

Influence of different gauge length and strain rate parameters on tensile properties of Kevlar® 29 yarn

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The effect of gauge length and strain rate parameters on tensile properties of Kevlar®29 yarn has been studied. Six distinct gauge lengths have been subjected to a comprehensive evaluation of tensile properties. Similarly, five distinct strain rates are used to examine the strain rate's effects. ANOVA has been carried out to analyse the co-relation between and with-in the tensile properties of Kevlar® 29 yarns samples. Experimental results indicate that the mechanical properties of Kevlar®29 are sensitive to gauge length and strain rate.

Keywords: Composite, Gauge length, Kevlar®29 yarn, Strain rate, Tensile property

1 Introduction

Aramid fibres are high strength-high modulus fibres and come under the category of high-performance fibres¹. The most common type of aramid fibre is Kevlar® and Nomex® by Dupont². Kevlar® fibres have been developed to offer an excellent balance between their tensile qualities and their ultimate performance. Zhu *et al.*³ investigated the stress and strain properties of Kevlar® yarn with the stress and strain properties of rubber reinforcement tyre yarns and observed that Kevlar® yarns is twice as robust as any other type of tyre yarn. Kevlar® yarns can be used to make a wide range of protective clothing, such as helmets, plates and armor for vehicles. In addition, these textiles are also used to manufacture cut-resistant mittens and rubber reinforcement composites for automobile lines. Researchers are working on the development of advanced textiles employing these high-performance fibres. Kevlar® 29 yarn has a variety of applications in the ballistics industry, as well as in high tension conveyor belts, ropes and cables for heavy-duty machinery^{3,4}.

Additionally, aramids are utilized as a reinforced composite material in a variety of applications, including the automobile industry and the confinement chambers of jet engines⁵. It is evident that these fibres are exposed to high-temperature variations, as well as mechanical and chemical environments, over

an extended period. A few researchers evaluated single fibre characteristics to determine compatibility with different fibres⁶. Tensile strength and modulus data are accessible in the form of quasi-static tensile strength data and are also application dependent⁶. Previously, several studies have been conducted to observe the stress-strain behavior of high-performance fibres yarns⁷. A few researchers⁸ have examined the variable strength of single aramid stands. They discovered that the distributions for liner density are highly variable, causing the failure loads to be highly variable and positively correlated. In contrast, the diversity of fibre examined across a yarn is greater than that along a single filament⁸. Some researchers⁹ studied the effect of fibre orientation on the failure behavior of fibre bundles and fabric performance. According to earlier reports, the tensile stress-strain data is provided in the range of 1-100 S⁻¹. Several researchers suggested new techniques to generate the tensile stress-strain data at a medium strain rate in the range of 1-200S⁻¹(refs 10-13).

Lim *et al.*¹⁴ studied the elastomeric reaction of the Kevlar®129 fibres. It has been discovered that the tensile strength of Kevlar® 129 fibre decreases, as the size of the specimen increased¹⁵. Kevlar® 49 single yarn has been studied for change in the mechanical characteristics under both quasi-static and dynamic tensile loading conditions¹⁶. The Young's modulus of Kevlar® 49 is 120 GPa, which is significantly greater than the value of 60 GPa found for standard Kevlar® (0.025 vs 0.040). Researchers^{17,18} studied the effects of strain rate and gauge length on the tensile properties of

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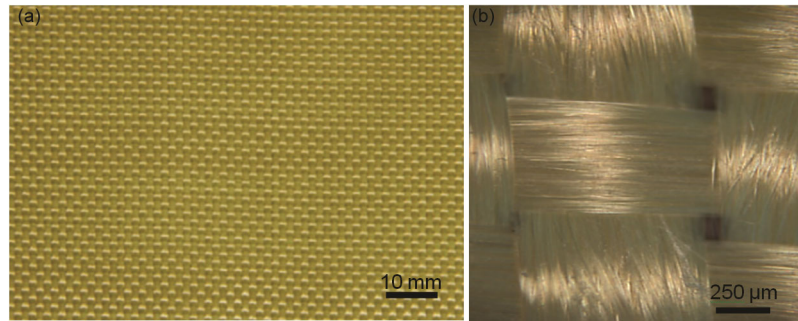


Fig. 1 — (a) Woven structure and (b) optical microscopic image of Kevlar®29 yarn

Kevlar® 49 single yarn and PTA fibre. The tensile strength of Kevlar® 29 fibre is comparable to that of carbon and glass fibres, and it has a lower density than both. A correlation study is carried out to investigate the relationship between yarn pull out performance and impact performance¹⁹. In the past, the micromechanical properties of composites made of Kevlar® 129 fibre and epoxy resin have been studied²⁰. The influence of strain rate on the mechanical characteristics of bundles of Kevlar® fibre has also been investigated²¹⁻²³.

In this study, the effect of gauge length and strain rate on Kevlar® 29 yarn tenacity (cN/tex) has been investigated. The tensile behavior of the Kevlar® 29 single yarn has been tested under both quasi-static and dynamic tensile loads.

2 Materials and Methods

A plain Kevlar-29 fabric, having a fabric set (7×7), GSM 300, EPI 13 and PPI 16 was purchased from Go Green products. Individual yarns were carefully extracted from the woven fabric (Fig. 1). Kevlar® 29 single yarns with different gauge lengths were tested under a constant strain rate of 100 mm/min and with a constant gauge length under different strain rates using a Zwick/Roell. Kevlar®29 yarns in the woven structure is composed of hundreds of filaments. Kevlar® 29 filament characteristics are discussed in Table 1.

The ZWICK REOLL Z005 universal tensile strength tester is utilized to analyze the performance of Kevlar®29 yarn under variable gauge length and strain rate. The machine works on the CRE (constant rate of elongation) principle. The breaking force (B-force) and elongation of yarn have been measured in accordance with the ASTM D2256 standard for measuring the tensile properties of monofilament, multifilament and spun yarn using the single-strand method.

All test samples have been conditioned prior to testing 24h at 27° C and 65% humidity. Thereafter the

Table 1 — Kevlar® 29 fibre characteristics

Properties	Values
Denier, den	1000
Density, g/cc	1.44
Liner density, g/cc	1.64
Breaking strength, N	338
Breaking tenacity, MPa	2920
Tensile modulus, MPa	70500
Elongation at break, %	3.6

tenacity of yarn is evaluated by varying gauge length (25,50,100,150,200 and 400 mm) at a constant strain rate (100 mm/min). Total 10 sample has been tested for each gauge length. Secondly, the test samples are also evaluated using different strain rates (40,80,200 and 400 mm/min) at a constant gauge length (100mm). Furthermore, the one-way ANOVA analysis of variance with a significance level of $p < 0.05$ has been carried out using the SPSS software. The correlation between and within the effect of gauge length and strain rate on tensile properties has been investigated using ANOVA analysis.

3 Results and Discussion

3.1 Effect of Gauge Length

Kevlar® 29 yarn samples are tested for tenacity at six different gauge lengths and at a constant strain rate (Table 2). Ten samples have been tested to determine the stress-strain behaviour of Kevlar® 29 yarn. It has been noticed that when the gauge length increases, the tensile values of all test samples decrease considerably, due to an increase in the defect population in the overall volume of material tested, the initial waviness and slack along the length of the fibres^{14,22}. Tensile strength has an insignificant effect for gauge lengths lower than 200 mm. However, as the gauge length value is increased to 200, 300, and 400 mm, a substantial decrease in the tensile properties is observed. As the gauge length is increased from 25 mm to 400 mm, the tensile strength

reduces from 233.42 cN/tex to 201.61 cN/tex (a loss of 15.77%). The stress-strain behaviour of all test specimens with varying gauge lengths has been studied (Fig. 2). It is observed that a single yarn's stress-strain behaviour is usually linear elastic before the failure stress and that the stresses drop right after the brittle failure.

3.2 Effect of Strain Rate

At a constant gauge length of 100mm, ten Kevlar® 29 yarn samples are examined for their tenacity at five different strain rate values (40, 80, 120, 160 and 200 mm/min). The results are shown in Table 3. It is discovered that the increase in strain rate increases the tenacity of all test samples significantly. The strain rate has been found to have a substantial effect on the tenacity properties of test yarn. The tenacity value improves by 79.43% as the strain rate value increases

from 40 mm/min to 200 mm/min at a constant gauge length. Figure 3 discusses the stress-strain behavior of all test specimens with variable strain rates. The stress-strain curve exhibits more bending for strain rates of 40, 80 and 120 mm/min respectively. Additionally, with increasing strain rate for single yarns with the same gauge length, the tensile strength of Kevlar® 29 single yarn is dependent on strain rate. At lower strain rate levels, the stress-strain curve fluctuation is observed. The stress-strain curve is found to be linear at 160 mm/min and 200 mm/min. It is observed that a higher strain rate contributes to a higher initial elastic modulus as well as a higher failure strain.

3.3 ANOVA Analysis

Table 4 displays the results of an ANOVA analysis for variation in the group, i.e. the effect of fibre

Table 2 — Effect of gauge length on tenacity of Kevlar® 29 yarn at a constant strain rate (100mm/min)

Samples No.	Tenacity, cN/tex					
	25mm	50mm	100mm	200mm	300mm	500mm
1	224.32	236.57	224.59	223.75	216.42	187.35
2	221.3	210.23	204.03	186.82	195.42	216.45
3	225.94	214.89	195.14	191.07	185.49	218.35
4	245.08	229.21	215.52	198.74	186.42	175.59
5	238.6	214.68	217.05	224.4	224.85	224.7
6	260.79	217.62	236.42	188.95	188.25	213.51
7	249.2	234.02	207.64	216.2	210.75	205.92
8	257.49	232.19	230.62	222.87	191.62	176.02
9	222.75	230.19	227.15	224.07	220.47	194.76
10	188.68	224.8	207.88	214.09	225.39	203.45
Mean	233.42	224.44	216.6	209.1	204.51	201.61
S.D.	21.45	9.37	13.08	15.89	16.62	17.57
C.V.	9.19	4.17	6.04	7.6	8.13	8.72

25, 50, 100, 200, 400 and 500 mm are gauge length values.

Table 3 — Effect of strain rate on tenacity of Kevlar® 29 yarn at constant gauge length (100 mm)

Sample No.	Tenacity, cN/tex				
	40mm/min	80 mm/min	120 mm/min	160 mm/min	200 mm/min
1	131.53	147.23	145.07	177.1	216.62
2	122.94	132.43	159.58	168.33	227.4
3	134.16	150.46	166.82	170.35	236.25
4	136.29	130.02	165.5	182.22	222.51
5	135.74	154.44	171.53	177.47	258.57
6	119.96	145.57	144.44	215.09	227.12
7	127.83	143.94	158.83	206.71	217.34
8	134.45	128.27	160.6	206.1	214.79
9	113.65	135.01	163.07	182.4	277.71
10	141.32	165.23	178.86	210.03	252.9
Mean	129.79	143.26	161.43	189.58	235.12
S.D.	10.35	10.75	10.65	17.84	21.18
C.V.	7.90	7.76	6.60	9.41	9.01

40, 80, 120, 160 and 200 mm/min are strain Rate values.

treatment on several fabric parameters, such as time to break, force applied, length, tenacity, and b-work. There are statistically significant differences between groups based on treatment for all attributes ($p < 0.05$).

The results of an ANOVA analysis done at $p < 0.05$ for the gauge length and strain rate of Kevlar® 29 are

shown in Table 5. For gauge length variation study, the degree of freedom for gauge length is 5 and for strain rate, it is 4.

In accordance with the results of ANOVA at $p < 0.05 = 0.335$, the variation in tenacity across groups classified by gauge length is investigated. Gauge length

Table 4 — ANOVA analysis on effect of gauge length on tenacity of Kevlar®29 yarn

Parameters		Sum of squares (SS)	Degree of freedom	Mean square (MS)	F- value
Time to break, s	Between groups	0.199	1	0.199	8.211
	Within groups	2.374	98	0.024	
	Total	2.573	99		
B-Force, gf	Between groups	27324.090	1	27324.090	13.719
	Within groups	195182.820	98	1991.661	
	Total	222506.910	99		
Elongation, %	Between groups	46.063	1	46.063	6.825
	Within groups	661.387	98	6.749	
	Total	707.451	99		
Tenacity, cN/tex	Between groups	15.366	1	15.366	13.766
	Within groups	109.393	98	1.116	
	Total	124.760	99		
B-Work, gf.cm	Between groups	50849734.810	1	50849734.810	22.959
	Within groups	217052020.180	98	2214816.532	
	Total	267901754.990	99		

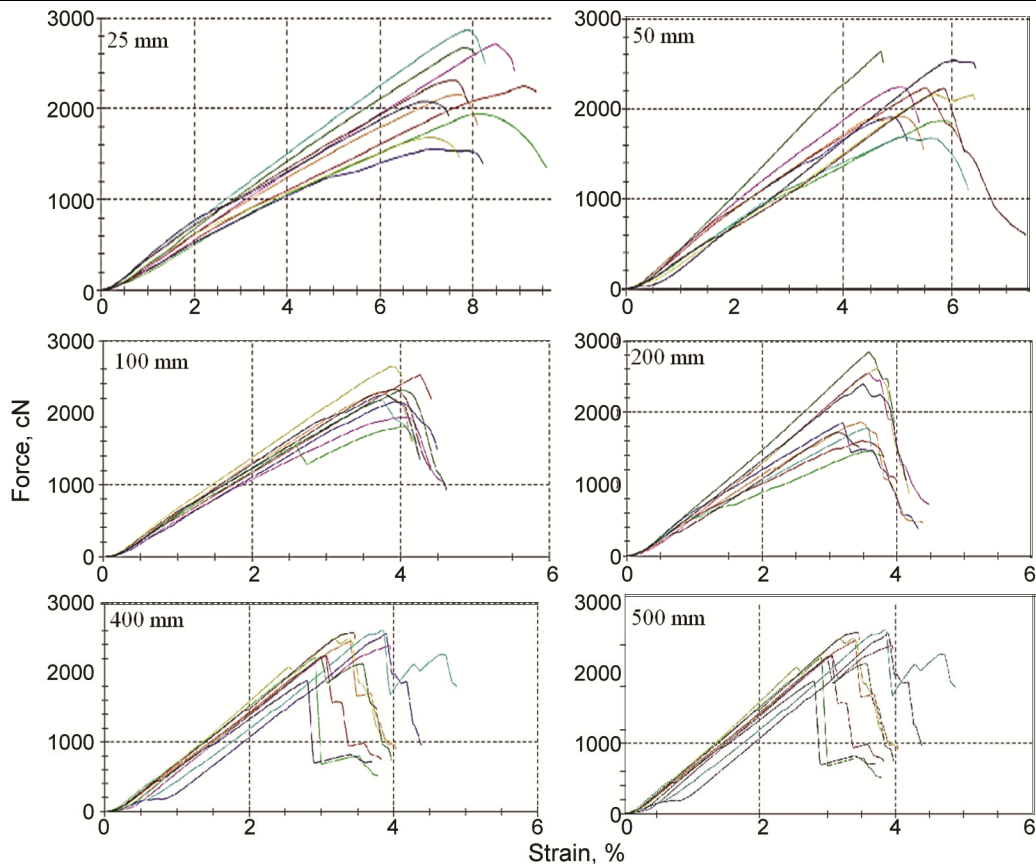


Fig. 2 — Stress-strain behaviour at different gauge length and constant strain rate (100mm/min) [each graph represents 10 test results of Kevlar@ 29 yarn]

classification reveals that statistically, there are no significant differences between groups. Accordingly, there is no significant difference in tenacity between groups managed by gauge length.

According to the ANOVA at $p < 0.05$, the change of tenacity between groups classified by strain rate and constant gauge length has been investigated. With $p < 0.05 = 0.01$, a statistically significant difference in group classification based on gauge length has been discovered. A significant difference in tenacity is seen between groups classified by strain rate.

The impact of variance in group length on the tenacity of Kevlar® yarn is investigated using a one-way ANOVA analysis. Additionally, the impact of strain rate change on the tenacity of Kevlar® yarn is assessed. The calculated value in Table 5 is 1.172, which is less than the table value of 2.45(5,54) degree of freedom at a significance level of 95%. Here, the null hypothesis is accepted. Therefore, statistically, there is no significant difference between sample variances. Whereas in Table 5, the calculated value is 35.402, which is greater than table value of 2.61 at a

Table 5 — ANOVA analysis on effect of gauge length and strain rate on tenacity of Kevlar®29 yarn

Parameters	Sum of squares		Degree of freedom		Mean square		F- value		Significance level	
	Gauge length	Strain rate	Gauge length	Strain rate	Gauge length	Strain rate	Gauge length	Strain rate	Gauge length	Strain rate
Between groups	7188.876	72116.3	5	4	1437.775	18029.1	1.172	35.402	0.335	0.001
Within groups	66256.063	22917.3	54	45	1226.964	509.274				
Total	73444.940		59							

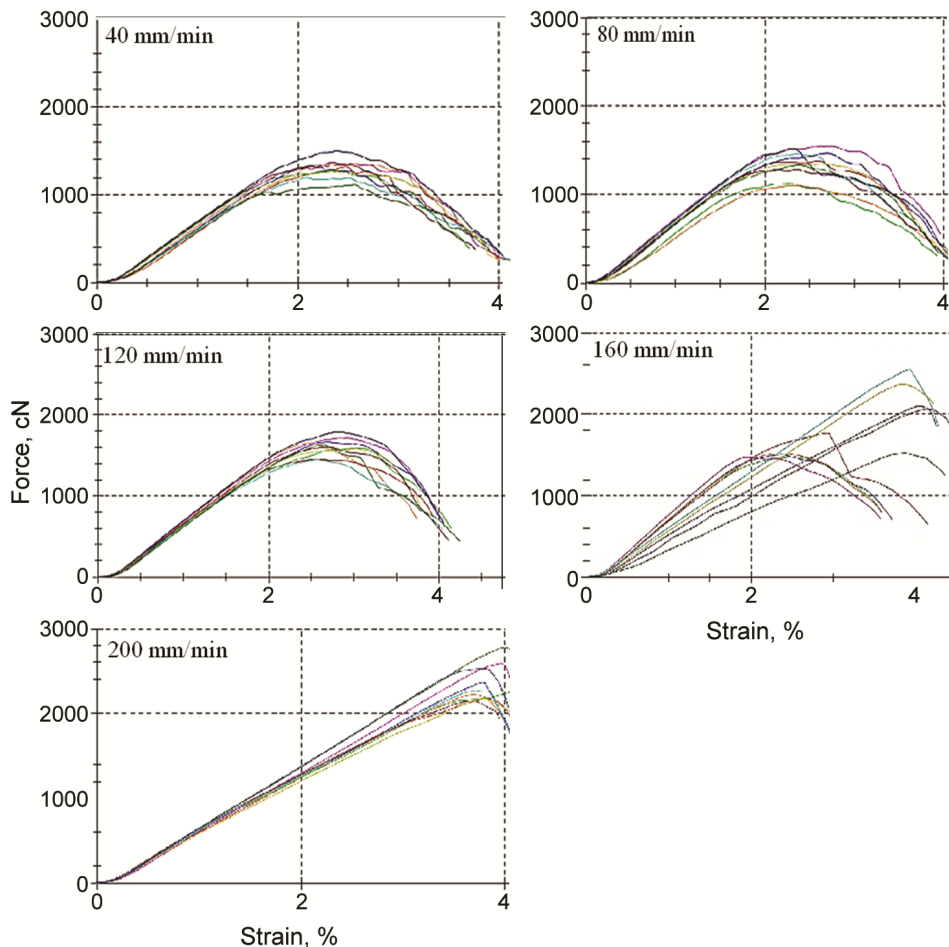


Fig. 3 — Stress-strain behavior with variable strain rate and constant gauge length (100 mm) [each graph represents 10 test results of Kevlar® 29 yarn]

95% confidence level for (4,45) degree of freedom. Here, the null hypothesis is rejected. Therefore, statically, there is a significant difference between the sample's variance. Hence, this variation in satin rate will affect the mechanical properties of the Kelvar®29. Table 5 shows the ANOVA results at a significance level of $p < 0.05$ to determine whether there is a statistically significant difference in tensile strength between groups defined by strain rate and gauge length. Consequently, this investigation reveals a significant difference in tenacity between groups classified by strain rate.

4 Conclusion

The effects of gauge length and strain rate on the mechanical characteristics of Kevlar® 29 single yarn have been investigated. The study shows that with an increase in gauge length from 25 mm to 400 mm, tenacity value decrease 15.77%, from 233.42 cN/tex to 201.61 cN/tex. Moreover, the 79.43% increase in the tenacity values 131.03 cN/tex to 235.12 cN/tex with an increase in strain rate from 40 mm/min to 200 mm/min. Kevlar® 29 single yarn's strain rate is found to be statistically significant with a P-value of 0.01. Therefore, the strain rate apparently affects the mechanical properties of the Kevlar®29 yarn. This study will be a solution for many high-performance applications.

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