Heliyon 9 (2023) e18784

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Impact of yarn compositions, loop length, and float stitches on the mechanical behavior of knitted fabrics via full factorial design and RSM

Thiago F. Santos [a], Caroliny M. Santos [a], Lucas Zilio [b], Mariana Dias [b], Praveenkumara Jagadeesh [c], Sanjay M R [c,*], Suchart Siengchin [c], Rubens Fonseca [b], Adriano Amaral [b], Marcos Aquino [a], Ivan Medeiros [a]

[a] *Post Graduation Program (PPgET), Federal University of Rio Grande do Norte, Natal, Rio Grande do Norte, Brazil*
[b] *Department of Textile Engineering, Textile Engineering Laboratory, Federal University of Rio Grande do Norte, ZIP Code: 59078-970, Natal, Rio Grande do Norte, Brazil*
[c] *Natural Composites Research Group Lab, Department of Materials and Production Engineering, The Sirindhorn International Thai-German Graduate School of Engineering (TGGS), King Mongkut's University of Technology North Bangkok (KMUTNB), Bangkok, Thailand*

ARTICLE INFO

Keywords:
Jersey
Composite materials
Statistical analysis
ANOVA
RSM

ABSTRACT

This article presents a study on the tensile properties of knitted fabrics commonly employed in polymeric matrix textile composites. The key mechanical parameters investigated include stress (Pa), strain, Young's modulus (Pa), and work of rupture (J). The knitted fabrics were developed using the Cixing Knitting System software and subsequently manufactured using a double jersey (electronic) flat knitting machine. The primary objective of this research was to explore the impact of various factors on the mechanical behavior of these knitted fabrics. The factors studied were wale and course directions, float stitch density, loop length (cm), and the type of synthetic knitting yarns used (100% polyester and 100% polyamide) along with different combinations of knitting yarns (100% cotton and 67% polyester/33% cotton hybrid). The adopted ASTM D 5034 standard, Response Surface Methodology (RSM), and Analysis of Variance (ANOVA) were employed to evaluate the mechanical performance of these fabric structures. The findings of the study revealed that the statistical adjustment of the data set for stress, strain, Young's modulus, and work of rupture in knitted fabric structures significantly reduced the standard deviations for mechanical responses. This information holds particular significance as it pertains to the frequent use of these knitted fabric structures as reinforcement in textile-reinforced composite materials. Overall, this study sheds light on the mechanical behavior in structures of knitted fabrics used in polymeric matrix composites, providing valuable insights for the design and optimization of advanced textile-based materials.

1. Introduction

The knitting process is widely recognized as the second most common technique in fabric formation technology. It involves the

* Corresponding author.
E-mail addresses: mavinkere.r.s@op.kmutnb.ac.th, mcemrs@gmail.com (S. M R).

https://doi.org/10.1016/j.heliyon.2023.e18784
Received 13 November 2022; Received in revised form 27 July 2023; Accepted 27 July 2023
Available online 28 July 2023

formation of fabrics using a single set of yarns, which can range from one to multiple yarns, through the looping or intermeshing of yarn loops using knitting needles [1,2]. Knitting processes can be categorized as either weft knitting or warp knitting, based on the direction of yarn movement during loop formation [2]. In both types of knitting, the fabric consists of sets of stitches aligned in specific directions. These stitches made by a single needle and aligned in the warp direction are called wales. On the other hand, a course refers to a set of stitches aligned in the weft direction, with each knitted stitch formed by a different needle [3,4]. The main distinction between the two classifications lies in the number of yarns required and their direction of knitting. In the process of warp knitting, the number of yarns matches the number of wales, and each yarn is knitted in the wale direction, alternately using two adjacent needles [3,5]. Conversely, in the process of weft knitting, a single yarn or multiple yarns are used, and they are knitted in the course direction by successive needles. As a result, a wale is formed by the stitches knitted by a single needle during the knitting of consecutive courses [3,6]. In the weft knitting process, a crucial component known as a cam is utilized within the knitting machines. The profile of a cam, which contains channels or grooves and provides a path for a needle during loop formation, is a metal plate that determines the height of a needle and the shape of a loop in knitted materials [7]. Cam is also responsible for defining the loop length. This paper concentrates on flat-weft knitting machines among various types of knitting machines. The stitch potential of these machines involves needle selection on either a Flat or Vee Bed. A machine of knitting consists of two beds of flat needle arranged in an inverted V shape. The flat machine offers greater versatility, particularly in terms of loop structure and pattern, when compared to weft knitting machines. This advantage in knitting is made possible because the cam machine can be changed after each course, allowing for easy knitting on one or both beds of the knitting machine [8,9]; then a high control of loop formation process provides the ability of being elevated to one of the stitches positions to produce a miss (omitted or float), a tuck (retained) or a knit stitch, according to the cam boxes that are fixed in a carriage, which travel along the beds [10,11]. In weft knitting, the construction of knitted fabric structures relies on the utilization of three fundamental types of stitches known as knit, tuck, and float (or missed) stitches. Therefore, weft-knitted fabrics and their derivatives are based on the combination of these stitches [12]. The knit stitch consumes a larger amount of yarn and comprises three parts: the head, body, and foot. On the other hand, the stitch of tuck is a loop that retains held yarn during its formation process. In contrast, the float stitch consumes less yarn and occurs when the needle machine does not operate or does not pick up the knitting yarn [13]. Scientific literature with topics about advanced knitting or knitting engineering and technology have been discussed about each stitch of knitted fabric structure promoting the most significant changes in intrinsic properties of knitted fabric. However, recently carried out studies investigated the effects and influence of stitches constructions of conventional and advanced knitted structures used for applications in reinforced knitting composites with knitted fabric [14–16]. As knitting is a complex process capable of significantly influencing the structural qualities of fabrics, it has become essential to study the effects of variations in structure, composition, and loop length on knitted fabric structures.

In recent years, only a limited number of publications have been dedicated to studying the influence of yarn types, stitches, loop length, count number, and the density of wales and courses in knitted fabric structures frequently employed as reinforcement in composite textiles [17]. This article focuses on the primary alterations in mechanical behaviors and performance that result in attractive mechanical properties, specifically stress, strain, Young's modulus, and work of rupture, which make these knitted fabric structures suitable for application as reinforcement in textile elements. Composite materials are classified based on their macroscopic scale, typically consisting of two or more constituents. The distribution and geometry of these constituents are carefully selected to optimize, improve and enhance one or more properties of the resulting composite material [18,19]. Textile-Reinforced Composite Materials (TRCM) exhibit a diverse array of properties that make them suitable for a wide range of applications, presenting numerous opportunities for various end-uses [20]. TRCM belongs to the broader category of engineered materials known as composite materials. When it comes to textile-reinforced composites, it should be remembered that there are two phases in composite materials: one denominated as matrix and another one known as reinforcement [19,21]. Fibrous reinforcement consists of continuous or non-continuous fibers, natural or non-natural, as well as high-performance fibers [22]. Thus, it is the fibrous reinforcement that promotes property improvements to the matrix, such as mechanical, structural, thermal, conductive, ballistic, chemical, bending stiffness, etc [19,23–25]. This emphasizes the significance of conducting studies that specifically concentrate on textile reinforcement using knitted fabrics. In particular, statistical approaches such as Response Surface Methodology (RSM) and analysis of variance-ANOVA (R^2, ρ-value, and F-value) are valuable tools for conducting such research. In order to promote understanding of the mechanical behavior and performance in conventional and advanced structures of knitting commonly used in textile composites. Fabrics are defined as textile materials that have two-dimensional (2D) or three-dimensional (3D) structures made of fibers, yarns, or a combination of both. These textile materials can be found as woven fabric, knitted fabric, non-woven fabric, etc. [26]. The primary benefits of reinforcing composites with knitted fabrics include the capability to produce net-shape/near-net-shape preforms, and the exceptional drapability of the knitted fabrics, enabling shaping over complex knitting paths using shaped tools [19,27]. This study focuses on weft-knitted fabrics and employs statistical analysis to investigate the main mechanical properties and their respective behaviours. By doing so, aims to advance the understanding of knitted reinforcement and, consequently, textile-reinforced composite materials, expanding the boundaries of knowledge in this area.

2. Materials and methods

2.1. Yarns used in the manufacture of knitted fabric structures

Various weft-knitted fabrics were produced using different yarn compositions, including 100% Polyester (100% PET), 100% Polyamide (100% PA), 100% Cotton (100% CO), and a blend of 67% Polyester/33% Cotton (67% PET/33% CO). All of these yarns were acquired from the textile industry and used in this study. Yarn counts used were 104 Tex for 100% Cotton and 88 Tex for 67%

Polyester/33% Cotton, 70 Tex for 100% Polyester, and 73 Tex for 100% Polyamide (100% PA), for synthetic ones.

2.2. Experimental preparation, planning, and fabrication of knitted fabric structures

The structures depicted in Fig. 1 were programmed using the Cixing Knitting System (CKS) software. The independent variables considered in this study were the different fabric structures (density of float stitch), yarn compositions (100% CO, 100% PET, 100% PA, and 67% PET/33% CO), and loop lengths (0.98–0.71 cm). A factorial design (2^3) of variables with 2 central points and 2 repetitions was employed using statistical software to conduct the experiments.

The CKS software was utilized to develop various knitted fabric structures, each corresponding to its specific knitting yarn. These knitting processes were carried out on a Cixing double jersey electronic flat knitting machine, model GE2-52C, with a gauge of 7. The knitting machine consisted of 346 needles and a 7-inch gauge. The resulting knitted fabrics displayed an average grammage of 28 $\pm$ 0.7 kg/m^2 for 100% cotton (CO) and 21 $\pm$ 0.3 kg/m^2 for a blend of 67% polyester (PET) and 33% cotton (CO). On the other hand, fabrics knitted using synthetic yarns showed an average grammage of 18.3 $\pm$ 0.1 kg/m^2 for 100% polyester (PET) and 26 $\pm$ 0.7 kg/m^2 for 100% polyamide (PA). Irrespective of their composition, all the knitted fabric structures exhibited a consistent course density of 5 $\pm$ 0.71 courses per centimeter (cpc) and a wale density of 5.6 $\pm$ 0.89 wales per centimeter (wpc) [28]. To conduct the tests, weft knitted fabrics were cut to dimensions of 15 cm in length and 2.5 cm in width. The evaluation of these fabrics was performed using MESDAN's Tensolab 3000 dynamometer, following the adopted ASTM D 5034 standard. The tests were conducted at a constant rate of 30 cm/min, with a distance of 10 cm between the claws [29].

2.3. Statistical analyses

In this study, the utilization of advanced statistical analysis played a pivotal role. The data underwent manipulation using the Design of Experiment (DOE), Analysis of Variance (ANOVA), and Response Surface Methodology (RSM) [30]. To thoroughly evaluate, analyze, and discuss the response mechanical properties (e.g., stress, strain, Young's modulus, and work of rupture), ANOVA was employed, which involved considering parameters like the coefficient of determination (R2), F-value, and ρ-value. To further validate the statistical findings presented in this paper, the researchers implemented the 3D Response Surface Methodology (RSM) using the Design Expert software. This comprehensive approach facilitated a robust examination of the mechanical properties and their interrelationships, thereby enhancing the reliability and significance of the study's conclusions [31,32].

3. Results and discussion

3.1. Knitted fabric structures with 100% CO, and 67% PET/33% CO yarns

3.1.1. Mechanical behaviour of stress

Fig. 2 presents a comprehensive analysis of the mechanical stress behavior exhibited by knitted fabrics constructed from two different yarn compositions: 100% cotton (Fig. 2 c and 2 d) and a blend of 67% polyester and 33% cotton (Fig. 2a and b). The figure also examines how various factors, such as loop length (0.71 cm, 0.84 cm, and 0.98 cm) and fabric structures (Structure 1 with 2 float stitches, Structure 2 with 5 float stitches, and Structure 3 with 8 float stitches), influence the wales and courses of the fabrics. One notable finding from the study is that knitted fabrics composed solely of 100% cotton yarns exhibit significantly higher stress properties compared to fabrics made from the hybrid polyester-cotton yarns. This observation holds true regardless of the loop length, fabric structure, or direction of wales in the fabric. Furthermore, the stress properties of the fabrics are strongly affected by two key factors: the density of float stitches and the loop length within the jersey-knitted fabric structures, which are commonly used as reinforcements in textile composites. When the loop length is reduced to 0.71 cm, there is a significant increase in the stress property of the fabric. This is mainly due to the pronounced effect of having a higher number of float stitches, which leads to an increase in fabric density and subsequently enhances the stress properties. On the other hand, when the loop length is extended to 0.98 cm, there is a reduction in stress property. This decrease is attributed to the influence of float stitch density on the wales and courses of the fabric. As

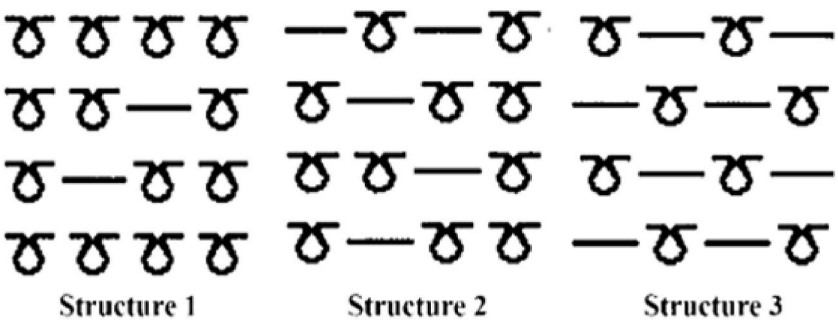

Fig. 1. Weft knitted fabric structures.

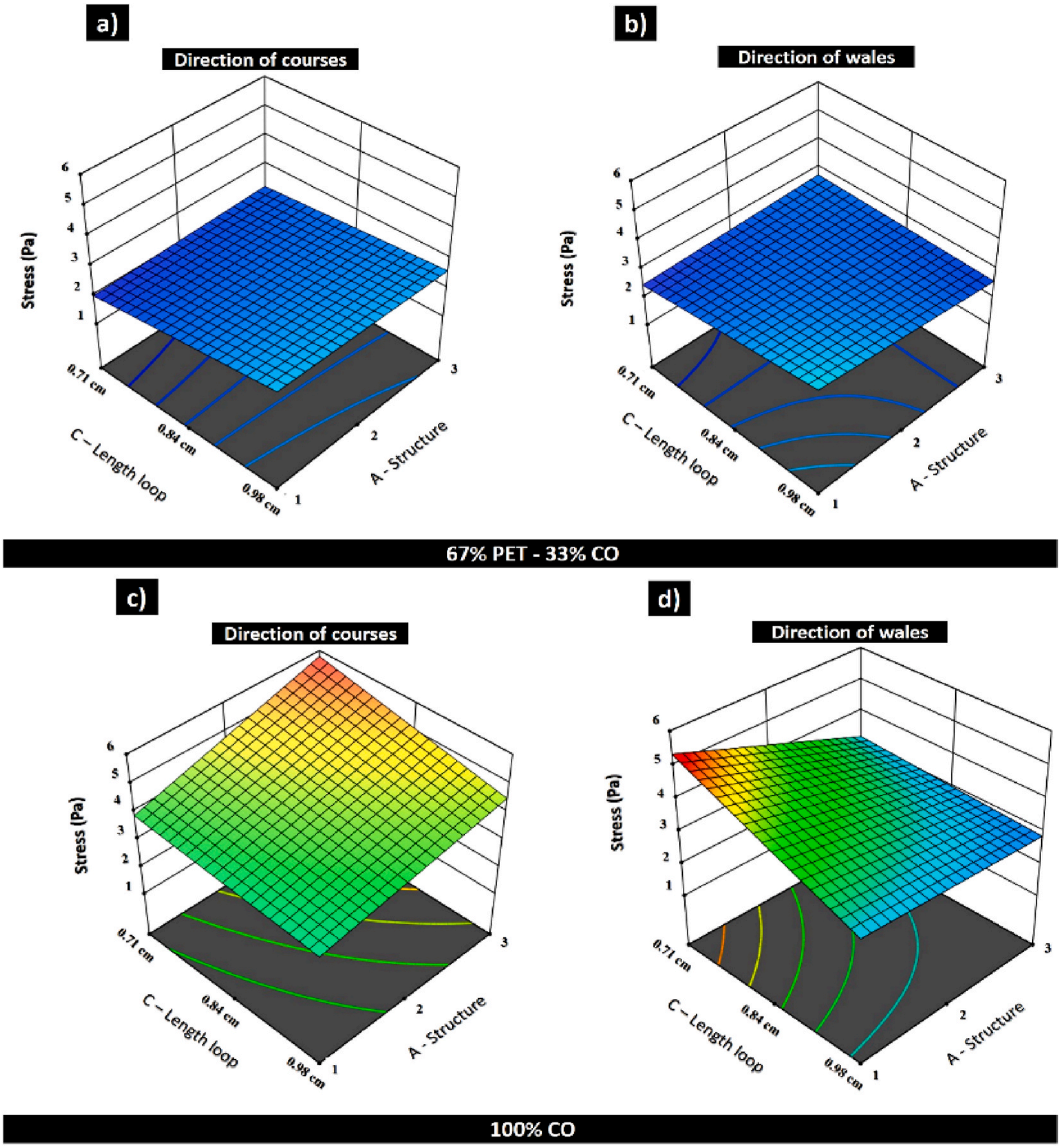

Fig. 2. Results of stress analyzed using response surface methodology (RSM).

the loop length increases, the density of float stitches decreases, resulting in a decrease in the overall stress properties. To summarize, the study concludes that the loop length plays a critical role in determining whether the stress property of the fabric increases or decreases. Additionally, the density of float stitches significantly impacts the change in stress property, further highlighting its importance in the mechanical behavior of knitted fabrics. These findings provide valuable insights into optimizing the mechanical properties of knitted fabrics for various applications, especially in textile composites where stress resistance is of utmost importance.

3.1.2. Mechanical behaviour of strain

Fig. 3 presents a comprehensive analysis of the property behavior of two types of textiles knitted fabric: one composed of 100% CO (Fig. 3 c and 3 d) and the other a blend of 67% PET and 33% CO (Fig. 3a and b). The study also explores the impact of different loop lengths (0.71 cm, 0.84 cm, and 0.98 cm) and fabric structures (1 to 3) on the wales, which are columns of stitches in the knitted fabric. When examining the strain behavior of knitted fabrics with 0.71 cm and 0.98 cm loop lengths and structures 1, 2, and 3, it was observed that they exhibited similar strain properties. The results showed that structure 1, characterized by a lower float stitch density, had a value of 2, while structure 2, with an intermediate float stitch density, yielded a value of 2.1. Structure 3, which had a higher float stitch density, resulted in a value of 2.2. These values demonstrate that an increase in float stitch density leads to a promotion of higher float stitch density, causing a 10% reduction in the strain property (Fig. 3c). Moreover, for knitted fabric structures 1 to 3 with a loop length of 0.71 cm (Fig. 3c), an increase in float stitch density led to a significant reduction of up to 60% in the strain property. On the

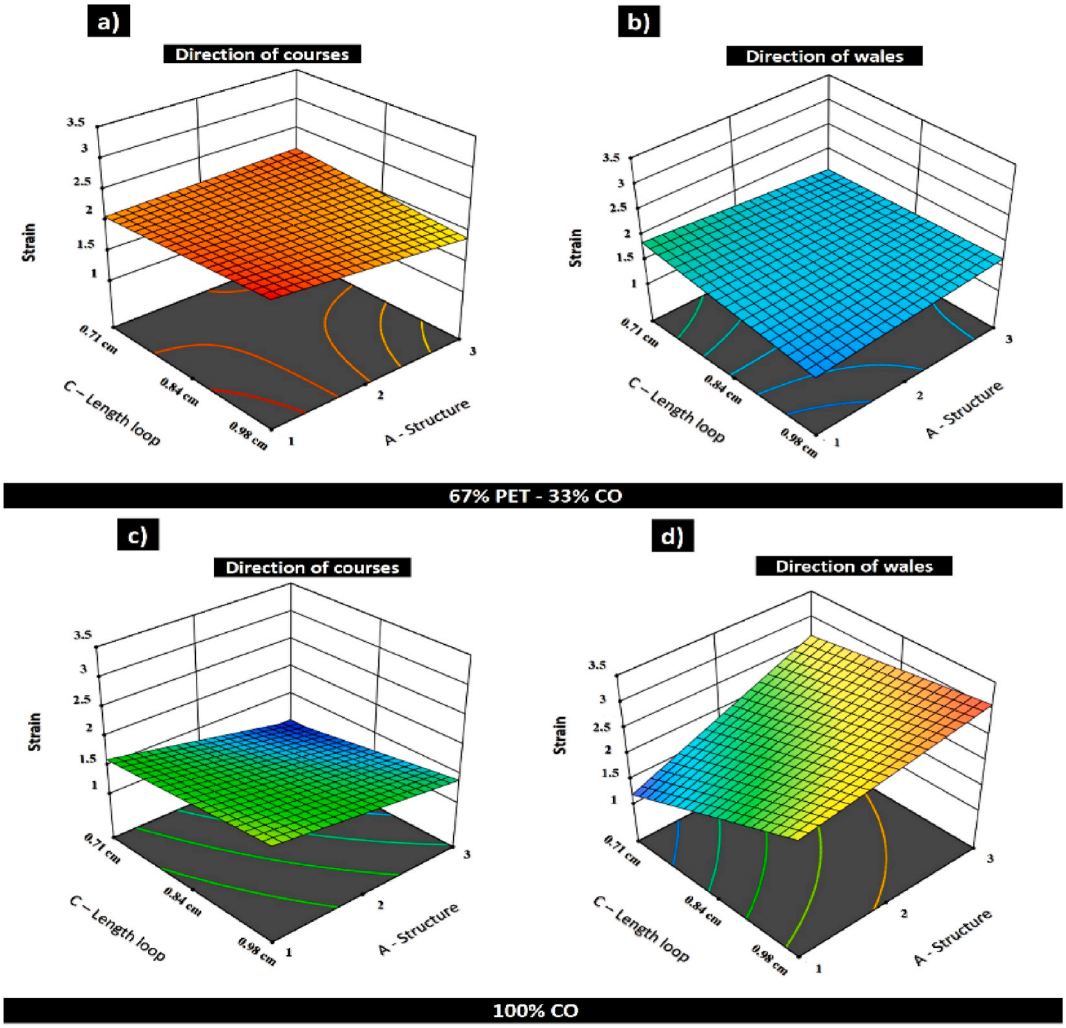

Fig. 3. Results of strain analyzed using response surface methodology (RSM).

other hand, in knitted fabric compositions with 67% PET and 33% CO, increasing the loop length significantly diminished the influence of float stitch density. For structure 1 in these compositions, the strain property in the course direction (rows of stitches) was higher compared to the 67% PET 33% CO composition, regardless of the loop length. However, when comparing different compositions, the strain property of 100% CO fabrics surpassed the hybrid composition, exhibiting values 25% to 50% higher in the course direction. In Fig. 3b and d, the strain property of knitted fabric structures composed of 100% CO and 67% PET 33% CO yarns, respectively, in the wale direction (columns of stitches), is depicted. It was observed that changes in float stitch density and loop length had distinct effects on the knitted fabric structures in the wale direction, which differed from the effects observed in the course direction. Additionally, the incorporation of a synthetic fiber (polyester) in the 67% PET/33% CO composition resulted in a 1.3-fold increase in strain property values in the wale direction compared to fabric structures composed entirely of 100% CO. Overall, Fig. 3 provides valuable insights into the tensile properties of knitted fabrics concerning composition, float stitch density, and loop length, offering essential information for understanding the performance and characteristics of these fabrics in various applications.

3.1.3. Mechanical behaviour of Young's modulus

In Fig. 4 a, and Fig. 4 b, Fig. 4 c, and Fig. 4 d illustrate the mechanical behaviour of textile materials used as reinforcement for composite materials in relation to Young's modulus (MOE). MOE can be determinated as the stress/strain ratio. Statistical analyses of MOE behaviour can be characterized by the maximum stress that material can receive without undergoing permanent changes in relation to strain. It quantifies stiffness and it's one of resistance indicators [13]. It is observed in Fig. 4a, and owns a uniformity of mechanical behaviour of Young's modulus in relation to structures and the loop length, but in Fig. 4b it is observed that structure 1 (2 float stitches) with loop length 0.98 cm has a significant increase in Young's modulus [33]. Knitted fabric structures composed of 100% CO with lower loop length (Fig. 4c and d) demostrated a remarkable increase in performance. This is providing to the fact that the reduced loop length induces greater contraction in the loops. Specifically, in Fig. 4c, fabric structures with higher float stitch density

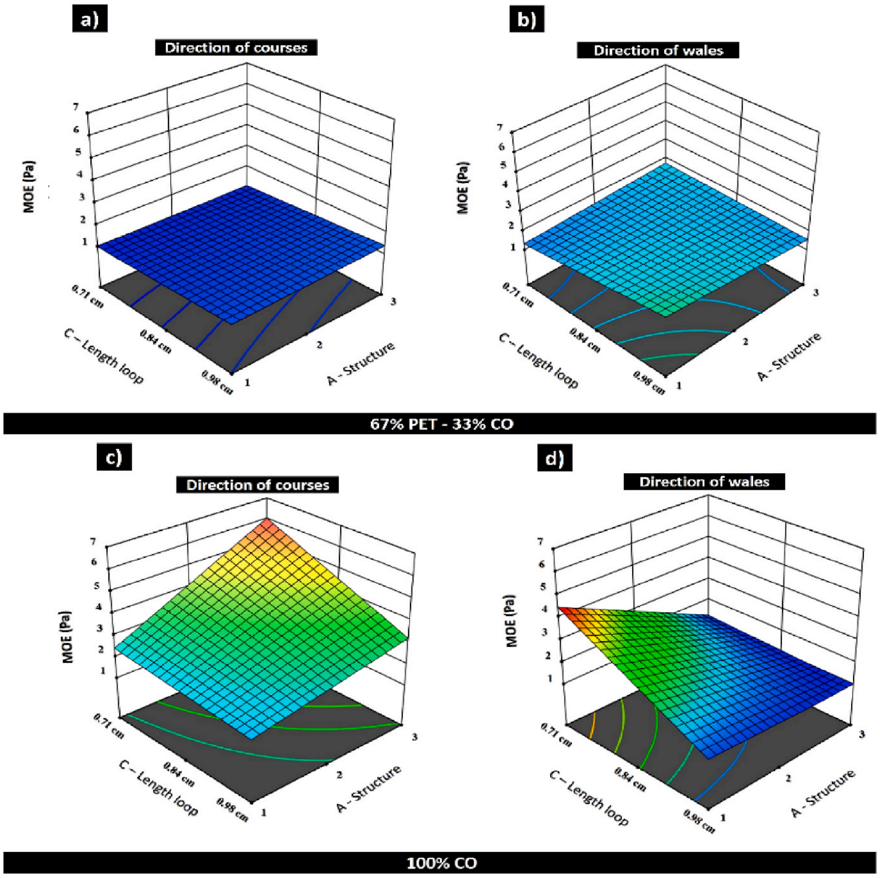

Fig. 4. Results of Young's modulus analyzed using response surface methodology (RSM).

and lower loop length demonstrated a significantly improved Young's modulus performance in the course direction for 100% CO fabrics. The float stitch density reduction allows improvement and stability to the knitted fabric structure, thus favouring mechanical behaviour. It is shown in Fig. 4d that the knitted fabric structures with lower loop length and lower float stitch density show significant improvement in the mechanical behaviour performance of Young's modulus. In other words, the lower float stitch density and lower loop length favor a greater contraction in the knitted fabric structure which makes it more resistant in relation to strain property. However, the elasticity is significantly reduced. Furthermore, it was observed that knitted fabric structures with intermediate loop length, regardless of the float stitch density, exhibit higher consistency and lower variation in the values of Young's modulus.

3.1.4. Mechanical behaviour of work of rupture

Based on the analyzed results, was defined that the work of rupture in jersey-knitted fabrics were affected by both float stitch density (2, 5, and 8 float stitches) and loop length (0.98 cm, 0.84 cm, and 0.71 cm) as depicted in Fig. 5. When the float stitch density is increased, the work of rupture also increases. However, the extent of this increase or decrease depends significantly on the loop length applied, as shown in Fig. 5a. With an increase in loop length, the positive effect of float stitch density becomes more pronounced, leading to a greater increase in rupture work. Conversely, when the loop length decreases, the negative influence of float stitches intensifies, resulting in reduced break energy values. These observations are visually represented in Fig. 5c. The intensity of the rupture work results is primarily determined by the float stitch density. For instance, when considering a loop length of 0.98 cm, increasing the float stitches from structure 1 to structure 3 (2, 5, and 8 float stitches) results in a 17.7% increase in the rupture work. However, for a knitted fabric structure with a loop length of 0.71 cm, increasing the float stitch density from structure 1 to 3 leads to a reduction of 45% in the rupture work value, as illustrated in Fig. 5c. Furthermore, the obtained results confirm that the rupture work in jersey-knitted fabric structures was influenced by both the presence of float stitches and loop length. Notably, as the length of loop increased, the work of rupture also increases, as demonstrated in Fig. 5c and d. For instance, with a loop length of 0.98 cm, an increment in float stitch density (from structure 1 to 3) leads to an 11.3% rise in the work of rupture. On the other hand, for a loop length of 0.71 cm, an increment in float stitch density (from structure 1 to 3) results in a significant increase of 57.3% in the work of rupture. These tests show that, in terms of an increase in rupture work, float stitch density has a more substantial impact than loop length. Moreover, it has been verified that the work of rupture is influenced by both the increased length of the loop and the number of float stitches. Specifically, a higher float stitch density (8 float stitches) indeed results in a greater work of rupture, regardless of length

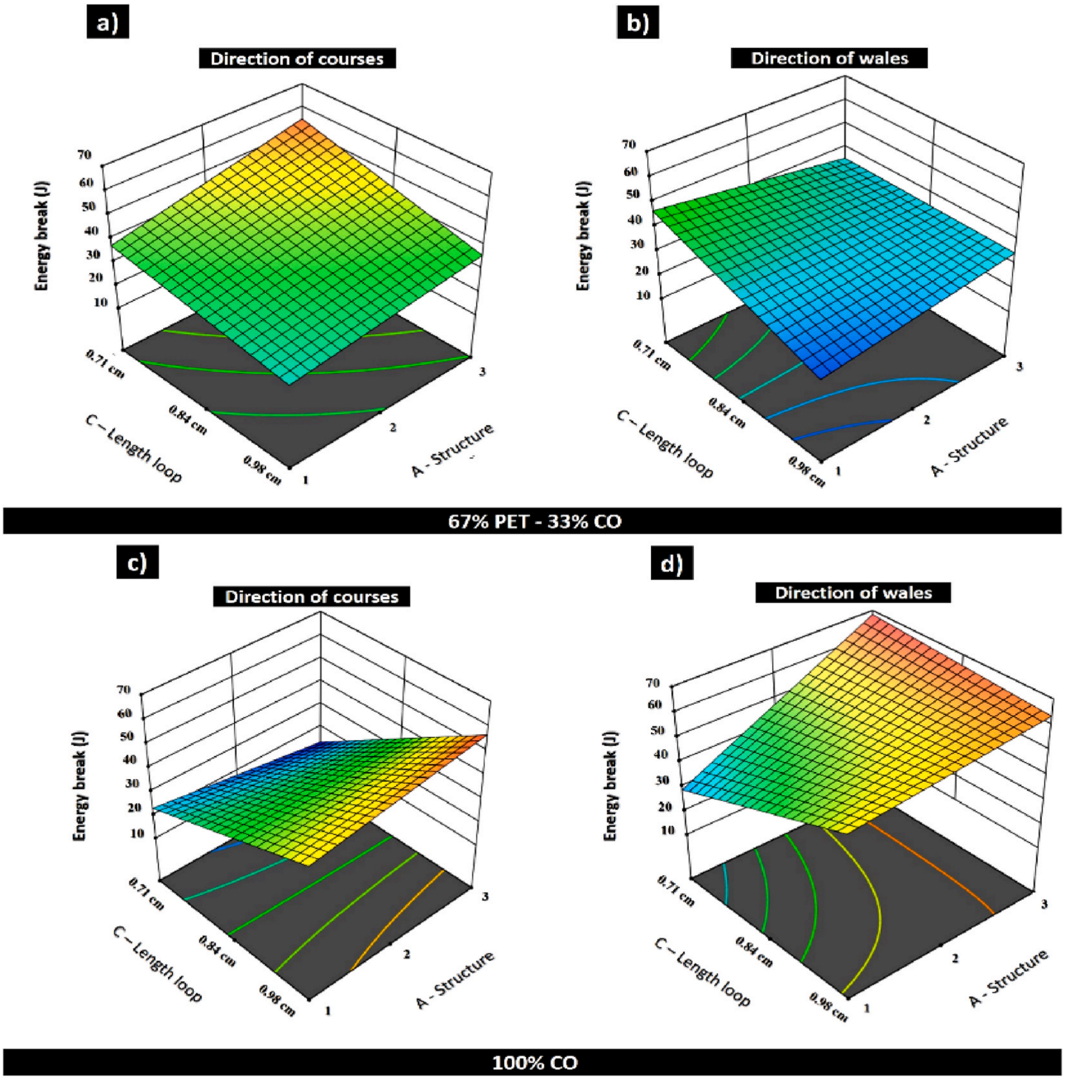

Fig. 5. Results of break energy analyzed using response surface methodology (RSM).

of loop, as exhibited in Fig. 5. For instance, in structure 1, for each loop length of 0.98 cm, the rupture work is 27 J, while for structure 3, it increases to 36.29 J, indicating a 25.6% increase. When float stitch density is increased from structure 1 to structure 3 (2, 5, and 8 float stitches, respectively), the rupture work increases by 31.8% for each loop length of 0.71 cm (Fig. 5a). In other words, the lower loop length promotes an improvement in the property of rupture work. The highest increase (31.8%) was observed for the lower loop length value (0.71 cm), while the highest loop length value (0.98 cm) obtained the smallest increase (25.6%). When the length of loop was shorter, the positive influence of float stitch density on increasing the rupture work was greater (Fig. 5a). Conversely, when the length of loop was increased, the positive influence of float stitch density on increasing the work of rupture is diminished (Fig. 5a). Additionally, it was observed that longer loop lengths promoted lower work of rupture, while smaller loop lengths promoted greater work of rupture (Fig. 5b). In conclusion, the study highlights the significance of float stitch density, and length of the loop on the rupture work in jersey-knitted fabrics. It demonstrates that higher float stitch density generally leads to an increase in rupture work, but the extent of this effect depends on the specific loop length used. The findings provide valuable insights for fabric design and manufacturing processes to achieve desired properties in jersey-knitted fabrics.

3.1.5. Analyses of variance (ANOVA) in natural and blended yarns

The ANOVA statistical models employed to analyze stress, strain, Young's modulus, and work of rupture in knitted fabric structures (100% CO and 67% PET/33% CO) are deemed validated when the set of data (residual values) exhibits a close alignment or well-distributed pattern along straight lines. This alignment and pattern serve as indicators of the models' reliability and accuracy in predicting and explaining the variation in the mechanical properties of the fabric structures. In such cases, the corresponding ρ-values exhibit values equal to or higher than 0.05 ($\rho \geq 0.05$), indicating a satisfactory level of statistical significance. As a result, the F-value is employed to statistically assess the extent of variation or distinction in the average of each response variable. A lower F-value indicates that the average squares of the statistical models are smaller compared to the larger values of average square residuals (higher errors). A higher error value indicates that the ρ-values for variables such as loop length, structure, and composition are less significant. The findings from this analysis are thoroughly examined in this section, and the interactions among these variables are presented in Tables 1 and 2.

The design of experiments revealed significant F-values for all factors: structure (A), composition (B), loop length (C), and their interactions (AB, AC, BC, and ABC) in a factorial design. Consequently, the response variables were adequately represented by the model, as indicated in Tables 1 and 2 Analyzing the factors and their interactions provided valuable insights into the considerable enhancements, maintenance, or reductions in the mechanical behavior and performance of jersey knitted fabric structures commonly employed in textile-reinforced composite materials. Through the statistical adjustment of the data set for stress, strain, Young's modulus, and work of rupture in knitted fabric structures with knitting yarns in the wale direction, significantly low standard deviations were obtained for stress (0.02 Pa), strain (0.06), Young's modulus (0.04 Pa), and work of rupture (0.90 J). This indicated that the level of data dispersion around the means promoted a lower coefficient of variation (CV%) in mechanical responses of knitted fabric structures commonly used in textile-reinforced composite materials (as shown in Table 1). Likewise, the statistical adjustment of the data set for stress, strain, Young's modulus, and work of rupture in knitted fabric structures in the course direction revealed significantly low standard deviations for stress (0.07 Pa), strain (0.05), Young's modulus (0.05 Pa), and work of rupture (0.99 J). These values indicated a lower data dispersion level around the respective averages of 3.47 Pa, 2.25, 1.76 Pa, and 37.84 J. Consequently, this promoted a lower variation coefficient (CV%) in mechanical responses of knitted fabric structures commonly used in textile-reinforced composite materials (as shown in Table 2).

3.2. *Knitted fabric structures with synthetic yarns*

3.2.1. *Mechanical behaviour of stress*

Mechanical behavior of 100% PA textile knitted fabric and 100% PET loading with the influence of loop length (0.71 cm, 0.84 cm, and 0.98 cm), as well as structure 1 (2 float stitches), structure 2 (5 float stitches) and structure 3 (8 float stitches) in wales and courses directions are shown in Fig. 6. Stress means the force/area ratio in order to measure the capacity of a deformable material. Both knitted structures obtained a significant improvement in mechanical stress performance due to the presence of the higher float stitch density (8 float stitches). The improved performance of the jersey knitted fabric structures can be attributed to the nature of float stitches, which are not subjected to the stress applied by knitting needles during the knitting process, unlike the knit and tuck stitches. This absence of stress on float stitches allows for better mechanical properties and performance in the fabric structures. Fig. 6a and b shows a comparison in direction of wales and courses of textile structures with a composition of 100% PET. As already mentioned in structural terms, jersey knitted fabrics with higher float stitch density showed greater performance, while course direction and loop length (0.98 cm) showed greater stress properties. A combination of 8 float stitches with higher loop length (0.98 cm) consequently provided improvement in stress property while lower rigid knitted fabric structures provided greater elasticity and thus more deformability [34].

3.2.2. *Mechanical behaviour of strain*

Fig. 7 presents the results depicting variations in the mechanical behavior of strain for two different yarn compositions, 100% PET (Fig. 7a and b) and 100% PA (Fig. 7c and d). The study explores the impact of loop length (0.71 cm, 0.84 cm, and 0.98 cm) and fabric structures (1, 2, and 3) on strain in both wale and course directions. For Fig. 7a, the strain in the course direction for structures 1, 2, and 3 with a loop length of 0.71 cm exhibited similar values. However, when the loop length increased to 0.84 cm and 0.98 cm, the strain values differed. This analysis indicates that a decrease in loop length leads to higher strain values. The increase in loop length contributed to a reduction in strain due to the increased density of float stitches. Moreover, the analysis revealed that for loop lengths

Table 1
ANOVA of mechanical behaviour and mechanical properties of knitted fabric structures in wale direction.

	Stress (Pa)		Strain		Young's modulus (Pa)		Break energy (J)	
	F-value	p-value (Prob > F)	F-value	p-value (Prob > F)	F-value	p-value (Prob > F)	F-value	p-value (Prob > F)
Model	2957.66	<0.0001	657.93	<0.0001	784.29	<0.0001	689.60	<0.0001
A – Structure	3569.61	<0.0001	951.46	<0.0001	764.83	<0.0001	625.39	<0.0001
B – Composition	6338.73	<0.0001	69.73	<0.0001	1689.06	<0.0001	1730.35	<0.0001
C - Loop length	1802.18	<0.0001	499.09	<0.0001	415.10	<0.0001	0.03	0.87
AB	2255.43	<0.0001	708.97	<0.0001	804.04	<0.0001	699.79	<0.0001
AC	474.44	<0.0001	228.27	<0.0001	30.59	0.0003	36.83	0.0001
BC	4456.95	<0.0001	1159.94	<0.0001	936.12	<0.0001	618.52	<0.0001
ABC	3550.15	<0.0001	1057.72	<0.0001	420.83	<0.0001	873.55	<0.0001
Standard dev.	0.02		0.06		0.04		0.90	
Mean	3.29		1.93		1.95		42.00	
C.V. %	0.69		1.26		1.83		2.14	
R^2	0.99		0.99		0.99		0.99	
Adjusted R^2	0.99		0.99		0.99		0.99	

Table 2
ANOVA of mechanical behaviour and mechanical properties of knitted fabric structures in course direction.

	Stress (Pa)		Strain		Young's modulus (Pa)		Break energy (J)	
	F-value	p-value (Prob > F)	F-value	p-value (Prob > F)	F-value	p-value (Prob > F)	F-value	p-value (Prob > F)
Model	638.22	<0.0001	2634.33	<0.0001	150.90	<0.0001	492.26	<0.0001
A - Structure	472.50	<0.0001	3217.90	<0.0001	200.95	<0.0001	172.38	<0.0001
B - Composition	3373.54	<0.0001	9817.21	<0.0001	773.41	<0.0001	64.87	<0.0001
C - Loop length	18.13	0.0017	908.29	<0.0001	34.15	0.0002	373.19	<0.0001
AB	428.78	<0.0001	2739.45	<0.0001	80.67	<0.0001	195.19	<0.0001
AC	76.09	<0.0001	604.21	<0.0001	3.79	0.0800	33.89	0.0002
BC	434.28	<0.0001	1922.89	<0.0001	67.63	<0.0001	2399.27	<0.0001
ABC	12.05	0.0060	685.69	<0.0001	47.96	<0.0001	205.46	<0.0001
Standard dev.	0.07		0.05		0.05		0.99	
Mean	3.47		2.25		1.76		37.84	
C.V. %	2.00		2.01		2.63		2.63	
R^2	0.99		0.99		0.99		0.99	
Adjusted R^2	0.99		0.99		0.99		0.99	

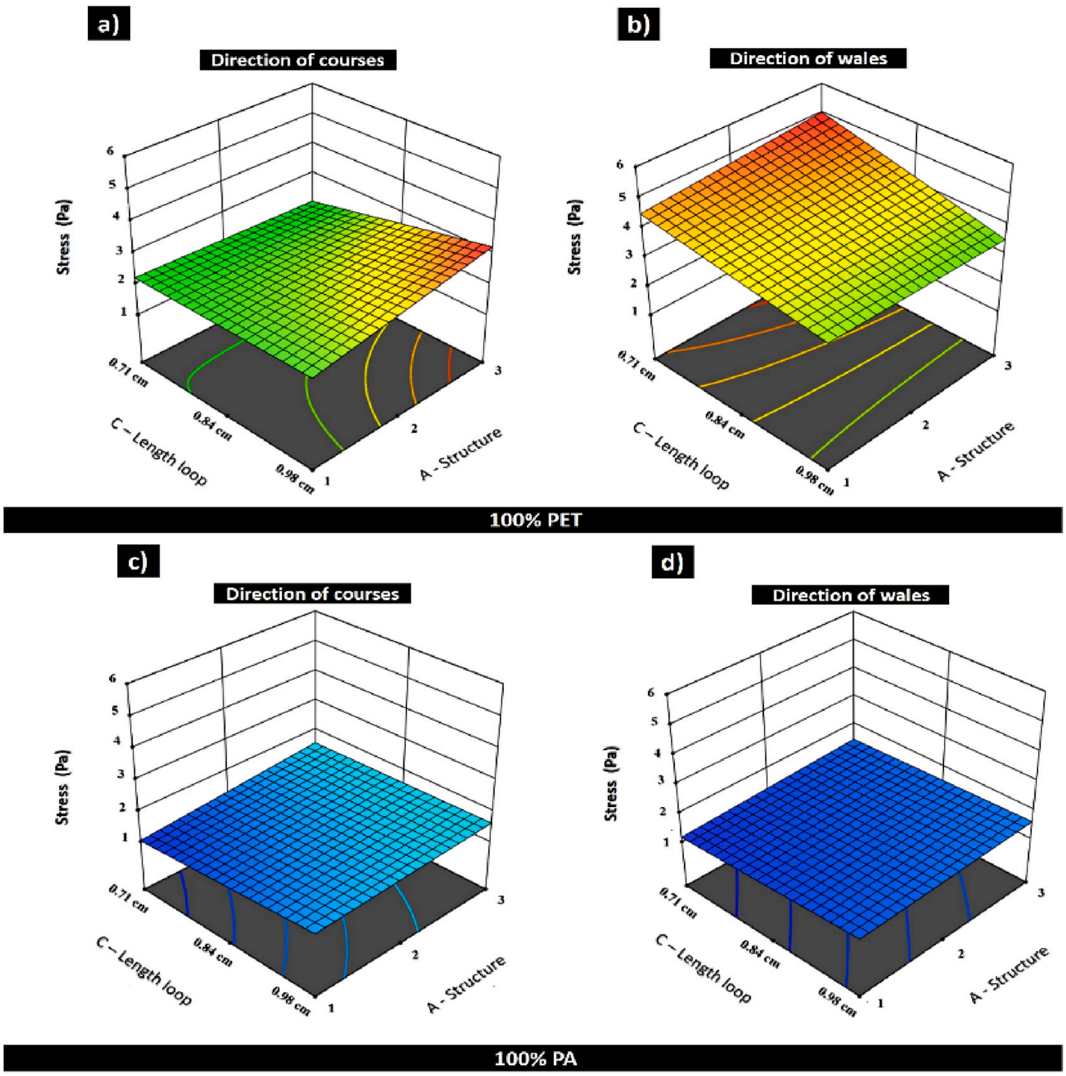

Fig. 6. Results of stress analyzed using response surface methodology (RSM).

of 0.84 cm and 0.98 cm, the strain values were significantly higher than the average observed for structures with 8 float stitches. Overall, Fig. 7 provides valuable insights into how loop length and fabric structures impact strain properties of knitted fabrics with different yarn compositions and directions, aiding in the understanding of the mechanical behaviour of these materials. Fig. 7b showed a reduction in strain mechanical behaviour of knitted fabric structure in the wale direction, while Fig. 7a presented the lower changes in relation to loop length and structures (1, 2, and 3). In comparison the results obtained from Fig. 7a and b (100% PET) and 7c, 7d (100% PA) revealed that the strain results were exposed for polyamide composition being superior when compared to polyester (100% PET). A slight homogeneity in results was observed in Fig. 7d. When comparing the structures with respect to loop length (0.71 cm, 0.84 cm, and 0.98 cm), the values of strain exhibited lower changes varying from 3 to 3.5 strain properties in knitted fabric structures.

Finally, the analysis of all data revealed the tests performed for compositions 100% PET and 100% PA that showed significantly different values of strain because of polyamide and polyester synthetic polymers. In the chemical structure of polyamide (PA), there are recurring amid groups (R–CO – NH — R′) as integral components of the main polymer chain. On the other hand, in the chemical structure of polyethylene terephthalate (PET), there are benzene rings that contribute to the rigidity of amorphous regions in polyester fibers used in composite knitted fabric structures [35,36]. Consequently, the knitted fabric structures composed of 100% polyamide (100% PA) exhibited strain values greater than those made of 100% polyester (100% PET). This observation highlights the significance of fabric compositions, with structures containing 100% cotton (100% CO) and a blend of 67% polyester/33% cotton (67% PET/33% CO) being commonly employed as reinforcement in textile composites. Together, this contributes significantly to increasing or decreasing the results of mechanical behaviour (strain) along with the type of structure (1, 2, and 3) and loop length [37].

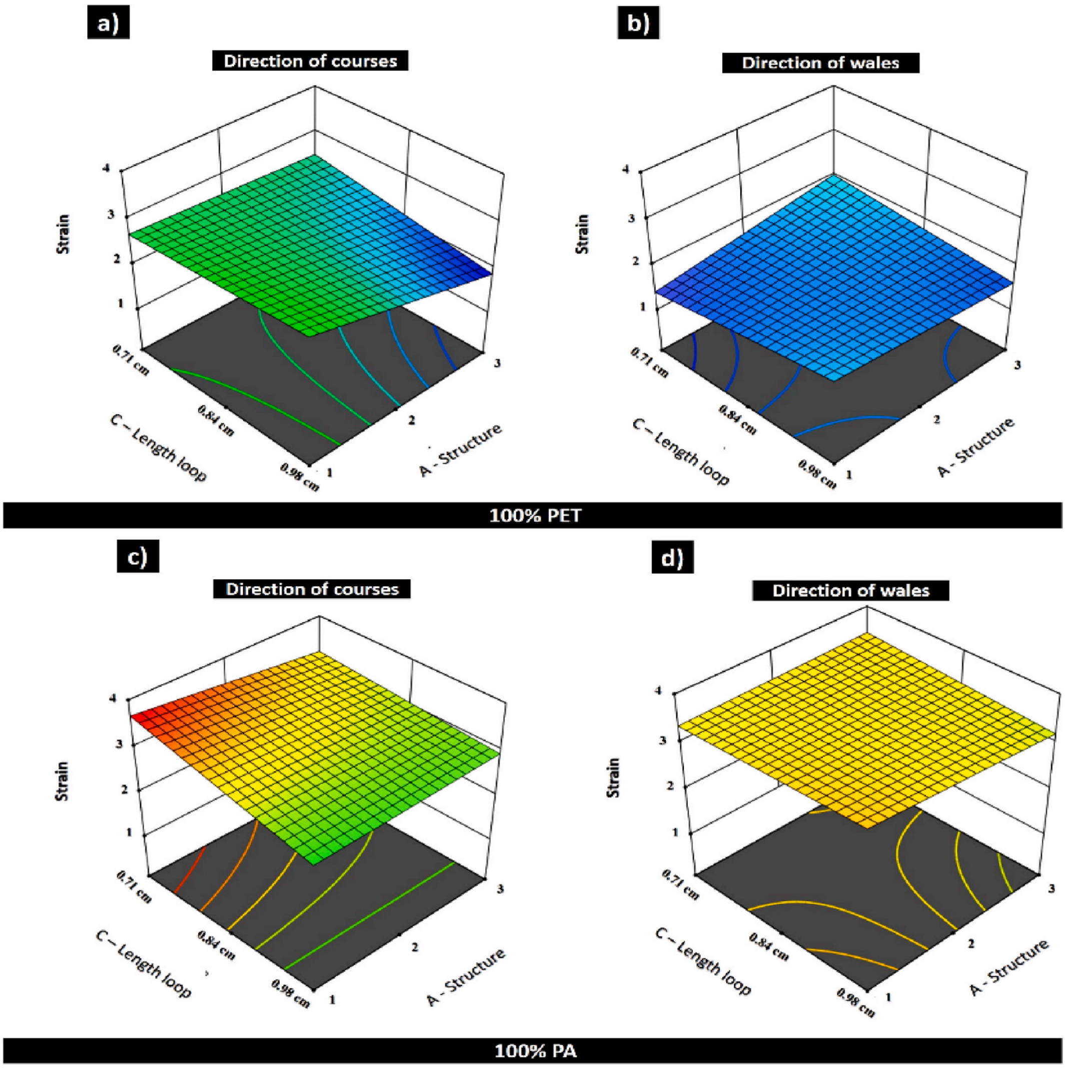

Fig. 7. Results of strain were analyzed using response surface methodology (RSM).

3.2.3. Mechanical behaviour of Young's modulus

As stated earlier, Young's modulus holds significant importance in the realm of composite materials, particularly when employing textiles like knitted fabrics. Fig. 8 shows the mechanical behaviour of textile materials used as reinforcement for composite materials. Fig. 8c and d showed uniformity of mechanical behaviour of Young's modulus in relation to structure 1, structure 2, structure 3, and for loop lengths 0.98 cm, 0.84 cm, and 0.71 cm. Observations from Fig. 8a and b indicate that structures with lower float stitch density (2 float stitches) and greater loop length (0.98 cm) exhibited a significant increase in performance and Young's modulus value. On the contrary, knitted fabric structures with higher float stitch density and lower loop length (0.71 cm) demonstrated significant improvement in terms of Young's modulus in both the wales and courses. In contrast, reducing the float stitch density contributed to the enhancement and greater stability of knitted fabric structure by favoring mechanical behaviour changes in Young's modulus. In conclusion, the relationship between variable loop length and structure in the course direction was found to be directly proportional, whereas in the wale direction, it was determined to be inversely proportional for the textile structures commonly used to reinforce textile composites, as depicted in Fig. 8a and b.

3.2.4. Mechanical behaviour of work of rupture

The influence of float stitch density and loop length on the course direction of knitted fabric structures, which utilized synthetic knitting yarns, was investigated in this study. The results, as depicted in Fig. 9c, indicate that both the number of float stitches (2, 5, and 8) and the loop length (0.98 cm, 0.84 cm, and 0.71 cm) have a significant impact on the work of rupture. The utilization of higher

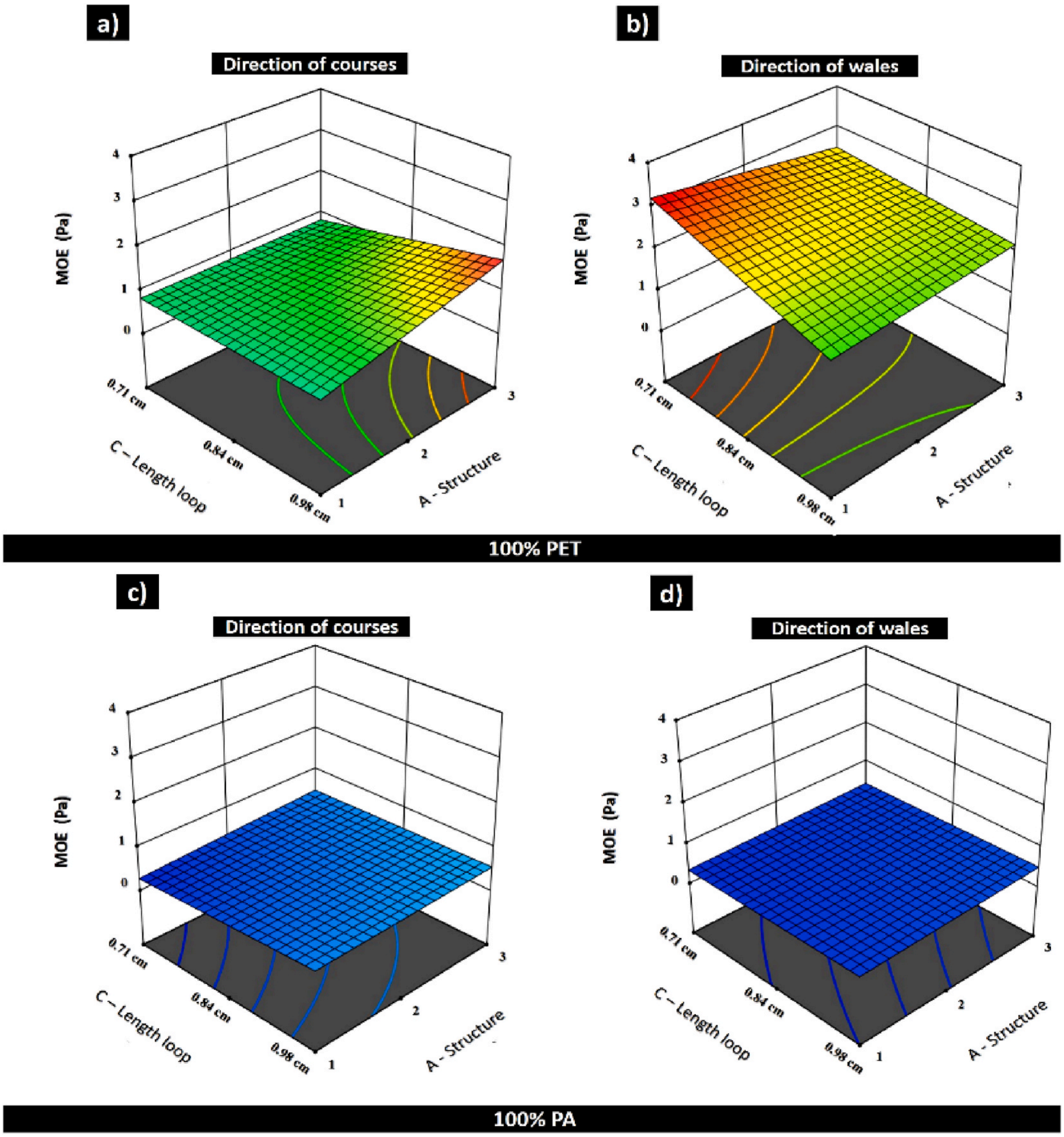

Fig. 8. The results of Young's modulus were analyzed using response surface methodology (RSM).

float stitch density resulted in notably high work of rupture values (J) as observed in Fig. 9c. Moreover, reduced values of work of rupture were obtained when employing a loop length (0.98 cm). Interestingly, the same loop length, when combined with an increase in float stitch density from structure 1 to structure 3, led to a substantial 44.3% increase in the work of rupture value. Whereas a 0.71 cm loop length increases the float stitch density from structure 1 to structure 3, which represents significantly higher values of work of rupture (32%). Also, an increase in work of rupture was obtained with greater intensity (exponential growth) in float stitches with a lower loop length (0.71 cm) and 100% PA composition as seen in Fig. 9c. The findings from the wale direction indicate a significant influence of float stitch density and, consequently, the length of the loop in knitted fabrics composed of 100% PA knitted yarns on the break energy, as visually represented in Fig. 9d. Was also observed that when the loop length variable decreases (0.71 cm), a greater positive influence of float stitch density (structure 1 to structure 3) on the work of rupture is obtained. Thus, loop length 0.98 cm and float stitch density exhibited a discrete reduction of 7.3% in work of rupture property, while loop length 0.71 cm with float stitch density promoted the improvement and significantly increased work of rupture by 32.5% of knitted fabric structures (Fig. 9d). When the float stitch density increased, the work of rupture values decreased significantly. Nevertheless, it was observed that when the loop length variable increased, the work of rupture property decreased in Structure 1 (2 float stitches) and experienced a slight increase in Structure 3 (8 float stitches), as depicted in Fig. 9a. Also, when comparing 100% PA and 100% PET structures, it was verified that the jersey-knitted fabric structures composed of polyester did not significantly improve the work of rupture when analyzed under identical structure conditions along with loop lengths (Fig. 9a and b). It is essential to highlight that the most substantial increase in the work of rupture property concerning float stitch density was observed in knitted fabric structures with a higher loop length (0.98 cm). For

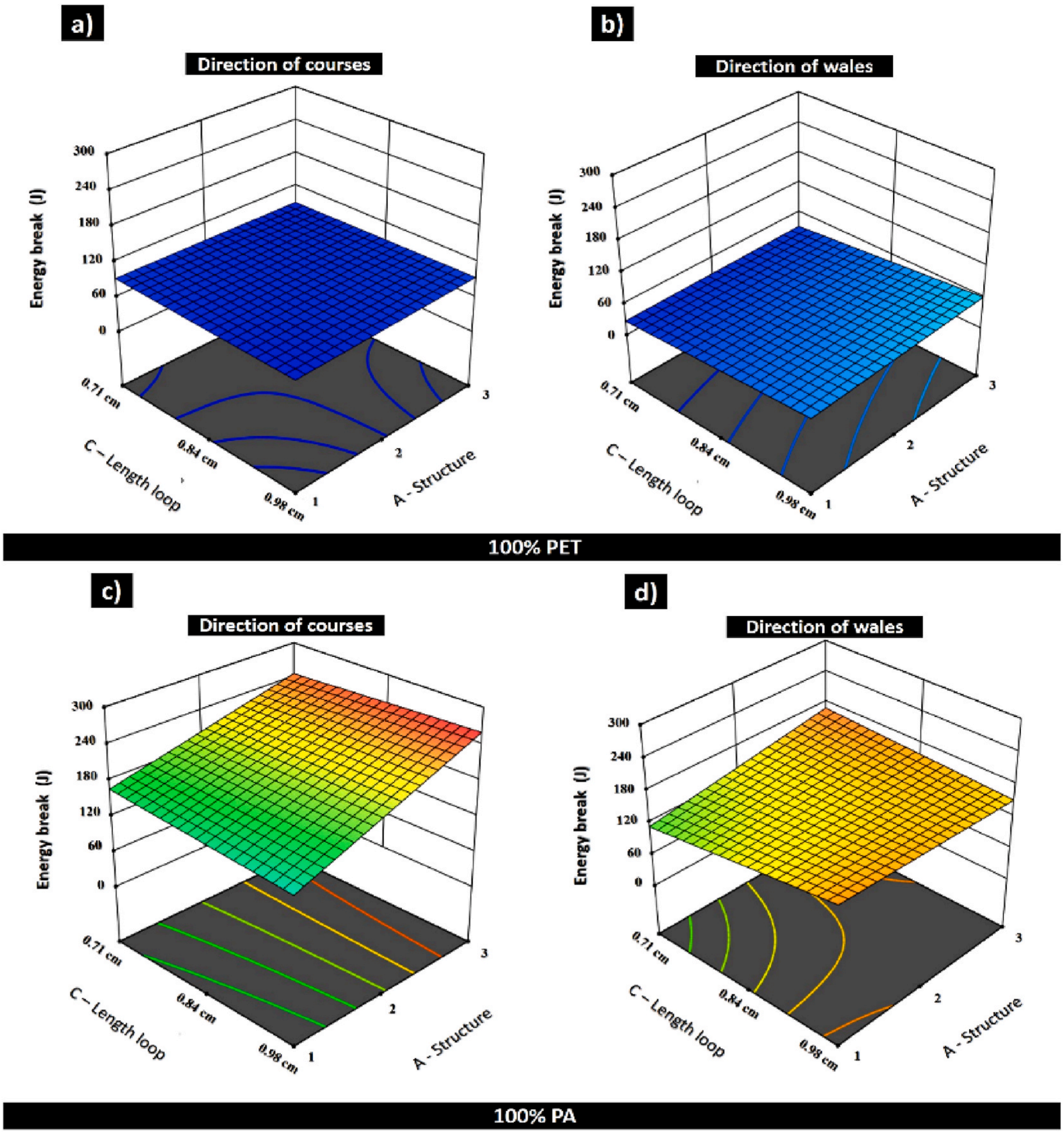

Fig. 9. Results of break energy analyzed using the response surface methodology (RSM).

example, there was a remarkable 22.8% increase from structure 1 to structure 3, as shown in Fig. 9b. This finding underscores the influence significant in length of loop on the work of rupture, emphasizing the importance of considering this factor when designing knitted fabric structures for specific applications [38].

3.2.5. Analysis of variance (ANOVA) in synthetic yarns

The subsequent analyses pertain to the statistical models of tensile properties for knitted fabrics produced using synthetic knitting yarns (100% PA, and 100% PET) in the wale direction. It is important to consider that the F-value provides a statistical assessment of the variation or distinctiveness in the average response for each variable. A lower F-value suggests that the average squares of the statistical model are smaller in comparison to larger values of average residual squares, indicating higher errors. When the error value is higher, it indicates that there is more variability in the data, and thus the ρ-values for the variables independent (A, B, and C) become less significant. Tables 3 and 4 present the interactions between different variables and their corresponding ρ-values.

The study's findings revealed that various knitted fabric structures created with synthetic knitting yarns (100% PA and 100% PET) showed significant F-values in factorial designs for the variables of structure (A), composition (B), loop length (C), as well as their interactions (AB, AC, BC, and ABC). The statistical model effectively represented the response variables, as evidenced in Tables 3 and 4 It was evident that the factors and their interactions studied had a considerable impact on the mechanical behavior of the knitted fabric structures, resulting in significant reductions or improvements. The performance of the mechanical properties of jersey-knitted fabrics made from synthetic knitting yarns was noteworthy. These fabrics are commonly used in textile-reinforced composite materials [39]. After adjusting the statistical data, the stress (0.05 Pa), strain (0.04), Young's modulus (0.08 Pa), and rupture work (3.37 J) for knitted fabric structures in the wale direction exhibited remarkably low standard deviations. Additionally, the level of data dispersion around the mean values of 2.74 Pa, 1.42, 2.59 Pa, and 99.79 J, along with the corresponding coefficient of variation (CV%) of 1.67%, 3.00%, 3.00%, and 3.38%, respectively, was obtained for the tensile responses of the knitted fabrics used as reinforcement in composite materials (see Table 3).

In conclusion, the statistical analysis of the data presented in Table 4, pertaining to knitted fabric structures composed of synthetic knitting yarns in the course direction, demonstrates remarkably low standard deviations for stress (0.03 Pa), strain (0.02), MOE (0.04 Pa), and rupture work (0.85 J) [40]. This indicates a limited level of data dispersion around the respective averages of 1.91 Pa, 0.74, 2.78 Pa, and 147.00 J, with a corresponding coefficient of variation percentages (CV%) of 1.74%, 2.70%, 1.20%, and 0.58%. These findings highlight the precise and consistent tensile responses of knitted fabrics used as reinforcement in composite materials. Furthermore, they solidify the potential of these structures for reliable and controlled applications in various engineering and industrial fields.

4. Conclusions

4.1. In the case of knitted fabrics with natural, and blended yarns

Knitted fabrics with 100% CO knitting yarns exhibited notably higher stress property values when compared to those composed of hybrid knitting yarns, considering various lengths of loops, structures, and directions of wales, and courses. The stress property was found to be significantly influenced by float stitch density and the loop length of jersey-knitted fabrics. Loop length was a major influencing factor that decides the increment or decrement in stress property, while float stitch density intensified the change in stress property. The increase in loop length for structures of 67% PET/33% CO composition significantly decreases the influence of the float stitch density in course direction. Independent of loop length, structures with 2 float stitches got higher strain properties in course direction for hybrid composition. The presence of PET in hybrid composition increases strain property in the wale direction by twice the amount as compared to structures composed of 100% CO. However, a composition with 100% CO was the highest value in strain. Knitted fabric structures made by 100% CO with 0.71 cm loop length showed a significant increase because of the lower loop length

Table 3
ANOVA of mechanical behaviour and mechanical properties of knitted fabric structures in wale direction.

	Stress (Pa)		Strain		Young's modulus (Pa)		Break energy (J)	
	F-value	p-value (Prob > F)	F-value	p-value (Prob > F)	F-value	p-value (Prob > F)	F-value	p-value (Prob > F)
Model	2802.70	<0.0001	1804.20	<0.0001	391.48	<0.0001	887.77	<0.0001
A – Structure	82.61	<0.0001	9.43	0.0118	0.12	0,7404	81.18	<0.0001
B – Composition	14972.4	<0.0001	9132.65	<0.0001	1782.66	<0.0001	4174.43	<0.0001
C - Loop length	415.51	<0.0001	283.42	<0.0001	0.05	0,8363	152.89	<0.0001
AB	1.75	0.2157	51.40	<0.0001	11.91	0,0062	14.71	0,0033
AC	71.45	<0.0001	135.25	<0.0001	72.09	<0.0001	70.33	<0.0001
BC	872.73	<0.0001	405.27	<0.0001	1.74	0,2170	7.70	0.0196
ABC	50.12	<0.0001	116.79	<0.0001	10.70	0,0084	133.89	<0.0001
Standard dev.	0.05		0.04		0.08		3.37	
Mean	2.74		1.42		2.59		99.79	
C.V. %	1.67		3.00		3.00		3.38	
R^2	0.99		0.99		0.99		0.99	
Adjusted R^2	0.99		0.99		0.99		0.99	

Table 4
ANOVA of mechanical behavior and mechanical properties of knitted fabric structures in course direction.

	Stress (Pa)		Strain		Young's modulus (Pa)		Break energy (J)	
	F-value	p-value (Prob > F)	F-value	p-value (Prob > F)	F-value	p-value (Prob > F)	F-value	p-value (Prob > F)
Model	920.75	<0.0001	978.13	<0.0001	527.89	<0.0001	15594.1	<0.0001
A – Structure	579.91	<0.0001	862.91	<0.0001	481.03	<0.0001	13551.3	<0.0001
B – Composition	3929.35	<0.0001	3305.79	<0.0001	1627.23	<0.0001	69994.0	<0.0001
C - Loop length	656.75	<0.0001	765.93	<0.0001	518.43	<0.0001	38.66	<0.0001
AB	0.1466	0.7098	272.10	<0.0001	150.09	<0.0001	12290.4	<0.0001
AC	193.84	<0.0001	380.24	<0.0001	22.29	0.0008	699.99	<0.0001
BC	122.47	<0.0001	176.38	<0.0001	156.00	<0.0001	10.84	0.0081
ABC	423.64	<0.0001	698.50	<0.0001	460.29	<0.0001	252.31	<0.0001
Standard dev.	0.03		0.02		0.04		0.85	
Mean	1.91		0.74		2.78		147	
C.V. %	1.74		2.70		1.20		0.58	
R^2	0.99		0.99		0.99		0.99	
Adjusted R^2	0.99		0.99		0.99		0.99	

that causes greater contraction in their loops, while structures with 8 float stitches and lower loop length showed significant Young's modulus performance in course direction. The float stitch density reduction allows improvement and stability to the knitted fabric structure by favoring mechanical behaviour. Longer loop lengths promoted lower work of rupture, and smaller loop lengths promoted greater work of rupture. As float stitch density was increased in structures with 0.71 cm loop length, the work of rupture tended to decrease. In another scenario, when the float stitch density was increased in structures with a loop length of 0.98 cm, there was a corresponding decrease in the rupture work value. In conclusion, the statistical adjustment of the dataset for mechanical responses in knitted fabrics, considering the yarns' wale and course direction, resulted in significantly low standard deviations. This finding highlights the reliability and consistency of the tensile properties obtained from these fabric structures.

4.2. In the case of knitted fabrics with synthetic yarns

Knitted structures featuring 8 float stitches exhibited a noteworthy enhancement in mechanical stress performance. This improvement can be attributed to the float stitches being free of stress applied by knitting needles during the knitting formation process, unlike the knit and tuck stitches. Consequently, the presence of float stitches contributed to the overall mechanical strength of the knitted fabric structures. A combination of 8 float stitches with 0.98 cm loop length consequently provided improvement in stress property, while lower rigid knitted fabric structures provided greater elasticity and thus more deformability. The 100% PET and 100% PA compositions showed significantly different values of strain because PA contains recurring amid groups as integral parts of the main polymer chain and PET contains benzene rings in chemical structure which provides rigidity to amorphous regions of polyester fibers that compose knitted fabric structures. Hence composition of 100% PA exhibited strain values higher than 100% PET. Structures with 2 float stitches and 0.98 cm loop length obtained a significant performance in stress applied to the ratio of strain. Also, structures with 8 float stiches and 0.71 cm loop length showed significant Young's modulus performance towards wales and courses, as well as 2 float stitches, allowed improvement and higher stability of knitted fabric structure. The relationship between variable loop length and structure in course direction was found to be directly proportional, while wale direction was inversely proportional to the textile structures. When comparing 100% PA and 100% PET structures, it was verified the jersey-knitted fabric structures composed of polyester did not significantly improve work of rupture when analyzed under identical structure conditions, as well as loop length. The most notable enhancement in the work of rupture property concerning float stitch density was observed in knitted fabric structures with a loop length of 0.98 cm, resulting in a remarkable 22.8% increment from structure 1 to structure 3. In conclusion, the statistical adjustment of the data set for mechanical responses in knitted fabric structures, specifically those made from synthetic yarns with variations in wale and course direction, exhibited significantly low standard deviations. This highlights the reliability and consistency of the obtained results in this study.

Author contribution statement

Lucas Zilio; Mariana Dias; Thiago Santos; Caroliny Santos; Praveenkumara Jagadeesh; Sanjay Mavinkere Rangappa; Suchart Siengchin; Rubens Fonseca; Adriano Amaral; Marcos Aquino: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Data availability statement

Data included in article/supplementary material/referenced in article.

Additional information

No additional information is available for this paper.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This study was supported by our Lord. We thank our colleagues at the Textile Quality Control Laboratory – LABCTEX and Textile Engineering Post Graduate Program - PPgET at the Federal University of Rio Grande do Norte.

References

[1] K.H. Leong, S. Ramakrishna, Z.M. Huang, G.A. Bibo, Potential of knitting for engineering composites - a review, Composites Part A Appl Sci Manuf 31 (2000) 197–220, https://doi.org/10.1016/S1359-835X(99)00067-6.
[2] S.C. Ray, Knitting at a Glance. Fundam. Adv. Knitt. Technol, Elsevier, 2012, pp. 1–11, https://doi.org/10.1533/9780857095558.1.
[3] G. Dusserre, G. Bernhart, Knitting processes for composites manufacture, Adv. Comp. Manuf. Process Des. (2015) 27–53, https://doi.org/10.1016/B978-1-78242-307-2.00002-6. Elsevier.
[4] V. Koncar, Composites and hybrid structures, Smart Text. Situ Monit. Compos., Elsevier (2019) 153–215, https://doi.org/10.1016/B978-0-08-102308-2.00002-4.
[5] B.S. Gupta, J.V. Edwards, Textile materials and structures for topical management of wounds, Adv. Text. Wound Care, Elsevier (2019) 55–104, https://doi.org/10.1016/B978-0-08-102192-7.00003-5.
[6] T. Gries, M. Raina, T. Quadflieg, O. Stolyarov, Manufacturing of textiles for civil engineering applications, Text. Fibre Compos. Civ. Eng., Elsevier (2016) 3–24, https://doi.org/10.1016/B978-1-78242-446-8.00002-1.
[7] Hafiz Shehbaz Ahmad, Introduction to knitting, in: Yasir Nawab, K.S. Syed Talha Ali Hamdani (Eds.), Struct. Text. Des. Interlacing Interlooping, first ed., CRC Press, Boca Raton, 2017, pp. 185–195.
[8] M. Blaga, Soft computing applications in knitting technology, in: A. Majumda (Ed.), Soft Comput. Text. Eng., Elsevier, 2011, pp. 217–245, https://doi.org/10.1533/9780857090812.3.217.
[9] R. Kovar, Intelligent yarn delivery systems in weft knitting, in: K.F. Au (Ed.), Adv. Knitt. Technol., Elsevier, 2011, pp. 89–109, https://doi.org/10.1533/9780857090621.2.89.
[10] S.C. Ray, Production of spacer fabrics in knitting, in: S.C. Ray (Ed.), Fundam. Adv. Knitt. Technol., Elsevier, 2012, pp. 283–292, https://doi.org/10.1533/9780857095558.283.
[11] S.C. Ray, Some aspects of weft-knitting science, in: Sadhan Chandra Ray, Editor. Fundam. Adv. Knitt. Technol., Elsevier, 2012, pp. 117–133, https://doi.org/10.1533/9780857095558.117.
[12] W. Ashraf, Patterning in weft knitting, in: Yasir Nawab, K.S. Syed Talha Ali Hamdani (Eds.), Struct. Text. Des. Interlacing Interlooping. 1, CRC Press, st, Boca Raton, 2017, pp. 197–229.
[13] L. Zílio, M. Dias, T. Santos, C. Santos, R. Fonseca, A. Amaral, et al., Characterization and statistical analysis of the mechanical behaviour of knitted structures used to reinforce composites: yarn compositions and float stitches, J. Mater. Res. Technol. 9 (2020) 8323–8336, https://doi.org/10.1016/j.jmrt.2020.05.089.
[14] S. Liu, C. Yang, Y. Zhao, X ming Tao, J. Tong, L. Li, The impact of float stitches on the resistance of conductive knitted structures, Textil. Res. J. 86 (2016) 1455–1473, https://doi.org/10.1177/0040517514555798.
[15] Z. Qin, Y. Xia, Study on tensile properties of weft knitted float stitch fabric reinforced composites, in: Proc. 3rd Int. Conf. Mater. Mech. Manuf. Eng., Atlantis Press, Paris, France, 2015, pp. 425–428, https://doi.org/10.2991/ic3me-15.2015.84.
[16] S. Uyanik, M. Topalbekiroglu, The effect of knit structures with tuck stitches on fabric properties and pilling resistance, J. Text. Inst. 108 (2017) 1584–1589, https://doi.org/10.1080/00405000.2016.1269394.
[17] H. Hasani, S. Hassanzadeh, M.J. Abghary, E. Omrani, Biaxial weft-knitted fabrics as composite reinforcements: a review, J. Ind. Text. 46 (2017) 1439–1473, https://doi.org/10.1177/1528083715624256.
[18] T. D'Antino, C. Papanicolaou, Mechanical characterization of textile reinforced inorganic-matrix composites, Compos. B Eng. 127 (2017) 78–91, https://doi.org/10.1016/j.compositesb.2017.02.034.
[19] S.L. Ogin, P. Potluri, Handb. Tech. Text, in: Textile-reinforced Composite Materials, Elsevier, 2016, pp. 1–26, https://doi.org/10.1016/B978-1-78242-465-9.00001-X.
[20] M.D. Wakeman, J.-A.E. Månson, Cost analysis, in: A.C. Long (Ed.), Des. Manuf. Text. Compos., Elsevier, 2005, pp. 364–404, https://doi.org/10.1533/9781845690823.364.
[21] S.L. Ogin, P. Brøndsted, J. Zangenberg, Composite Materials. Model. Damage, Fatigue Fail. Compos. Mater, Elsevier, 2016, pp. 3–23, https://doi.org/10.1016/B978-1-78242-286-0.00001-7.
[22] M. Monzón, R. Paz, M. Verdaguer, L. Suárez, P. Badalló, Z. Ortega, et al., Experimental analysis and simulation of novel technical textile reinforced composite of banana fibre, Materials 12 (2019) 1134, https://doi.org/10.3390/ma12071134.
[23] R. Mansur de Castro Silva, F. de Andrade Silva, Carbon textile reinforced concrete: materials and structural analysis, Mater. Struct. 53 (2020) 17, https://doi.org/10.1617/s11527-020-1448-4.
[24] J.-J. Gou, C.-L. Gong, L.-X. Gu, S. Li, W.-Q. Tao, The unit cell method in predictions of thermal expansion properties of textile reinforced composites, Compos. Struct. 195 (2018) 99–117, https://doi.org/10.1016/j.compstruct.2018.04.045.
[25] C. Mitchell, L. Dangora, C. Bielmeier, J. Sherwood, Investigation into the changes in bending stiffness of a textile reinforced composite due to in-plane fabric shear: Part 2 – numerical analysis, Composites Part A Appl Sci Manuf 85 (2016) 138–147, https://doi.org/10.1016/j.compositesa.2016.03.018.
[26] A.K. Roy Choudhury, Antishrink finishing, in: A.K.R. Choudhury (Ed.), Princ. Text. Finish., Elsevier, 2017, pp. 41–59, https://doi.org/10.1016/B978-0-08-100646-7.00003-5.
[27] A.D. Zamanov, Natural vibrations of a strip made of a composite material with a locally curved structure, Mech. Compos. Mater. 41 (2005) 49–54, https://doi.org/10.1007/s11029-005-0006-z.
[28] ASTM D3776/D3776M-09a, Standard Test Methods for Mass Per Unit Area (Weight) of Fabric, West Conshohocken, 2017, https://doi.org/10.1520/D3776_D3776M-09AR17, 2017.
[29] ASTM D5034-09(2017), Standard Test Method for Breaking Strength and Elongation of Textile Fabrics (Grab Test), West Conshohocken, 2017, https://doi.org/10.1520/D5034-09R17.
[30] K.M. Melo de, TF dos Santos, C.M.S. Santos da, R.T. Fonseca da, N.D. Lucena de, J.I. Medeiros de, et al., Study of the reuse potential of the sisal fibers powder as a particulate material in polymer composites, J. Mater. Res. Technol. 8 (2019) 4019–4025, https://doi.org/10.1016/j.jmrt.2019.07.010.

[31] T.F. Santos, C.M. Santos, M.S. Aquino, F.R. Oliveira, J.I. Medeiros, Statistical study of performance properties to impact of Kevlar® woven impregnated with Non-Newtonian Fluid (NNF), J. Mater. Res. Technol. 9 (2020) 3330–3339, https://doi.org/10.1016/j.jmrt.2020.01.027.
[32] L. Silva, T. Panzera, V. Velloso, J. Rubio, A. Christoforo, F. Scarpa, Statistical design of polymeric composites reinforced with banana fibres and silica microparticles, J. Compos. Mater. 47 (2013) 1199–1210, https://doi.org/10.1177/0021998312446499.
[33] T.F. dos Santos, C.M. da Silva Santos, R.T. da Fonseca, V.S. dos Santos, M.G. Grosschopf, M.S. de Aquino, Influence of structure and composition in the mechanical properties of textile polymeric fabrics, Polym. Polym. Compos. 27 (2019) 222–227, https://doi.org/10.1177/0967391118823075.
[34] M. Aquino, J. Guerra, S. Holanda, H. Andrade, M. Melo, L. Zilio, T. Santos, C. Santos, An evaluation and characterization study of knitted fabrics for use as telecommunication device substrate, J. Mater. Res. Technol. 12 (2021) 2076–2084, https://doi.org/10.1016/j.jmrt.2021.04.002.
[35] X. Gong, X. Chen, Y. Zhou, Advanced Weaving Technologies For High-Performance Fabrics. High-Performance Appar., Elsevier, 2018, pp. 75–112, https://doi.org/10.1016/B978-0-08-100904-8.00004-3.
[36] S. Grishanov, Structure and properties of textile materials, in: Handb. Text. Ind. Dye., Elsevier, 2011, pp. 28–63, https://doi.org/10.1533/9780857093974.1.28.
[37] M.S. Aquino, S.M. Holanda, T.F. Santos, M.V. Melo, N.D.L. Junior, I.S.Q. Júnior, H.D. Andrade, Analysis of polymeric knitted fabrics on properties for telecommunications devices application, Fibers Polym. 20 (2019) 2348–2354, https://doi.org/10.1007/s12221-019-8724-3.
[38] S.M. de Holanda, J.P. da Silva, I.S. Queiroz de, H.D. de Andrade, J.R.F. Guerra, J.A.P. Magno de, M.S. de Aquino, M.V. de Melo, N.O.L. Filho, Microstrip antenna based on knitted fabrics with biodegradable synthetic fibers, J. Mater. Sci. Mater. Electron. 28 (2017) 15118–15126, https://doi.org/10.1007/s10854-017-7387-3.
[39] T.F. Santos, C.M. Santos, M. Dias, L. Zilio, K.M. Melo, M.E. Cavalcante, L.F. Castro, E.K. Hussein, M.S. Aquino, Mechanical behavior of natural/synthetic weft-knitted structures commonly used as reinforcement of hybrid composites via full factorial design: yarn compositions and float stitches, in: Green Hybrid Compos. Eng, Non-Engineering Appl, 2023, https://doi.org/10.1007/978-981-99-1583-5_15.
[40] T.F. Santos, C.M. Santos, E.K. Hussein, L. Zilio, M. Dias, M.R. Sanjay, R. Fonseca, A. Amaral, M. Aquino, Tensile Behavior of Weft-Knitted Structure for Potential Use in Composite Reinforcement via Factorial and 3D Surface, in: Green Hybrid Compos. Eng. Non-Engineering Appl., n.d. https://doi.org/10.1007/978-981-99-1583-5_14.