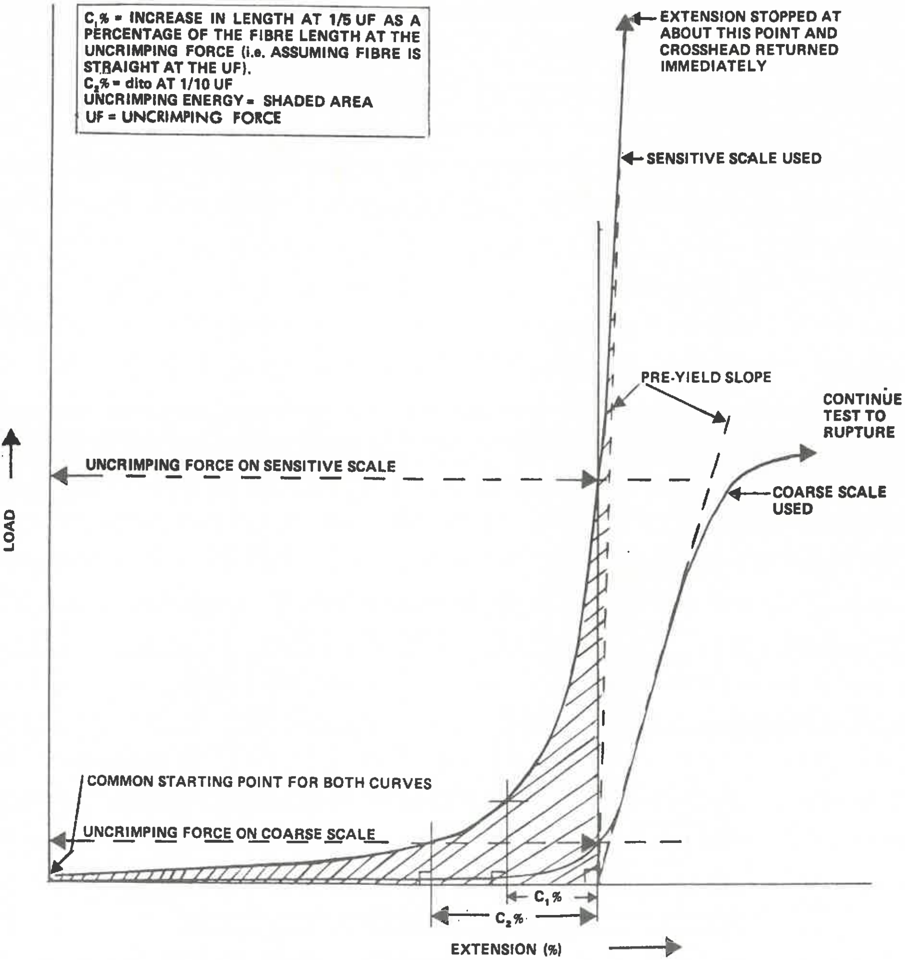
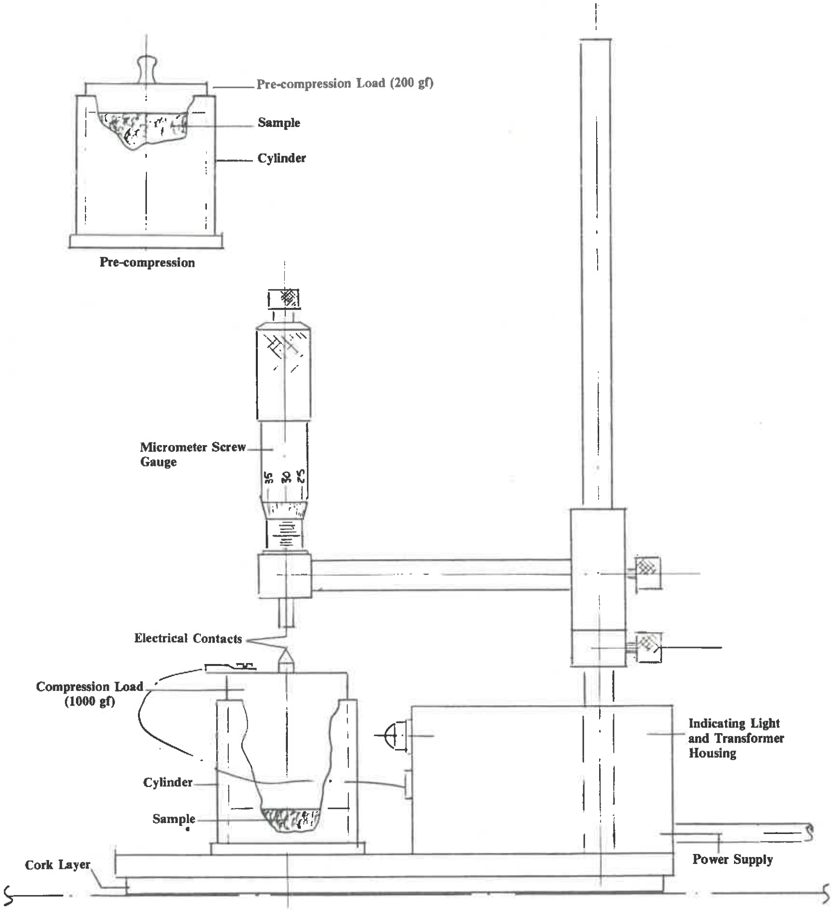


Fig. 1 – Load-extension Diagram to illustrate the Method used to Determine the Crimp Parameters.



Testing after Pre-compression

Fig. 3 – Diagram of SAWTRI Compressibility Tester.

RESULTS AND DISCUSSION

Because of the large number of results involved, the individual values have not been incorporated in this report, only the average values being shown in Table I.

Both quadratic (results in their standard form) and log-log regression analyses were carried out on the data. The forward selection procedure was followed with significance being tested at the 95% ($p = 0,05$) level. It was found that the two types of regression analyses generally provided equations which fitted the data equally well and it was decided therefore to report only the results of the log-log analyses.

Simple Correlations

The simple correlation coefficients (log-log analysis) between the various *polyester* fibre properties are given in Table II. According to this table, very high correlations ($r \approx 0,9$) were obtained between the uncrimping force (X_7) and either fibre linear density (X_2) or fibre diameter (X_1) and also between the variables X_9 to X_{12}, the latter being four measures of single fibre crimp obtained on the Instron.

Bulk resistance to compression (Y_1) correlated similarly (r varied from 0,85 to 0,91) with the four measures of fibre crimp (X_9 to X_{12}) obtained on the Instron and referred to above, but was generally poorly correlated with the other measures of fibre crimp investigated. It is interesting to note that the staple crimp (X_4) was negatively correlated with the fibre diameter (or linear density) as is generally the case with wool. Fig. 4 shows staple crimp plotted against fibre linear density, the Duerden[44] "average" line for wool being superimposed. This figure shows that, for the relatively fine fibres, synthetic fibre manufacturers insert crimp frequencies similar to those found in Duerden type wools whereas for coarser fibres they insert higher crimp frequencies.

Multiple Regression Analyses

The next step in this investigation was to determine the correlation between bulk resistance to compression and various combinations of the fibre crimp and fineness parameters. To this end, multiple regression analyses were carried out and the results obtained are summarised in Table III. From this table it is apparent that, for the polyester results on their own, the highest correlations were obtained between bulk resistance to compression and either a combination of fibre linear density (X_2) and staple crimp (X_4) or a measure of fibre crimp in terms of either uncrimping force (X_9 or X_{10}) or uncrimping energy (X_{11} or X_{12}). It is worth noting that in the case of wool, bulk resistance to compression is also generally best correlated with the product of fibre diameter and staple

TABLE I

AVERAGE FIBRE PROPERTIES

FIBRE PROPERTIES	POLYESTER				Nylon	Acrylic	Polypro-pylene
	High Tenacity	Medium Tenacity	Low Tenacity	Overall Mean			
Approx. No. of Samples	7	27	11	45	12	12	3
Resistance to Compression							
Mean (mm)	23,8	24,3	19,4	23,1	14,3	22,9	23,9
CV %	11	15	24	19	10	12	17
Fibre Diameter							
Mean (μm)	13,7	18,8	20,7	18,5	34,4	26,1	32,8
CV %	35	42	34	41	28	23	33
Linear Density							
Mean (dtex)	2,39	4,71	4,59	4,34	10,9	4,27	8,9
CV %	78	96	52	89	49	69	70
Initial Pre-yield Modulus							
Mean (cN/tex)	377	341	313	340	101	436*	187
CV %	16	17	28	20	54	0	9
Staple Crimp							
Mean (cm^{-1})	6,3	5,4	5,1	5,5	5,5	5,2	4,4
CV %	12	18	22	19	14	22	4
Crimp Frequency Percentage							
Mean	41	42	40	41	47	46	52
CV %	17	25	17	25	17	25	52
Crimped Length							
Mean (%)	39	34	35	35	28	23	26
CV %	8	17	15	16	21	26	31
Uncrimping Force							
Mean (cN)	0,278	0,519	0,386	0,444	0,456	0,377*	0,488
CV %	62	95	60	91	50	42	33
Uncrimping Stress							
Mean (cN/tex)	1,253	1,004	0,847	1,004	0,458	0,878*	0,634
CV %	22	10	17	20	22	2	8
Crimp at 0,2 x Uncrimping Force							
Mean (%)	1,91	2,49	2,25	2,33	3,92	1,33*	2,71
CV %	34	27	42	33	37	3	26
Crimp at 0,1 x Uncrimping Force							
Mean (%)	3,76	5,04	4,38	4,66	6,76	2,68*	4,94
CV %	34	26	46	34	38	2	28
Uncrimping Energy at 0,2 x Uncrimping Force							
Mean	0,024	0,025	0,019	0,023	0,018	0,012*	0,017
CV %	28	31	43	34	39	4	33
Uncrimping Energy at 0,1 x Uncrimping Force							
Mean	0,046	0,050	0,037	0,046	0,031	0,023*	0,032
CV %	27	29	44	34	40	3	35
Product of Staple Crimp and Linear Density							
Mean (cm^{-1} x dtex)	14,3	22,4	26,1	21,6	65,4	21,3	48,3
CV %	63	67	46	65	32	51	56

* Only 2 samples tested

TABLE II

SIMPLE CORRELATION COEFFICIENTS* FOR POLYESTER SAMPLES

	Y_1	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}	X_{12}
Y_1	1,000	0,515	0,509	-0,391	-0,269	-0,133	0,073	0,613	0,296	0,846	0,863	0,886	0,905
X_1		1,000	0,993	-0,592	-0,800	-0,503	-0,251	0,968	-0,350	0,711	0,668	0,464	0,449
X_2			1,000	-0,591	-0,801	-0,520	-0,231	0,973	-0,357	0,717	0,677	0,466	0,453
X_3				1,000	0,324	0,092	-0,063	-0,583	0,176	-0,673	-0,569	-0,529	-0,439
X_4					1,000	0,653	0,260	-0,759	0,454	-0,495	-0,510	-0,256	-0,296
X_5						1,000	0,149	-0,518	0,183	-0,163	-0,149	-0,029	-0,029
X_6							1,000	-0,175	0,259	-0,067	-0,080	0,132	0,111
X_7								1,000	-0,134	0,760	0,722	0,609	0,591
X_8									1,000	-0,003	0,014	0,468	0,452
X_9										1,000	0,985	0,881	0,880
X_{10}											1,000	0,873	0,897
X_{11}												1,000	0,988
X_{12}													1,000

* Log-log analysis ($n \approx 35$)

Y_1 = Resistance to Compression (mm)
X_1 = Fibre diameter (μm)
X_2 = Actual Linear Density (dtex)
X_3 = Initial Pre-yield Modulus (cN/tex)
X_4 = Staple Crimp (cm^{-1})
X_5 = Crimp Frequency Percentage
X_6 = Crimped Length (%)
X_7 = Uncrimping Force (cN)
X_8 = Uncrimping Stress (cN/tex)
X_9 = Crimp at 0,2 x Uncrimping Force (%)
X_{10} = Crimp at 0,1 x Uncrimping Force (%)
X_{11} = Uncrimping Energy at 0,2 x Uncrimping Force (arbitrary units)
X_{12} = Uncrimping Energy at 0,1 x Uncrimping Force (arbitrary units)

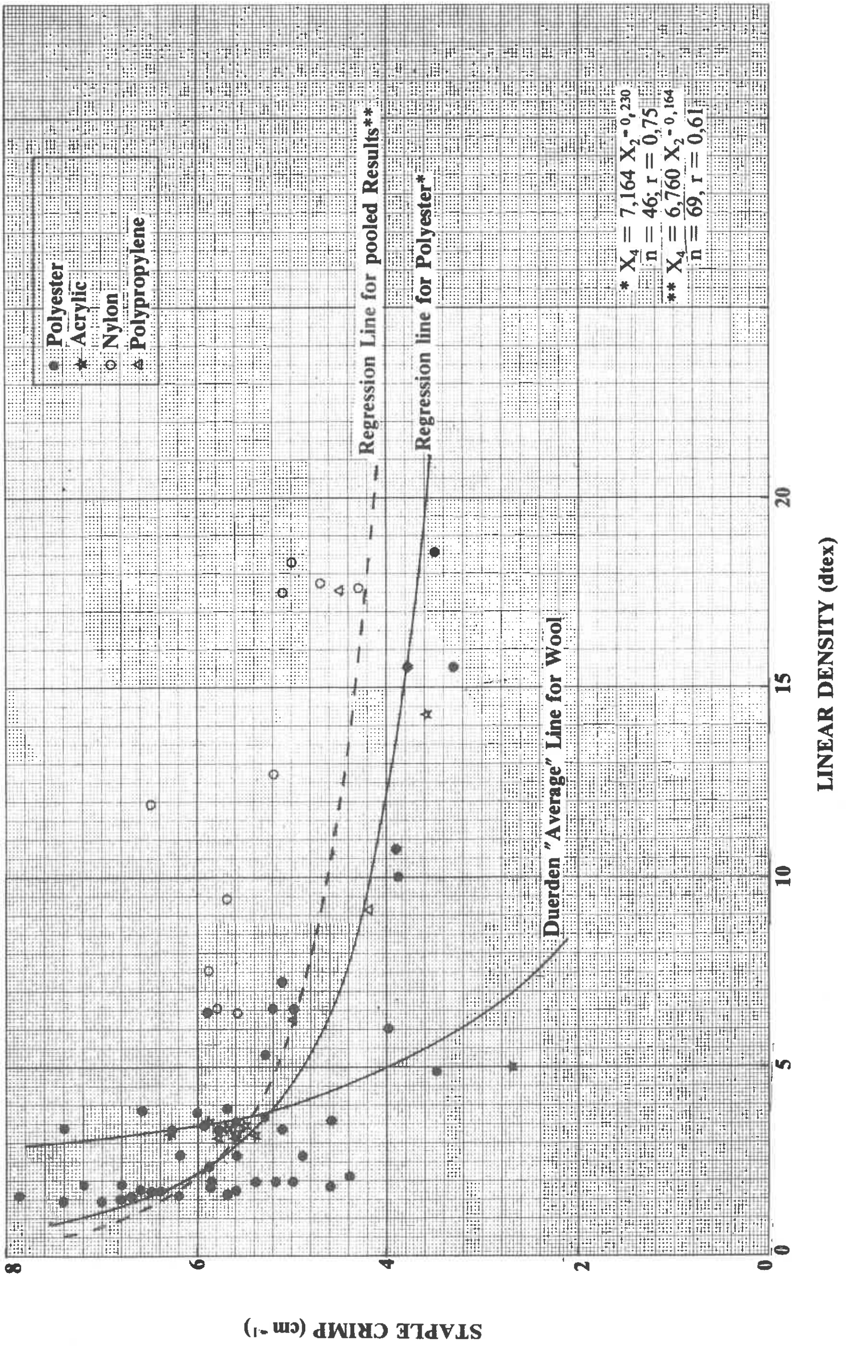


Fig. 4 – Staple Crimp (X_4) vs. Fibre Linear Density (X_2)

TABLE III

SUMMARY OF MULTIPLE REGRESSION ANALYSES (log-log) WITH RESISTANCE TO COMPRESSION AS DEPENDENT VARIABLE

	CONTRIBUTION OF EACH INDEPENDENT VARIABLE TO THE OVERALL CORRELATION (%)											SIGNIFICANT REGRESSION EQUATIONS**	n	r	% fit
	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}	X_{12}				
Polyester	61	n.s.	23	*	*	*	*	*	*	*	*	$5{,}44\ X_2^{0{,}296}\ X_4^{0{,}684}$	31	0,92	85
	36	5	18	*	*	*	*	*	*	*	*	$1{,}16\ X_2^{0{,}330}\ X_3^{0{,}257}\ X_4^{0{,}665}$	38	0,76	58
	34	n.s.	*	n.s.	*	*	*	*	*	*		$20{,}1\ X_2^{0{,}134}$	38	0,58	34
	34	n.s.	*	*	n.s.	*	*	*	*	*	*	$20{,}1\ X_2^{0{,}134}$	38	0,58	34
	19	n.s.	*	*	*	34	*	*	*	*	*	$85{,}7\ X_2^{-0{,}481}\ X_7^{0{,}683}$	36	0,72	52
	33	n.s.	*	*	*	*	20	*	*	*	*	$17{,}7\ X_2^{0{,}202}\ X_8^{0{,}678}$	36	0,72	52
	n.s.	7	*	*	*	*	*	71	*	*	*	$1{,}60\ X_3^{0{,}371}\ X_9^{0{,}665}$	36	0,88	77
	n.s.	n.s.	*	*	*	*	*	*	75	*	*	$11{,}0\ X_{10}^{0{,}517}$	36	0,86	75
	n.s.	n.s.	*	*	*	*	*	*	*	79	*	$151\ X_{11}^{0{,}490}$	36	0,89	79
	n.s.	n.s.	*	*	*	*	*	*	*	*	82	$107\ X_{12}^{0{,}486}$	36	0,90	82
All Fibre Types Pooled	19	42	9	*	*	*	*	*	*	*	*	$0{,}221\ X_2^{0{,}341}\ X_3^{0{,}553}\ X_4^{0{,}610}$	50	0,84	70
	16	41	*	13	*	*	*	*	*	*	*	$0{,}601\ X_2^{0{,}224}\ X_3^{0{,}474}\ X_5^{0{,}172}$	50	0,77	60
	15	41	*	*	3	*	*	*	*	*	*	$1{,}07\ X_2^{0{,}176}\ X_3^{0{,}387}\ X_6^{0{,}175}$	50	0,77	60
	4	23	*	*	*	*	*	*	*	*	48	$14\ X_2^{0{,}076}\ X_3^{0{,}26}\ X_{12}^{0{,}35}$	56	0,87	75
	*	*	*	*	*	*	*	*	*	*	55	$80{,}4\ X_{12}^{0{,}41}$	56	0,74	55

n.s. = non-significant at 95%
* = Variable excluded from statistical analyses
** = All regression equations are significant at the 95% level or better

X_2 = Linear Density (dtex)
X_3 = Initial Pre-yield Modulus (cN/tex)
X_4 = Staple Crimp (cm^{-1})
X_5 = Crimp Frequency Percentage
X_6 = Crimp Length (%)
X_7 = Uncrimping Force (cN)
X_8 = Uncrimping Stress (cN/tex)
X_9 = Crimp at 0,2 x Uncrimping Force (%)
X_{10} = Crimp at 0,1 x Uncrimping Force (%)
X_{11} = Uncrimping Energy at 0,2 x Uncrimping Force (arbitrary units)
X_{12} = Uncrimping Energy at 0,1 x Uncrimping Force (arbitrary units)

crimp[14, 32, 33]. In Fig. 5 bulk resistance to compression has been plotted against the product of staple crimp and fibre diameter for the different fibre types, the average regression curves for both wool and polyester being superimposed. It can be seen from the figure that the points corresponding to the nylon fibres lie away from the others, mainly because of their lower bending stiffness (see Table I). This is referred to again later.

Rather surprisingly, no significant correlation was found between bulk resistance to compression and either the crimp frequency percentage or the percentage crimped length. These two properties are, however, not always so easy to measure accurately. It is felt that, where a sample still contains undisturbed coherent staples, staple crimp frequency is probably a better and more accurate measure of fibre crimp than the single fibre crimp frequency.

The best fit regression equation obtained on the results of the polyester fibres with the multiple quadratic analyses (on the results in their standard form), was as follows:

$$Y_1 = -0{,}11\ X_2^2 + 0{,}25\ X_4^2 + 2{,}83\ X_2 + 8{,}4 \quad \ldots\ldots (1)$$

% Contribution = 24 19 44

Number of data points (n) = 31

Correlation coefficient (r) = 0,93

For the ranges of polyester fibre linear densities covered here, resistance to compression increased with an increase in both fibre linear density (X_2) and staple crimp (X_4). An analysis involving only the product of X_2 and X_4 produced an almost equally good correlation ($r = 0{,}87$) which is in agreement with numerous findings on wool[14].

When the results of the various fibre types were pooled, and the multiple regression analysis repeated, initial pre-yield modulus (X_3) emerged as highly significant (see Table III). From Table III it can be seen that the best correlation ($r = 0{,}87$) obtained was that between resistance to compression and a combination of fibre linear density (X_2) initial pre-yield modulus (X_3) and uncrimping energy at 0,1 x uncrimping force (X_{12}). The next best correlation was that between resistance to compression and a combination of fibre linear density (X_2), initial pre-yield modulus (X_3), and staple crimp (X_4). Clearly, the bending stiffness of the fibres, represented here by the initial pre-yield modulus, is important in determining bulk resistance to compression when different fibre types are involved, which is to be expected from Van Wyk's[32, 33] theoretical analysis.

Fig. 6 shows bulk resistance to compression plotted against the

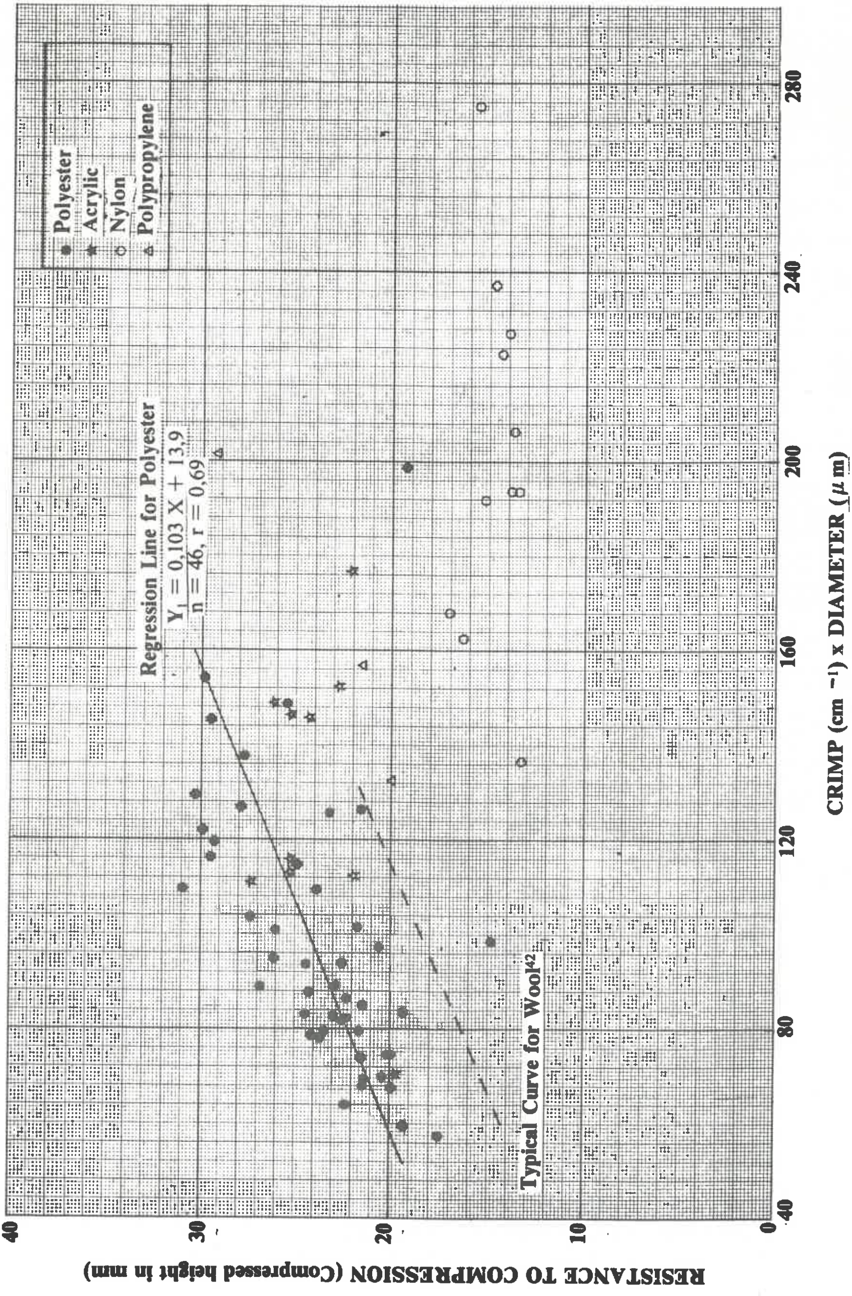


Fig. 5 – Bulk Resistance to Compression vs. the Product of Staple Crimp and Fibre Diameter

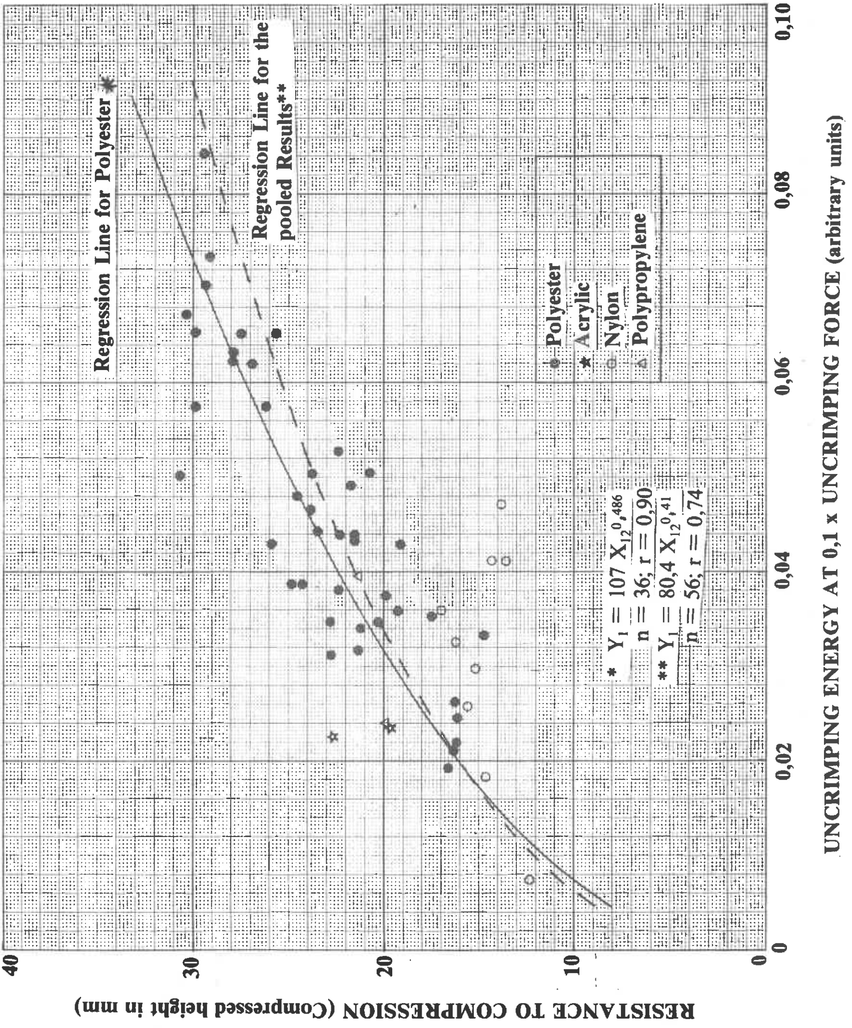


Fig. 6 – Bulk Resistance to Compression (Y_1) vs. Uncrimping Energy at 0,1 x Uncrimping Force (X_{12}).

uncrimping energy at 0,1 x uncrimping force, the corresponding regression curves (see Table III) for both polyester only and pooled results, being superimposed. On this graph the points representing the different fibre types tend to follow the same pattern, mainly because the uncrimping energy is a function of both crimp and fibre stiffness.

SUMMARY AND CONCLUSIONS

The use of bulk resistance to compression, determined on a SAWTRI Compressibility Tester, as a quick and easy measure of the crimp of staple synthetic fibres has been investigated. A total of 45 polyester (7 high tenacity, 27 medium tenacity and 11 low tenacity), 12 nylon, 12 acrylic and 3 polypropylene fibre samples, were tested. Their bulk resistance to compression was measured on a SAWTRI Compressibility tester while the single fibre uncrimping stress, force and energy values were measured on an Instron tensile tester. Staple and single fibre crimp frequencies were also determined by counting.

According to regression analyses carried out on the results of the polyester fibres, with bulk resistance to compression as dependent variable and each of the other measures of fibre crimp taken alternatively as independent variable, bulk resistance to compression was best correlated ($r \approx 0,9$) with the single fibre uncrimping force and energy values obtained on the Instron. Bulk resistance to compression, however, was generally poorly correlated with the other measures of fibre crimp on their own.

Multiple regression analyses were also carried out on the data, with bulk resistance to compression as dependent variable and single fibre linear density and initial pre-yield modulus combined alternatively with each of the different measures of crimp, as independent variables. The analyses were first of all carried out on the polyester fibre results only and then on the results of all the fibres combined.

According to the multiple regression analyses carried out on the results of the polyester fibres, the highest correlations were obtained between either bulk resistance to compression and a combination of fibre linear density and staple crimp ($r \approx 0,92$) or between bulk resistance to compression and either uncrimping force or uncrimping energy as measured on the Instron ($r \approx 0,9$). When the results obtained on the different types of fibres were pooled, the highest correlation ($r \approx 0,87$) was obtained between bulk resistance to compression and a combination of fibre linear density, initial pre-yield modulus and uncrimping energy, the second highest correlation ($r \approx 0,84$) being obtained between bulk resistance to compression and a combination of fibre linear density, initial pre-yield modulus and staple crimp. Clearly, for the different fibre types, fibre bending modulus, represented here by the initial pre-yield modulus, was an very important parameter in line with Van Wyk's theoretical work.

It is concluded that, for most practical purposes, the bulk resistance to compression determined on a SAWTRI Compressibility Tester provides a fairly simple, quick and sufficiently accurate measure of the crimp characteristics of staple polyester fibres and possibly even of other synthetic fibre types. Where fibre linear density varies, it will have an effect on bulk resistance to compression and where different fibre types are involved the bending modulus of the fibres will also have an effect on the bulk resistance to compression.

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USE OF PROPRIETARY NAMES

The names of proprietary products where they appear in this report are mentioned for information only. This does not imply that SAWTRI recommends them to the exclusion of other similar products.

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