EFFECT OF PRELOAD MAGNITUDE AND DURATION ON THE MECHANICAL PROPERTIES OF FLAX YARNS

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This study introduces a novel comparative analysis of three commercially produced flax-based yarn types - cotton/flax (70/30), PAN/flax (70/30), and pure flax - with a focus on breaking force and breaking elongation under varying preload magnitudes and durations. The preload magnitude was expressed as a percentage of the breaking force for each yarn type and ranged from 10% to 50%. The preload duration was between 0.5 and 3.5 hours for all types of yarn. The results demonstrate that yarn behavior is strongly influenced by raw material composition. Cotton/flax and PAN/flax yarns exhibited structural stability under different preloading conditions, with minimal variations in breaking force (1–2%) and breaking elongation (1–2% for PAN/flax), whereas pure flax yarn showed higher sensitivity, particularly to preload magnitude, with changes of up to 10–11% in elongation. Preloading reduced breaking force and elongation across all yarns, with the most pronounced reductions observed for blended yarns. PAN/flax yarn consistently achieved the highest breaking elongation, approximately three times that of cotton/flax yarn, highlighting the reinforcing effect of PAN fibers. Breaking time was largely unaffected in cotton/flax and flax yarns, but PAN/flax yarn exhibited a decrease of up to 10% with increasing preload magnitude. These findings emphasize the critical role of fiber composition and preloading conditions in optimizing yarn performance, reducing breakage, and improving knitting efficiency.

Keywords: flax yarn, knitting, flax-containing yarn, cotton/flax, PAN/flax

Introduction

The growing demand for eco-friendly fibers in the textile industry has created significant opportunities for expanding the use of natural fibers [1, 2]. Cotton and flax are two widely used natural fibers in textile production, each with distinct properties. Cotton is the second most common fiber globally, after polyester, and is valued for its softness, breathability, and moisture absorbency, which ensure comfort in textile applications [1]. Flax, in contrast, offers high tensile strength, stiffness, and excellent moisture-wicking properties, along with environmental sustainability, making it a durable and eco-friendly option [3-7]. Blending flax with other fibers has emerged as an effective strategy to harness its advantages while mitigating inherent limitations. In recent years, the incorporation of flax-containing yarns in knitting has attracted increasing attention due to the rising need for sustainable and biodegradable textile materials [2]. The ideal flax mix is usually about 20-30% flax to 80-70% other fibers. Higher flax levels tend to cause more fabric creasing and less comfort, often feeling prickly [8], a negative influence on yarn properties and spinning process [9-16]. Blending cotton with flax combines the softness and comfort of cotton with the strength and stability of flax, producing yarns and fabrics suitable for high-performance and sustainable knitwear. The study shows that cotton–flax blends exhibit different properties compared to pure cotton or flax yarns [10]. Five yarns (100% cotton, 80:20, 70:30, 45:55, 100% flax) were tested for evenness, strength, and elongation. Evenness was highest in pure cotton and optimal in the 80:20 blend, while pure flax had the poorest evenness but the highest strength and lowest elongation. Increasing flax content generally reduced evenness and elongation, highlighting that blends like 80:20 offer a balanced combination of yarn quality and performance (Table 1).

Yarns and textile materials display viscoelastic behavior when exposed to mechanical loading. When subjected to forces below their breaking strength and subsequently released, they do not fully or immediately return to their original length. The extent of recovery depends on several factors, including the magnitude of the applied force, the duration of loading, and the time allowed for relaxation after unloading. These parameters govern the balance between the elastic and plastic components of deformation, which is fundamental to understanding the mechanical performance of fibers and yarns [18].

During yarn processing, knitting, and subsequent product use, yarns are exposed to various tensile stress-

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es that may cause deformation or breakage. To evaluate a yarn's resistance to such stresses, key strength indicators - most notably breaking load and breaking elongation - are commonly assessed [6, 7, 17]. The breaking load characterizes a yarn's ability to withstand tension during technological processing, while variability in strength can interrupt loop formation and cause localized yarn breakages. Similarly, inconsistent breaking elongation disrupts the knitting process, leading to unequal, irregular loop dimensions after relaxation.

Despite existing research on the mechanical performance of natural and blended yarns, limited attention has been given to the tensile behavior of flax-containing yarns, particularly in the context of flat and circular knitting applications [6]. A comprehensive understanding of their stress–strain response is crucial for optimizing knitting efficiency and ensuring fabric uniformity.

This study introduces a novel comparative analysis of three commercially produced flax-based yarn types - cotton/flax, PAN/flax, and pure flax - focusing on their breaking force and elongation under varying preload magnitudes and durations. By examining how flax content and preloading conditions affect tensile performance, the research aims to identify optimal yarn compositions and process parameters that minimize breakage, enhance loop regularity, and ultimately improve the quality and durability of knitted fabrics.

Table 1. Properties of cotton/flax blends depending on fiber ratios

Blend ratio (Cotton: Flax)	Evenness	Strength	Elongation	Comfort	Key Notes	Reference
100:0	Highest	Moderate	High	Excellent	Best regularity, dries slowly	[10], [11]
80:20	Good	Good	Moderate	Good	Optimal properties, balanced performance	[10], [12]
70:30	Good	Good	Moderate	Good	Good balance, slightly less optimal than 80:20	[12]
60:40	Moderate	Reduced	Low	Moderate	Decline in yarn properties	[12], [9]
45:45	Poor	Low	Low	Moderate	Low quality, poor stability	[9]
0:100	Poorest	Highest	Lowest	Poor	Strong but stiff, poor elongation, and comfort	[10], [13]

Materials and methods

Yarn

Optimal knitting performance depends on the mechanical properties of the yarn, particularly breaking force and elongation, which determine its resistance to tensile stresses during processing and use.

This study used three types of yarn (Figure 1), and their primary characteristics are presented in Table 2. The yarn was coated with wax in this project to ensure optimal results during knitting.

The mechanical properties of three yarn types – cotton/flax (CF), PAN/flax (PF), and flax (F) - show notable differences (Table 2). CF yarn had the highest twist level (303 turns/m), 23% more than F yarn (246 turns/m) and three times more than PF yarn (101 turns/m), indicating stronger fiber cohesion.

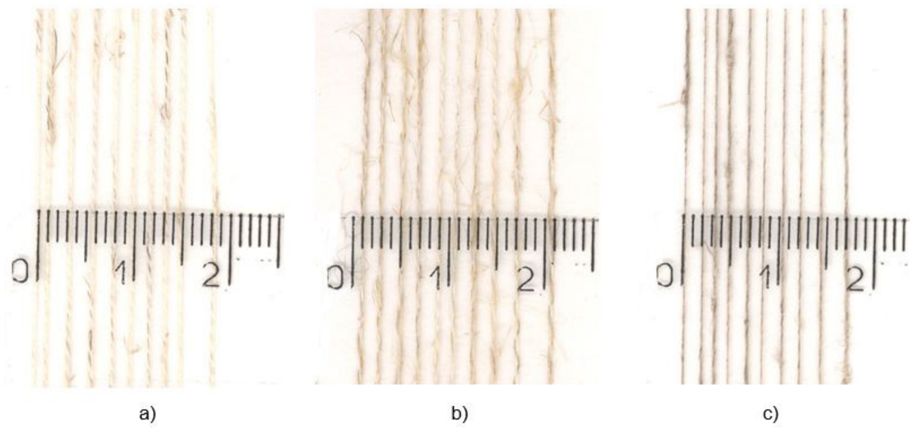


Figure 1. The investigated yarns: a) cotton/flax (CF), b) PAN/flax (PF), c) pure flax (F) yarn

Table 2. The experimental value of the main characteristics of the yarns

Characteristics of the yarn	Types of yarn		
	CF	PF	F
Raw material composition of yarn, %	70% cotton, 30% flax	70% PAN, 30% flax	100% flax
Nominal linear density T_n, tex	25x2	31x2	46
Experimental linear density T_e, tex	49.2±1.0	61.5±1.0	50.9±0.5
Twist T, turns/m	303.1±9.4	100.9±6.7	246.3±28.9
Breaking force P_p, cN	880±49	768±79	1689±221
Tenacity P_u, cN/tex	17.89	12.49	33.18
Breaking elongation E_p, %	0.96±0.10	2.80±0.50	0.73±0.12

*CF – cotton/flax, PF – PAN/flax, F – flax

The effect of the raw material composition on yarn characteristics is noticeable. Table 2 indicates that pure flax yarn (F) exhibits pronounced strength irregularities, which lead to frequent yarn breakages and consequently lower knitting efficiency. In comparison with cotton/flax (CF) and PAN/flax (PF) blends, pure flax yarn (F) demonstrates lower breaking elongation (Ep) but higher tenacity (Pu), as mentioned in the studies [6, 7, 12]. Nevertheless, the elevated variability in twist (T), breaking force (Pp), and breaking elongation (Ep) of flax yarn contributes to difficulties during the knitting process. The breaking elongation values of cotton/flax (CF) and PAN/flax (PF) yarns are comparable; however, PAN/flax yarn attains significantly greater elongation owing to the intrinsic properties of PAN fibers. Specifically, the breaking elongation of PAN/flax yarn is approximately three times that of the cotton/flax blend. Although the incorporation of 30% flax fibers diminishes the elongation capacity of PAN/flax yarn, it nevertheless retains the highest value when contrasted with cotton/flax and pure flax yarns. It is essential to highlight that pure flax yarn consistently exhibits the lowest breaking elongation. In contrast, PAN/flax yarn surpasses the other variants due to the advantageous characteristics of PAN fibers.

Determination of yarn's properties

In compliance with ISO 139:2005 [19], the yarn samples were conditioned in a standard atmosphere before testing. The linear density of the yarns was determined according to ISO 2060:2012 [20], based on an average of twenty measurements per yarn type. The twist in yarns, as described in ISO 2061:2016 [21], was determined from twenty measurements per yarn type. The breaking force, tenacity, and breaking elongation were evaluated in accordance with ISO 2062:2012 [22] and ISO 6939:1988 [23, 18]. The reported values represent the average of fifty measurements for each yarn type.

Planning experiment

The research was carried out by implementing the planning matrix for an orthogonal central composition experiment according to the K_{o2} plan. The following were taken as the controlled factors:

- the magnitude of the preload P_n, sN/thread (x_1),
- the duration of the preload t_n, s (x_2).

In this case, the preload value for each yarn type varies because it was calculated as a percentage of each yarn's breaking force. The factors and their levels of variation of yarn are shown in Table 3.

Table 3. The levels of the factors for the types of yarn

No	Factors		Types of yarn	Levels of variation			Variation step
				-1	0	+1	
1	The magnitude of the preload	P_n, sN/thread (x_1)	CF	88	234	440	176
			PF	77	230	384	154
			F	169	528	845	317
2	The duration of the preload	t_n, s (x_2)	all	0.5	2.0	3.5	1.5

Before conducting the research, the yarn was conditioned under standard climatic conditions. The necessary number of yarn samples was then prepared and mounted as loops (Figure 2a) on a "rack" relaxometer (Figure 2b), with a tensile force P_n applied per thread, corresponding to 10%, 30%, and 50% of the breaking force P_p. For this purpose, the test yarn length was set at 80 cm, with each loop measuring 40 cm. After a 2-day conditioning period, the loops were cut into four equal segments and tested to failure using a tensile testing machine.

A tensile testing machine with a constant elongation rate and with flat-faced jaw clamps was used for the experiment. A straight specimen was used, and a pre-tension of 0.5 cN/tex was applied to remove slack or kinks in the yarns without inducing significant extension. The length between the clamps was set to 100 mm. The lower clamp was moved at a speed of 80 mm/s, corresponding to approximately a 20-second duration to break.

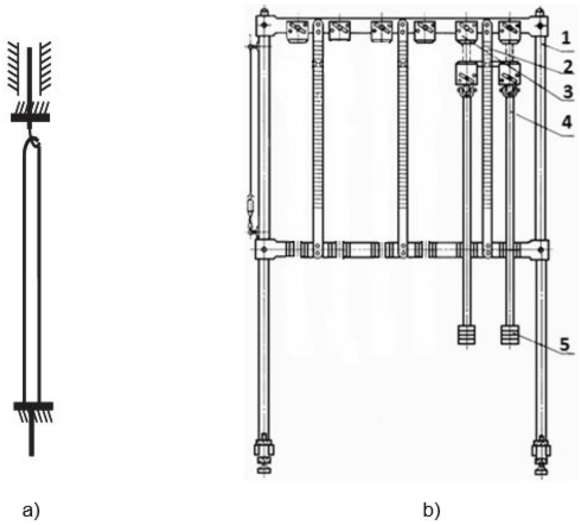


Figure 2. The yarn samples as loops (a) and "rack" relaxometer (b): 1 - stand, 2 - ruler, 3 - clamps, 4 - hanger, 5 – load

Results and discussion

Table 4 shows the planning matrix and the results of experimental studies, depending on the levels of the preload magnitude P_n (x_1) and preload duration t_n (x_2) of the mechanical properties of the yarns.

Figure 3 presents the breaking force P_p and breaking elongation E_p of the yarn before and after preload at medium levels of preload magnitude x_1 (P_n) and duration x_2 (t_n).

The composition of yarn raw materials affects its behavior. The breaking force P_p after preload was lower than before preload for all yarn types. For the blended yarns, the reduction was more pronounced, amounting to 42% for cotton/flax and 47% for PAN/flax yarns. In contrast, the pure flax yarn (F) exhibited a comparatively smaller decrease of 17% (Figure 3a). The breaking elongation Ep also decreased after preload across all yarn types (Figure 3b), with reductions of 3%, 15%, and 22% for cotton/flax, PAN/flax, and flax yarns, respectively.

Table 4. Planning matrix and research results for yarns after preload

No	Matrix		Variants of yarn								
			Cotton/flax (CF)			PAN/flax (PF)			flax (F)		
	x_1 (P_n)	x_2 (t_n)	P_p, cN	E_p, %	t_p, s	P_p, cN	E_p, %	t_p, s	P_p, cN	E_p, %	t_p, s
1	+	+	507	0,85	17,2	390	1,87	19,1	1288	0,56	13,5
2	−	+	504	1,01	16,5	404	2,95	19,4	1362	0,68	14,4
3	+	−	508	0,88	17,1	391	2,10	18,0	1272	0,62	13,2
4	−	−	523	1,00	17,0	406	3,22	20,9	1324	0,69	13,7
5	+	0	505	0,82	17,2	377	1,93	17,5	1332	0,56	13,3
6	−	0	532	1,04	17,5	414	3,05	20,9	1287	0,60	13,2
7	0	+	503	0,90	16,2	420	2,41	19,0	1461	0,68	14,4
8	0	−	508	0,98	17,0	399	2,44	19,7	1351	0,58	13,6

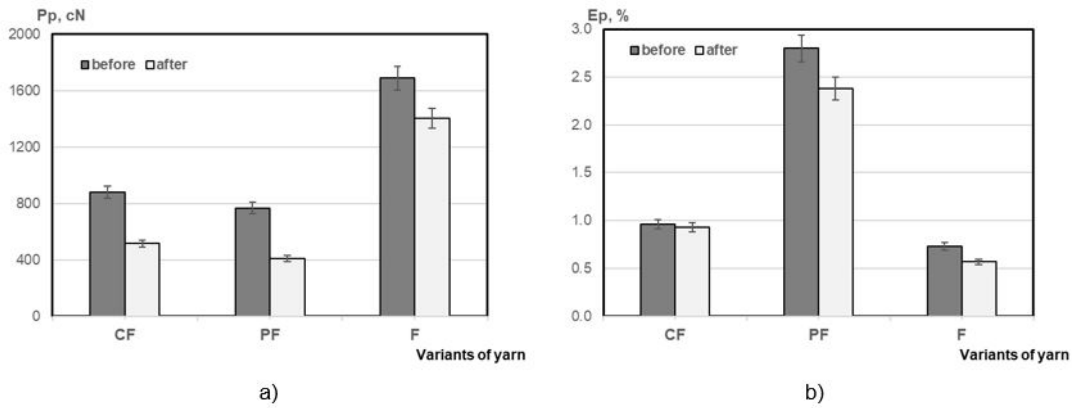


Figure 3. The breaking force P_p (a) and elongation E_p (b) before and after preload (x_1 = 0, x_2 = 0) of the investigated yarns

Breaking force of the yarn after the preload

As a result of the conducted research, considering the significance of the regression coefficients, a second-order equation was derived in coded values for the breaking force P_p of yarn: based on the Fisher coefficient and the condition $F_c < F_t$, which confirmed that the received equation is adequate:

$$Y\{P_{p\,(CF)}, cN\} = 514.0 + 4.9 \cdot x_1^2 - 8.3 \cdot x_2^2 \quad (F_t = 2.381,\ F_c = 1.018) \qquad (1)$$

$$Y\{P_{p\,(PF)}, cN\} = 407.3 - 11.0 \cdot x_1 - 11.9 \cdot x_1^2 + 2.3 \cdot x_2^2 \quad (F_t = 2.538,\ F_c = 0.786) \qquad (2)$$

$$Y\{P_{p\,(F)}, cN\} = 1403.8 - 94.5 \cdot x_1^2 + 2.4 \cdot x_2^2 \quad (F_t = 2.381,\ F_c = 0.452) \qquad (3)$$

The adequacy of the obtained model was confirmed by comparing the calculated Fisher coefficient (F_c) with the tabulated value (F_t) and p = 0,95, with $F_c < F_t$.

Based on the received equations (1–3) for breaking force P_p of the cotton/flax, PAN/flax, and pure flax yarns, Figure 4 illustrates the dependence of the breaking force Pp on both the preload magnitude P_n (x_1) and the preload duration t_n (x_2).

The results show that the breaking force of cotton/flax ($P_{p(CF)}$) and PAN/flax ($P_{p(PF)}$) yarns is largely unaffected by both the magnitude of the applied preload (P_n, x_1) and the duration of preload application (t_n (x_2)), with observed variations limited to only 1–2% (Figures 4a and 4c). This suggests that the presence of cotton or PAN fibers provides structural stability, allowing the yarns to maintain their mechanical integrity under different preloading conditions. At the same time, the breaking force of pure flax yarn ($P_{p(F)}$) is insensitive to preload duration (t_n (x_2)) (Figure 4d). Still, it demonstrates a clear dependence on preload magnitude (P_n (x_1)), with changes of approximately 7% (Figure 4b). This heightened sensitivity can be attributed to the lower flexibility and higher stiffness of flax fibers, which make the yarn more responsive to applied tension. These findings highlight the importance of fiber composition in determining how yarns react to preloading and indicate that blended yarns are more robust under variable processing conditions, as mentioned in the papers [6, 7]. In contrast, pure flax yarn requires careful control of tension to minimize breakage.The specifically in the knitting process of the knitted fabric, the Swiss double pique produced on the circular knitting machines noted in paper [6].

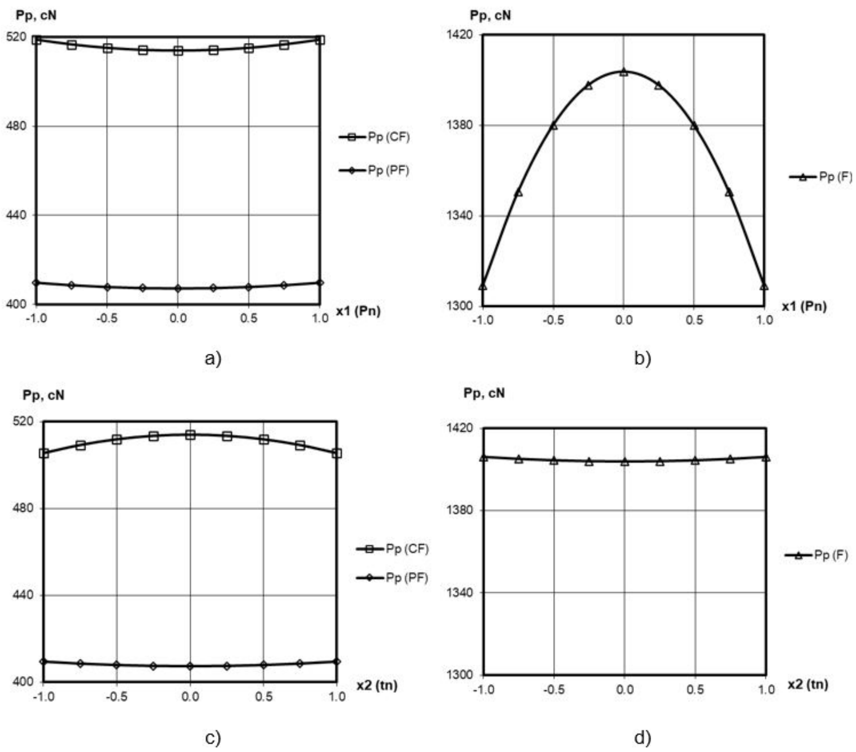


Figure 4. Dependence of yarn breaking force P_p on the preload magnitude P_n (x_1) and preload duration tn (x_2) for cotton/flax (CF) and PAN/flax (PF) yarns (a and c) and flax (F) yarn (b and d)

Breaking elongation of the yarn after the preload

Based on the research and considering the importance of the regression coefficients, a second-order equation was formulated in coded variables for the yarn's breaking elongation:

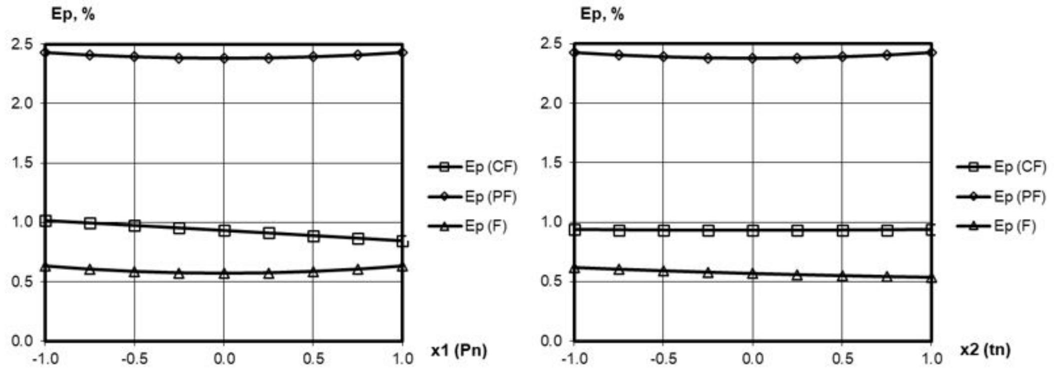
$$Y\{E_{p\,(CF)}, \%\} = 0.93 - 0.09 \cdot x_1 - 0.002 \cdot x_1^2 - 0.004 \cdot x_2^2 \; (F_t = 2.538,\ F_c = 2.197) \quad \text{....(4)}$$

$$Y\{E_{p\,(PF)}, \%\} = 2.38 - 0.55 \cdot x_1 + 0.11 \cdot x_1^2 + 0.05 \cdot x_2^2 \; (F_t = 2.538,\ F_c = 1.184) \quad \text{.....(5)}$$

$$Y\{E_{p\,(F)}, \%\} = 0.57 - 0.04 \cdot x_1 + 0.01 \cdot x_1^2 + 0.06 \cdot x_2^2 \; (F_t = 2.538,\ F_c = 2.417) \quad \text{.......(6)}$$

Figure 5 shows the dependence of breaking elongation E_p of cotton/flax, PAN/flax, and pure flax yarns on both the preload magnitude P_n (x_1) and the preload duration t_n (x_2), based on equations (4–6).

The breaking elongation of the investigated yarns is generally not strongly determined by their raw material composition. For cotton–flax yarn, the results indicate a clear dependence on the preload magnitude (P_n (x_1)), while remaining largely unaffected by preload duration (t_n (x_2)). Specifically, increasing the preload magnitude from 88 to 440 cN/thread over a two-hour preload period resulted in a notable reduction of approximately 17% in breaking elongation ($E_{p(CF)}$) (Figure 5a). This suggests that cotton/flax yarn is sensitive to the initial tension applied, which may affect its extensibility during subsequent processing. In contrast, PAN/flax yarn exhibited remarkable stability: its breaking elongation ($E_{p(PF)}$) showed negligible changes - only about 1–2% - under variations in both preload magnitude and duration (Figure 5). This behavior can be attributed to the high flexibility and strength of PAN fibers, which provide resistance to preloading effects. Pure flax yarn, however, displayed pronounced sensitivity to both preload parameters. Its breaking elongation ($E_{p(F)}$) decreased by approximately 10–11% with increasing preload magnitude (P_n (x_1)) and further declined by an additional 13% when the preload duration (t_n (x_2)) was extended. This indicates that pure flax fibers, due to their stiffness and lower extensibility, are more vulnerable to preloading, emphasizing the need for careful control of tension and time during processing to minimize elongation loss and potential breakage.



a) b)

Figure 5. Dependence of yarn breaking elongation E_p on the preload magnitude P_n (x_1) and preload duration t_n (x_2) for cotton/flax (CF) and PAN/flax (PF) yarns (a and c) and flax (F) yarn (b and d)

Breaking time of the yarn after the preload

As a result of the research conducted, considering the significance of the regression coefficients, a second-order equation was derived in coded values for the breaking time of yarn:

$$Y\{t_{p\,(CF)}, s\} = 17.0 - 0.4 \cdot x_1^2 - 0.4 \cdot x_2^2 \; (F_t = 2.381,\ F_c = 1.024) \quad \text{..............(7)}$$

$$Y\{t_{p\,(PF)}, s\} = 19.1 - 1.0 \cdot x_1 + 0.1 \cdot x_1^2 + 0.\cdot 3\, x_2^2 \; (F_t = 2.538,\ F_c = 1.440) \quad \text{....(8)}$$

$$Y\{t_{p\,(F)}, s\} = 13.6 - 0.32 \cdot x_1^2 + 0.42 \cdot x_2^2 \; (F_t = 2.381,\ F_c = 0.319) \quad \text{............(9)}$$

Based on the equations (7–9) for the breaking time tp of cotton/flax, PAN/flax, and pure flax yarns, Figure 6 shows how the breaking time tp depends on both the preload magnitude P_n (x_1) and the preload duration t_n (x_2).

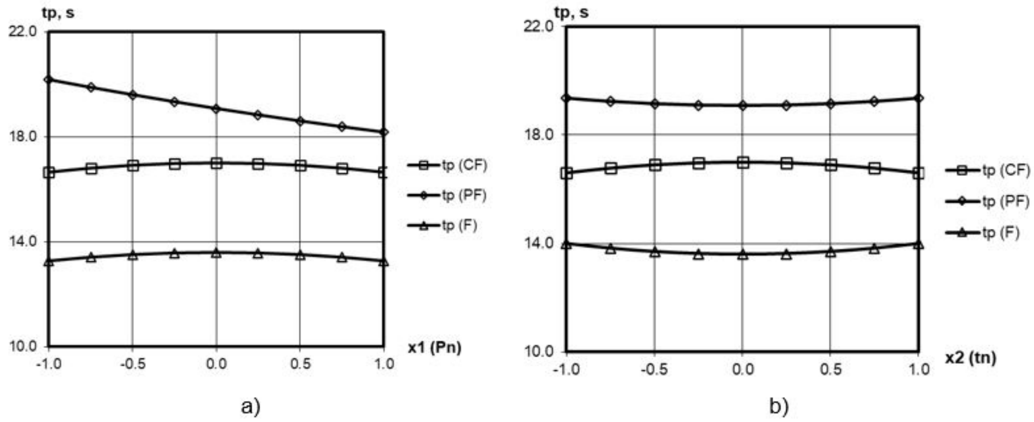


Figure 6. Dependence of yarn breaking force on the preload magnitude P_n (x_1) and preload duration t_n (x_2) for cotton/flax (CF) and PAN/flax (PF) yarns (a and c) and flax (F) yarn (b and d)

The results show that the breaking time of cotton/flax ($t_{p(CF)}$) and pure flax ($t_{p(F)}$) yarns is largely unaffected by both the magnitude of the applied preload ($P_{n\,(x1)}$) and the duration of preload application (t_n (x_2)), with variations limited to only 2–3% (Figure 6). This suggests that these yarns possess a stable structural response under different preloading conditions, likely due to the intrinsic mechanical properties of cotton and flax fibers. In contrast, PAN/flax yarn ($t_{p(PF)}$) demonstrates a clear dependence on preload magnitude (P_n (x_1)), with the breaking time decreasing by approximately 10% as preload magnitude P_n increases. Additionally, $t_{p(PF)}$ shows moderate sensitivity to preload duration (t_n (x^2)), with changes of about 2%. This behavior can be attributed to the influence of PAN fibers, which combine high strength with flexibility, causing the yarn to respond more noticeably to variations in preloading. These findings highlight the importance of yarn composition in controlling breaking behavior and suggest that PAN/flax yarns require careful adjustment of both preload magnitude and duration to optimize performance during knitting.

Conclusion

The study shows that the composition of raw materials influences the mechanical properties of flax-based yarns. Blended yarns, such as cotton/flax (CF) and PAN/flax (PF), demonstrate high structural stability under various preload conditions (preload magnitude between 10% and 50% of the breaking force of each type of yarn and preloading duration between 0.5 and 3.5 hours), with fewer variations in breaking force, elongation, and breaking time. In contrast, pure flax yarn (F) is more sensitive to preload magnitude and, in some cases, duration, leading to reduced elongation and a higher risk of breakage during knitting. Due to the inherent properties of PAN fibers, PAN–flax yarn achieves the highest breaking elongation and exhibits better resistance to preload effects. Conversely, pure flax yarn consistently shows the lowest elongation and greater variability in mechanical response. These findings suggest that blended yarns are better suited for high-performance knitting applications, offering improved knitting process stability, fewer breakages, and enhanced fabric quality. For pure flax yarns, careful control of tension and processing conditions is essential to minimize damage and maintain process efficiency.

Applying a controlled preload to yarns before knitting stabilizes their structure by reducing residual twist and internal stresses, thereby minimizing tension variability during loop formation. This results in more uniform stitches, fewer defects, and lower yarn breakage rates - improving knitting efficiency and reducing waste. However, the preload level must be carefully optimized, as excessive tension may damage fibers or alter yarn elasticity, negatively affecting fabric quality.

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Izvod

UTICAJ VELIČINE I DUŽINE PREDOPTEREĆENJA NA MEHANIČKA SVOJSTVA LANENOG PREDIVA

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Ova istraživanja prikazuju novu uporednu analizu mehaničkih svojstava tri komercijalno proizvedena prediva koja sadrže lan: pamuk/lan (70/30), PAN/lan (70/30) i čisti lan, sa fokusom na prekidnu silu i izduženje pod različitim veličinama i trajanjem predopterećenja. Veličina predopterećenja izražena je kao procenat prekidne sile za svaki tip prediva i kretala se od 10% do 50%. Trajanje predopterećenja za sve tipove prediva iznosilo je između 0,5 i 3,5 sati. Rezultati pokazuju da je ponašanje prediva snažno zavisno od sastava sirovina. Pamuk/lan i PAN/lan prediva pokazala su strukturnu stabilnost pod različitim uslovima predopterećenja, sa minimalnim varijacijama prekidne sile (1–2%) i izduženja (1–2% za PAN/lan), dok je čisto laneno predivo bilo znatno osetljivije, posebno na veličinu predopterećenja, sa promenama izduženja do 10–11%. Predopterećenje je dovelo do smanjenja prekidne sile i izduženja kod svih tipova, pri čemu su najizraženija smanjenja zabeležena kod mešanih prediva. PAN/lan predivo je dosledno postizalo najveće prekidno izduženje, približno tri puta veće od pamuk/lan prediva, što ukazuje na ojačavajući efekat PAN vlakana. Vreme prekida u pamuk/lan i lanenom predivu ostalo je u velikoj meri nepromenjeno, dok je kod PAN/lan prediva zabeleženo smanjenje do 10% sa povećanjem veličine predopterećenja. Ovi nalazi ističu ključnu ulogu sastava vlakana i parametara predopterećenja u optimizaciji mehaničkih svojstava prediva, smanjenju prekida i poboljšanju efikasnosti procesa pletenja.

Ključne reči: lanena pređa, pletenje, lanena mešana pređa, pamuk/flax, PAN/flax