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The Effect of Rib Fabric Pattern and Yarn Composition on the Mechanical Properties of Polyester Matrix Composites Reinforced by Weft-Knitted Fabric

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ABSTRACT

In this study, polyester matrix composites reinforced by 1x1, 2x2, half- and full-cardigan rib pattern weft-knitted fabrics from glass and glass/aramid hybrid yarns were produced. Physical properties such as thickness and volumetric density were determined. Tensile, flexural and low velocity impact tests were applied to the composite samples. The 2x2 rib pattern composite showed the highest thickness and density. The hybridization of glass yarn with aramid yarn increased the thickness, while it decreased the density of composites. The 2x2 rib pattern composite showed the highest tensile modulus and tensile strength. Yarn hybridization increased tensile strength at statistically significant level. The composite with full-cardigan rib pattern displayed considerably higher flexural modulus and flexural strength than the composites with the other patterns. When glass and hybrid composites were considered separately, the rib fabric pattern exhibited significant effect on maximum load. The rib fabric pattern displayed also significant effect on absorbed energy for glass composites. The yarn hybridization dramatically increased maximum load and absorbed impact energy. Rib fabric pattern and yarn composition variables displayed the parallel effect on bursting strength of the soft knitted fabrics and maxium impact load of the composites.

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KEYWORDS

Glass yarn, aramid yarn, weft knitted fabric, composite materials, mechanical properties

1. INTRODUCTION

Today's modern industries demand lightweight, stiff, strong, corrosion-, and impact-resistant products. However, it is a big challenge to meet all these requirements using a single type of material. This expanded the use of composite materials that contain at least two different material types in their structures. In fiberglass - a typical example of composite materials - short glass fibers (aka reinforcement) that stiffen and strengthen the composite structure are embedded in polyester matrix that enhances the ductility and reduces the density of the whole body [1-3].

Heat resistant, durable, ductile and lightweight aramid fibers that have a high level of energy absorption capacity are used to produce protective soft fabrics or to reinforce polymers. Due to their more flexible structure as compared with glass and carbon fibers, aramid fibers are more easily transformed into weft knitted fabrics with less fiber damage. However, the use of expensive aramid fibers alone in fabric production increases the cost. Converting aramid fibers together with cheaper glass fibers into hybrid fabric is expected to modify mechanical properties without increasing the cost too much.

Due to their integrated structure containing interlaced yarns, textile reinforcement fabrics resist and show tolerance against impact damage more than the unidirectional prepregs do [4-7]. The complex internal structure of weft knitted fabrics that can be rapidly produced with low cost and consisting of interlocked loops makes them different from other reinforcements. Thanks to their porous, flexible and stretchable structure, 3D monolithic preforms can be shaped from these fabrics

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without any wrinkle, folding and rupture. As a result of easy to compress and nesting capability of the layers, the composites from weft knitted fabrics keep the impact damage within a limited area and absorb high level energy without delaminations [8-10]. However, their low fiber contents without a specific direction reduce their in-plane load carrying capabilities. This disadvantage can be eliminated using different types of stitches (tuck, skip stitches) and inlay yarns in the course or wale directions [11-15]. Weft knitting needles that can form plain, tuck or skip stitches in different sizes enable to obtain numerous fabric patterns. The literature review shows that the mechanical properties of weft knitted fabric reinforced composites can be designed by the fabric pattern.

De Araújo et al. investigated the effect of fabric pattern (single jersey, 1x1 jersey and fleece) on tensile properties of weft knitted glass fabrics and the composites reinforced by these fabrics [16]. They concluded that the introduction of tuck and skip stitches increased the strength, while it reduced the elongation of both dry fabric and the composite. They also reported that pre-tension of the fabric before composite production improved the tensile properties. Soyaslan investigated the effect of fabric pattern on electromagnetic shielding performance of the composites and reported that fabric pattern had important role on EMSE of the composites [17]. Alpyildiz et al. studied the composites from the weft knitted glass fabrics with 1x1 rib and full cardigan derivative patterns [18]. Tuck stitches enabled the full cardigan derivative composite – containing more fibers – to exhibit more isotropic behavior, higher course-direction tensile strength, greater impact performance with more limited damage area, and better compression-after-impact properties.

Pamuk produced composites reinforced by the weft-knitted spacer fabrics from various yarns; and stated that the composite from double tuck stitched fabric displayed superior impact resistance than the composite from the single tuck stitched fabric [19]. Abounaim et al. stated that the tuck stitch formation in weft-knitted spacer fabrics caused less yarn strength loss than the plain stitch formation, and the dry fabric with tuck stitches exhibited the same course-direction tensile strength as the fabric with inlay yarns did [20]. Similarly, they noted that the tuck stitched composite exhibited higher tensile, bending and impact strength than the plain stitched composite, and approached the weft-inlay yarn composite in terms of impact strength.

In this study, firstly weft-knitted fabrics were manufactured at four different rib fabric pattern (1x1, 2x2, half- and full-cardigan) with glass and glass/aramid hybrid yarns. Secondly, these fabrics converted into polyester matrix composites via vacuum infusion process. Thereafter, the effect of rib fabric pattern and yarn composition on physical (thickness and density) and mechanical properties (tensile, flexural and impact) were investigated.

2. MATERIAL AND METHOD

2.1 Material

In this study, 136 tex multifilament E-glass yarn with 9 µm filament diameter and 1500 denier multifilament aramid yarn (m-aramid, Dupont) were used for fabric production. Unsaturated polyester resin (CE 92), MEKP (initiator), and 6% Cobalt Naphtanate (promoter) were used for composite production.

2.2 Fabric and composite production

The manual double bed weft knitting machine (Brother KH-864) with a fineness of 5E was used to produce the knit fabrics in 1x1, 2x2, half- and full-cardigan rib patterns. Both 3-ply glass yarns and 2-ply glass/1-ply aramid yarns were used for each rib fabric pattern. Totally 8 different knit fabric samples were produced (Figure 1). The constructional properties of the knitted fabrics and fiber weight percentages of the composite plates are given in Table 1.

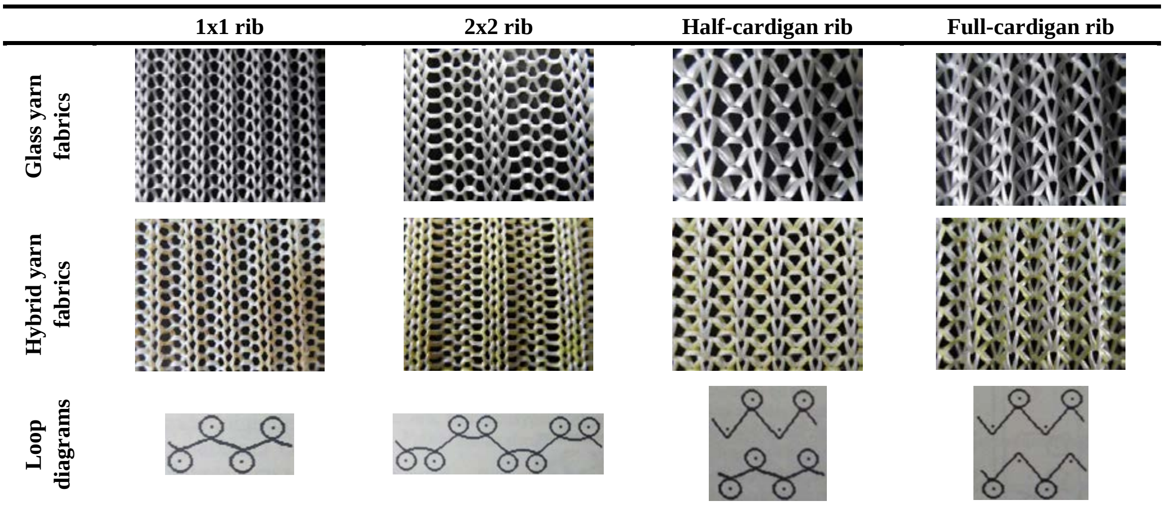

Figure 1. The photographs of the knit fabrics and loop diagrams

Table 1. Constructional properties of the knitted fabrics and fiber weight percent of the composite plates

Yarn composition	Rib fabric pattern	Thickness [mm]	Wale density [#/cm]	Course density [#/cm]	Areal density [g/m^2]	Fiber weight percent of conposite [%]
Glass	2x2	2.08	10.4	4.6	1178	60.3
	Full-cardigan	2.18	11.5	3.8	1157	70.1
	1x1	1.44	4.06	2.6	708	48.2
	Half-cardigan	1.56	5.2	4.0	792	55.7
Hybrid	2x2	3.07	7.6	4.6	1142	40.7
	Full-cardigan	3.23	10.2	3.6	1112	46.6
	1x1	2.66	4.8	2.9	857	43.6
	Half-cardigan	2.62	5.4	4.0	889	44.4

Each composite panel was produced from 2-layer fabrics with the same rib fabric pattern and the yarn composition via vacuum infusion composite production technique. Two-layer dry knitted fabrics were placed in stretched form over the waxed glass table, then the top surface of the fabric stack was covered with peel ply fabric and infusion mesh, respectively. Thereafter, spiral tubes were placed over edges of resin inlet and outlet lines. The overall stack was sealed by vacuum bag using tacky tape along the periemeter of the stuck. The air under the vacuum bag was completely evacuated by the vacuum pump that was connected to spiral tube at the resin outlet. Resin propagated through the spiral tube at the resin inlet and wetted the complete stack upto resin outlet. 24 hours were waited at room temperature for complete curing of the resin. The vacuum infusion set up for the composite production with the composite panel specimens was given in Figure 2. Test specimens for physical and mechanical tests were cut via CNC router according to the related standards.

2.3 Physical tests

Thickness, width and length of the specimens were measured by digital calliper. The weights of the specimens were measured by a precision scale. The density of the specimens was calculated as weight over volume.

2.4 Mechanical tests

Tensile and three-point bending tests were performed on Shimadzu Universal Tester with a load cell capacity of 300 kN. Tensile test were applied on dog-bone shaped specimens according to ASTM D3039. Three-point bending tests were applied according to ASTM D790. Low velocity drop tower impact test was performed on Besmak BMT-2000DW impact tester. Impact energy level was adjusted as 25 J. Also, the soft reinforcement knitted fabrics were subjected to bursting strength on SDL Atlas M229 hydraulic bursting tester according to BS EN ISO 13938-1. The average of five bursting strength measurements was calculated for each different soft fabric.

2.5 Statistical analysis

The tests' results were subjected to statistical analysis of variance (ANOVA) and Tukey-Kramer test to assess the effects of rib fabric pattern and yarn composition on the physical and mechanical properties of the composites using Jump statistical software (JMP the latest trial version). Data analysis was supported by visual and self-explanatory graphs. The results were considered significant at $p \leq 0.05$.

3. RESULTS AND DISCUSSION

3.1 Physical test results

The effect of rib fabric pattern on thickness and density of the composite samples were given in Figure 3 and Table 2. The 2x2 rib pattern showed the highest thickness and density. It can be related to fabric tightness. The dramatic narrowing in the width of the 2x2 rib pattern due to internal tension stemming from consecutive binary placement of loop bars from face and back plain stitches created a tight fabric structure. Also higher thickness and density values of full-cardigan rib pattern could be arisen from the tuck stitches on both sides, which cause tight fabric structure. Although full cardigan rib pattern had the highest thickness in fabric form (Table 1), 2x2 rib pattern in composite form displayed the highest thickness. This can be related to higher inter-layer nesting tendency of soft-touch full cardigan rib pattern fabric as compared with that of hard-touch 2x2 rib pattern fabric, where two-layer fabric in composite production was considered. Half-cardigan rib pattern showed the lowest thickness and density due to its loose structure with low fabric internal tension. The effect of rib fabric pattern on thickness and density of the composite samples was statistically significant ($p < 0.05$).

Figure 2. The composite production via vacuum infusion (left), the composite panel specimens (right)

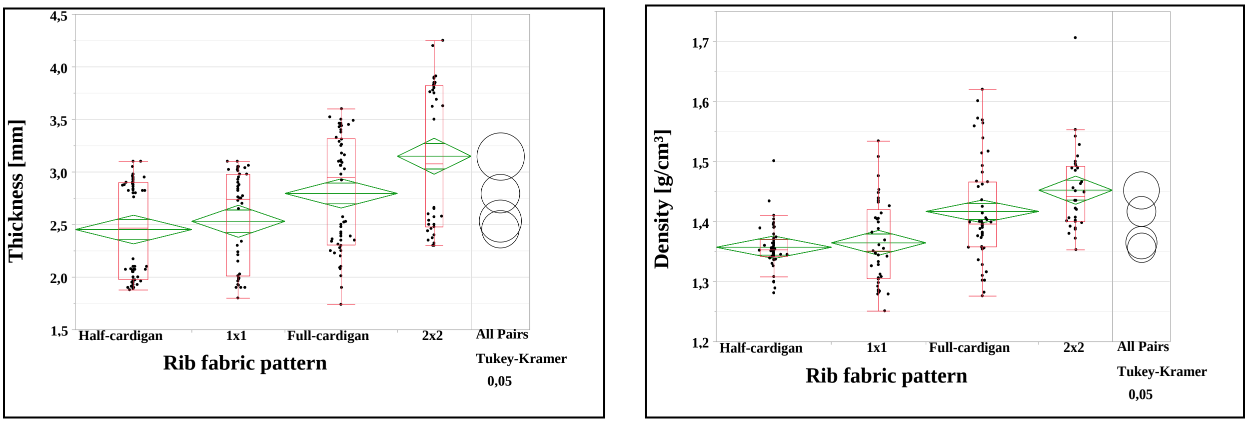

Figure 3. Effect of rib fabric pattern on thickness (left) and density (right) of the composite

Notes: The distance between top and bottom ends of green diamond represents the 95% confidence interval. Comparison circles (given on the right column) for means those are significantly different either do not intersect, or intersect slightly. The height of red box (known as interquartile range) is a quantitative indication of variation.

Table 2. Effect of rib fabric pattern on thickness and density of the composite

Property	Rib fabric pattern				n	Mean	SD	LL	UL	p-value
Thickness [mm]	2x2	A			38	3.15	0.70	2.92	3.38	< 0.0001
	Full-cardigan		B		58	2.80	0.54	2.66	2.94	
	1x1		B	C	48	2.53	0.46	2.40	2.67	
	Half-cardigan			C	60	2.45	0.46	2.33	2.57	
Density [g/cm^3]	2x2	A			32	1.45	0.07	1.43	1.48	< 0.0001
	Full-cardigan	A			49	1.42	0.08	1.39	1.44	
	1x1		B		41	1.36	0.07	1.34	1.39	
	Half-cardigan		B		50	1.36	0.04	1.35	1.37	

Note: Sub-levels of a variable are classified by alphabetical capital letters (e.g. A, B, C). The sub-levels not connected by the same alphabetical capital letter are significantly different from each other at significance level of 0.05. n:number of observations, SD: standard deviation, LL: lower limit, UL: upper limit. Limits are based on a confidence level of 95%.

The effect of yarn composition on thickness and density of the composite samples were given in Figure 4 and Table 3. Replacing the third glass yarn ply with the aramid yarn ply (i.e. yarn hybridization) increased the thickness, while it decreased the density of composites. These can be related to higher yarn count (1500 denier ≈ 167 tex) and lower raw material density (ρ=1.44 g/cm^3) of aramid yarn. The effect of yarn composition on thickness and density of the composite samples was statistically significant ($p<0.05$).

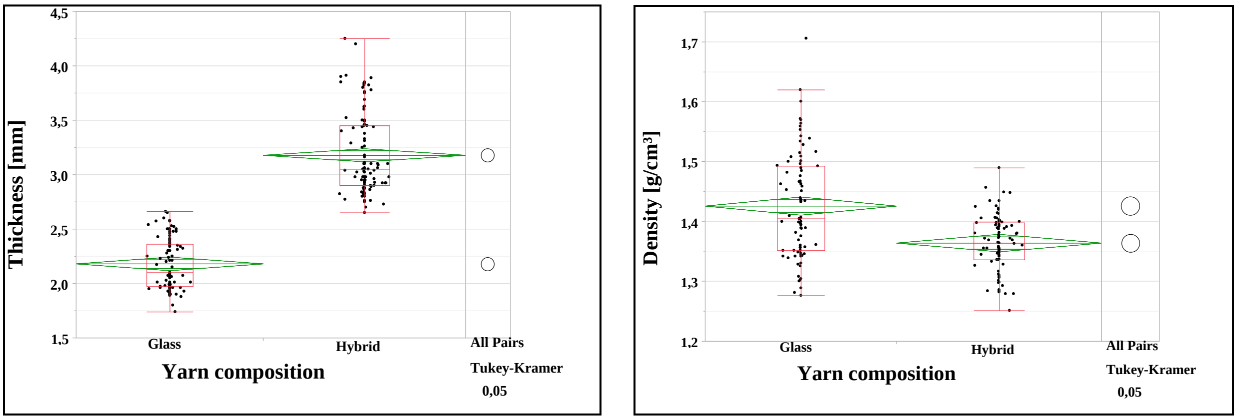

Figure 4. Effect of yarn composition on thickness (left) and density (right) of the composite samples

Table 3. Effect of yarn composition on thickness and density of the composite samples

Property	Yarn Composition			n	Mean	SD	LL	UL	p-value
Thickness [mm]	Hybrid	A		106	3.18	0.37	3.11	3.25	< 0.0001
	Glass		B	98	2.18	0.23	2.13	2.23	
Density [g/cm^3]	Hybrid	A		83	1.43	0.09	1.41	1.44	< 0.0001
	Glass		B	89	1.36	0.05	1.35	1.37	

3.2 Tensile test results

The effect of rib fabric pattern on tensile modulus and strength of the composite samples were given in Figure 5 and Table 4. The 2x2 rib pattern composite showed the highest tensile modulus and strength. This can be related to physical properties of 2x2 rib pattern composite which has the highest thickness and density values. Similarly, inferior physical properties of half-cardigan rib pattern composite are responsible for the lowest tensile modulus and strength. Likewise, a positive correlation between physical properties (tightness) and tensile was detected [21]. The effect of rib fabric pattern on tensile modulus and strength of the composite samples was statistically significant ($p<0.05$).

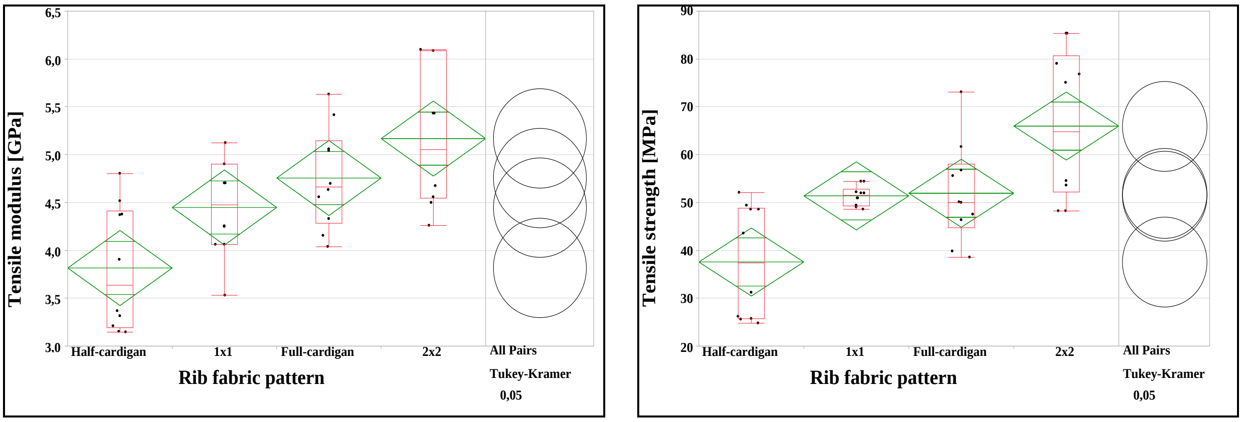

Figure 5. Effect of rib fabric pattern on tensile modulus (left) and strength (right) of the composite samples

Table 4. Effect of rib fabric pattern on tensile modulus and strength of the composite samples

Property	Rib fabric pattern				n	Mean	SD	LL	UL	p-value
Tensile Modulus [GPa]	2x2	A			10	5.17	0.74	4.64	5.70	0.0002
	Full-cardigan	A			10	4.76	0.53	4.38	5.13	
	1x1	A	B		10	4.45	0.50	4.09	4.80	
	Half-cardigan		B		10	3.82	0.65	3.35	4.28	
Tensile Stregth [MPa]	2x2	A			10	65.98	15.58	54.83	77.13	0.0002
	Full-cardigan		B		10	51.94	10.33	44.56	59.33	
	1x1		B		10	51.39	2.02	49.94	52.84	
	Half-cardigan			C	10	37.57	11.75	29.16	45.98	

The effect of yarn composition on tensile modulus and strength of the composite samples were given in Figure 6 and Table 5. Yarn hybridization generally decreased tensile modulus at statistically non-significant level ($p = 0.1012$), while it increased tensile strength at statistically significant level ($p = 0.0006$). Aramid yarns are more ductile than glass yarns, which plays role on lower tensile modulus. On the other hand, higher tensile strength of hybrid composites results from higher tensile strength of aramid yarn than that of glass yarn.

3.3 Flexural test results

The effect of rib fabric pattern on flexural modulus and strength of the composite samples were given in Figure 7 and Table 6. The full-cardigan rib pattern composite showed the highest flexural modulus and strength. The other fabric patterns' composites showed similar results. This significant differnce on flexural modulus and strength of the full-cardigan rib pattern composite can be related with presence of tuck stitches on both faces of that pattern. Because, tuck stiches increase fiber content per unit volume of knit fabrics [18-20]. The effect of rib fabric pattern on flexural modulus and strength of the composite samples was statistically significant ($p<0.05$).

The effect of yarn composition on flexural modulus and strength of the composite samples were given in Figure 8 and Table 7. Yarn hybridization decreased flexural modulus at statistically non-significant level, while it didn't change flexural strength. Lower flexural modulus of the hybrid composite is related to higher deformability of aramid yarns than glass yarns.

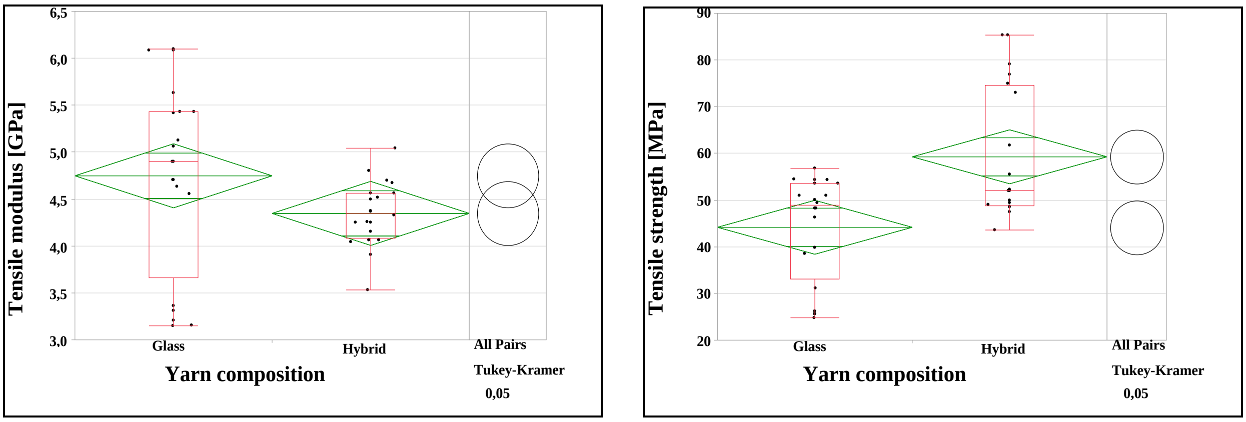

Figure 6. Effect of yarn composition on tensile modulus (left) and strength (right) of the composite samples

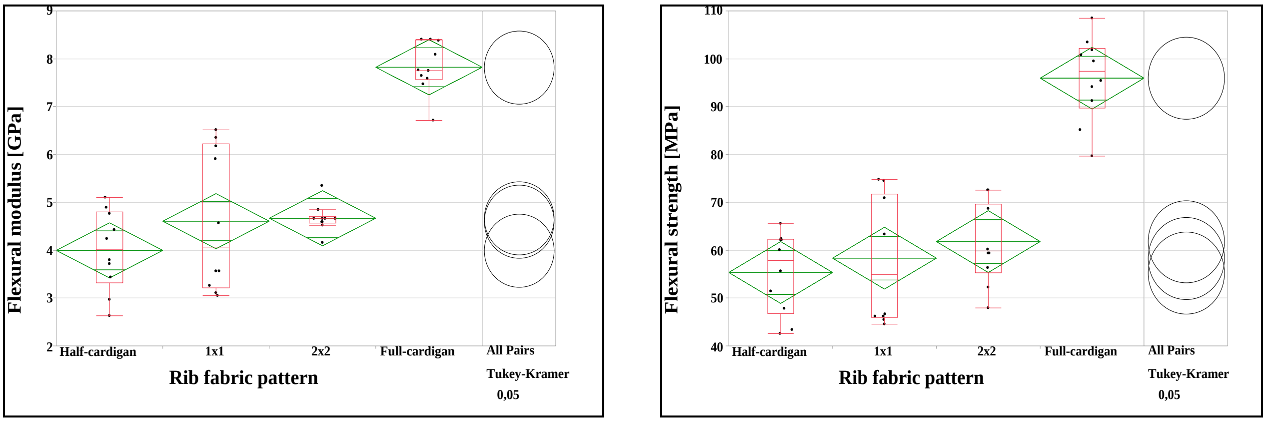

Figure 7. Effect of rib fabric pattern on flexural modulus (left) and strength (right) of the composite samples

Table 5. Effect of yarn composition on tensile modulus and strength of the composite samples

Property	Yarn composition			n	Mean	SD	LL	UL	p-value
Tensile Modulus [GPa]	Glass	A		20	4.75	1.01	4.28	5.22	0.1012
	Hybrid	A		20	4.35	0.34	4.19	4.51	
Tensile Stregth [MPa]	Glass	A		20	59.27	14.03	52.70	65.83	0.0006
	Hybrid		B	20	44.18	11.34	38.87	49.48	

Table 6. Effect of rib fabric pattern on flexural modulus and strength of the composite samples

Property	Rib fabric pattern		n	Mean	SD	LL	UL	p-value
Flexural Modulus [GPa]	Full-cardigan	A	10	7.82	0.53	7.44	8.20	< 0.0001
	2x2	B	10	4.67	0.30	4.46	4.88	
	1x1	B	10	4.61	1.47	3.55	5.66	
	Half-cardigan	B	10	4.00	0.83	3.40	4.59	
Flexural Strength [MPa]	Full-cardigan	A	10	95.96	8.77	89.68	102.23	< 0.0001
	2x2	B	10	61.80	8.53	55.70	67.91	
	1x1	B	10	58.33	13.58	48.62	68.05	
	Half-cardigan	B	10	55.34	8.49	49.27	61.42	

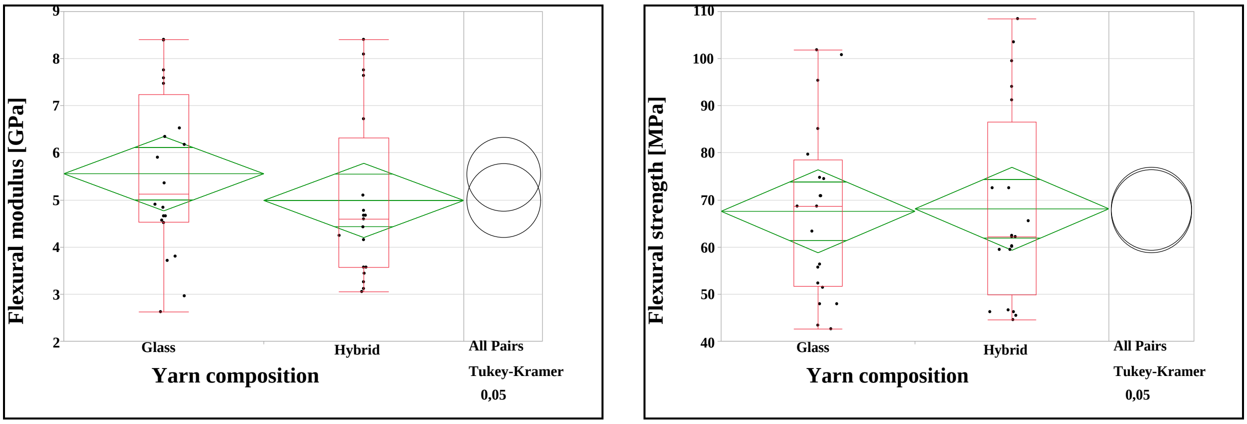

Figure 8. Effect of yarn composition on flexural modulus (left) and strength (right) of the composite samples

Table 7. Effect of rib fabric pattern on flexural modulus and strength of the composite samples

Property	Yarn composition		n	Mean	SD	LL	UL	p-value
Flexural Modulus [GPa]	Glass	A	20	5.56	1.74	4.74	6.37	0.1547
	Hybrid	A	20	4.99	1.75	4.17	5.81	
Flexural Stregth [MPa]	Glass	A	20	67.60	18.34	59.01	76.18	0.4662
	Hybrid	A	20	68.12	20.52	58.52	77.72	

3.4 Impact test results

The effect of rib fabric pattern on maximum load and absorbed energy at maximum load of the composite samples were given in Figure 9 and Table 8. When all composite samples were evaluated, there was no statistically significant effect of rib fabric pattern on maximum load and absorbed energy. The data at the bottom legs of the box plots belong to glass composites, while those at the top legs of the box plots belong to hybrid composites on Figure 9. Thus, when glass and hybrid composites were considered separately, the rib fabric pattern showed significant effect on maximum load (p-values of 0.0006 and <0.0001, respectively). This can be related to higher physical properties (thickness and density) of 2x2 and full-cardigan rib pattern composites. Furthermore, the rib fabric pattern showed significant effect on absorbed energy for glass composites (p<0.0001), while it showed negligible effect for hybrid composites. The reason of non-significant effect of rib fabric pattern on absorbed energy for hybrid composites can be related to superior ductility of aramid yarns. On the other hand rib fabric pattern played a significant role on absorbed energy for glass composites due to brittle nature of glass yarns.

The effect of yarn composition on maximum load and absorbed energy of the composite samples were given in Figure 10 and Table 9. Yarn hybridization increased maximum load and absorbed energy at statistically significant level. This result can be linked to higher tensile strength and ductility of aramid yarns as compared with glass yarns. The photographs of the composite specimens after the impact test were given in Figure 11.

To reveal the relationship between impact performance of the composites and bursting strength of the soft knitted reinforcements, the bursting strength of the soft fabrics were measured. The results were given in Table 10. Rib fabric pattern and yarn composition factors exhibited the similar effect on maxium impact load of the composites and bursting strength of the soft knitted fabrics. Rib fabric pattern modified the bursting strength of glass and hybrid soft fabrics separately. 2x2 rib fabric pattern displays the highest bursting strength values. This may be related to the compact and thick fabric structure of 2x2 rib pattern. Similar to the impact performance of the composites, hybrid soft knitted fabrics showed higher bursting strength values than glass ones. This can be attributed to higher tensile strength of aramid yarns than glass yarns.

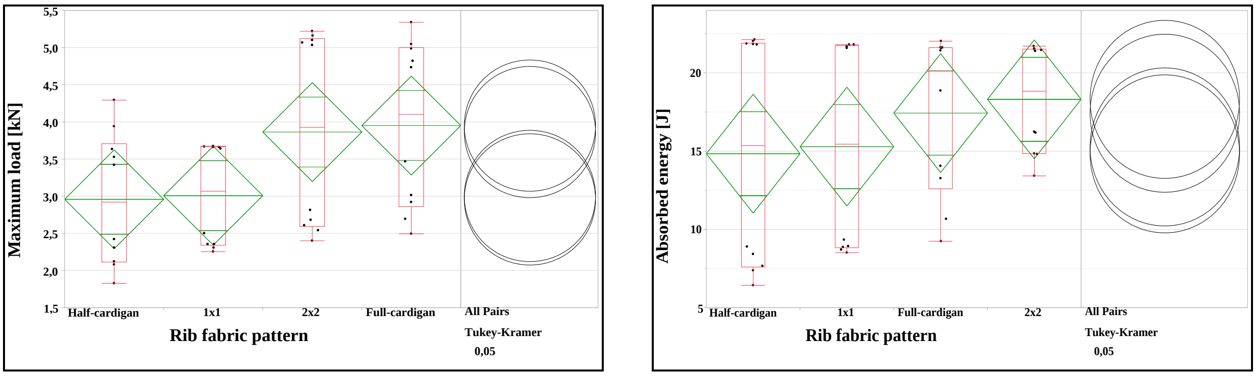

Figure 9. Effect of rib fabric pattern on maximum load (left) and absorbed energy (right) of the composite samples

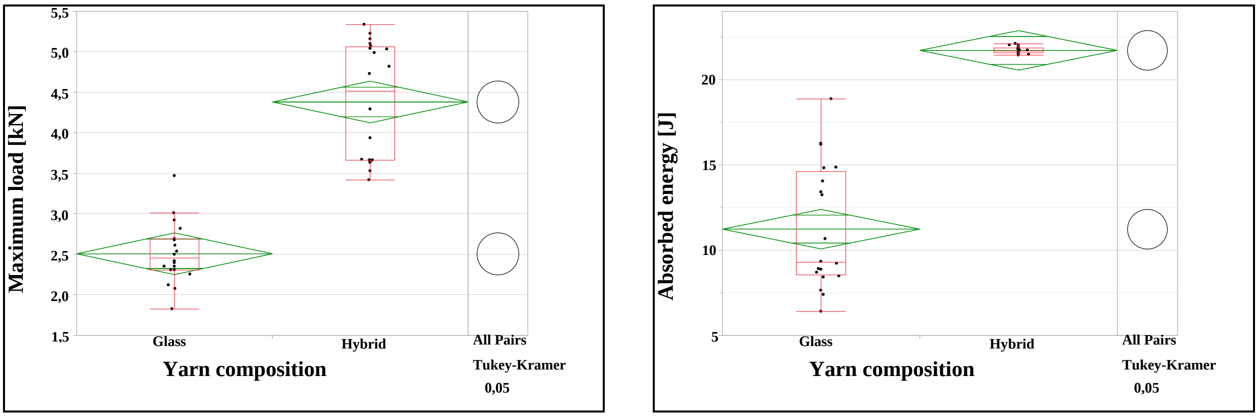

Figure 10. Effect of yarn composition on maximum load (left) and absorbed energy (right) of the composite samples

Table 8. Effect of rib fabric pattern on maximum load and absorbed energy of the composite samples

Property	Rib fabric pattern		n	Mean	SD	LL	UL	p-value
Maximum Load [kN]	Full-cardigan	A	10	3.95	1.13	3.15	4.76	0.0629
	2x2	A	10	3.86	1.33	2.91	4.81	
	1x1	A	10	3.01	0.69	2.51	3.50	
	Half-cardigan	A	10	2.96	0.90	2.32	3.60	
Absorbed Energy [J]	2x2	A	10	18.32	3.48	15.83	20.81	0.5039
	Full-cardigan	A	10	17.44	5.10	13.79	21.08	
	1x1	A	10	15.29	6.78	10.44	20.14	
	Half-cardigan	A	10	14.84	7.51	9.47	20.21	

Table 9. Effect of yarn composition on maximum load and absorbed energy of the composite samples

Property	Yarn composition			n	Mean	SD	LL	UL	p-value
Maximum Load [kN]	Hybrid	A		20	4.38	0.72	4.06	4.72	< 0.0001
	Glass		B	20	2.51	0.36	2.34	2.68	
Absorbed Energy [J]	Hybrid	A		20	21.71	0.20	21.62	21.81	< 0.0001
	Glass		B	20	11.23	3.61	9.54	12.92	

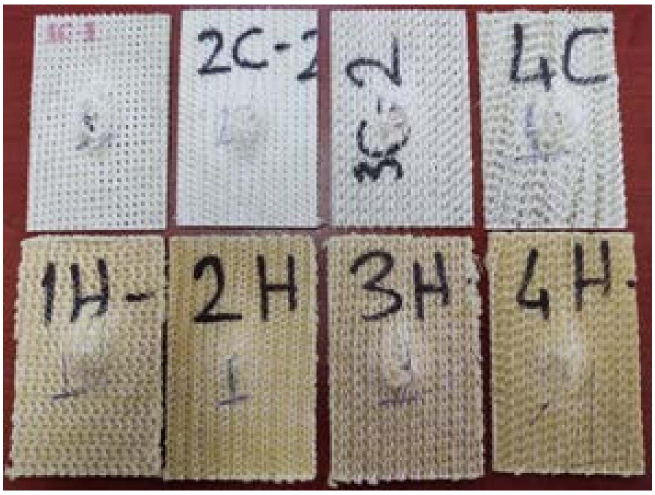

Figure 11. The photographs of the composite specimens after the impact test. a) 1x1 rib glass, b) 2x2 rib glass, c) half-cardigan rib glass, d) full-cardigan rib glass, e) 1x1 rib hybrid, b) 2x2 rib 1x1 rib hybrid, c) half-cardigan rib 1x1 rib hybrid, d) full-cardigan rib 1x1 rib hybrid

4. CONCLUSION

The effect of rib fabric pattern and yarn composition on physical and mechanical properties of composite samples was investigated in this study. The 2x2 rib pattern showed the highest thickness and density. Yarn hybridization increased the thickness, while it decreased the density of composites. The 2x2 rib pattern composite showed the highest tensile properties. Yarn hybridization generally decreased tensile modulus at statistically non-significant level, while it increased tensile strength at statistically significant level. The full-cardigan rib pattern composite showed the highest flexural modulus and strength. The other fabric patterns' composites showed similar flexural results. When glass and hybrid composites were considered separately, the rib fabric pattern exhibited significant effect on maximum load. The rib fabric pattern displayed also significant effect on absorbed energy for glass composites, while no significant effect was detected for hybrid composites. Yarn hybridization increased maximum load and absorbed energy at statistically significant level. The effects of rib fabric pattern and yarn composition on bursting strength of the soft knitted fabrics were similar to those of maxium impact load of the composites.

Table 10. Bursting strength test results of the soft knitted reinforcements

Yarn composition	Rib fabric pattern	Bursting strength [kPa]	Distension [mm]
Glass	2x2	1665	20,7
	Full-cardigan	1294	23
	1x1	1319	22
	Half-cardigan	1329	26
Hybrid	2x2	4308	21,4
	Full-cardigan	3824	22,4
	1x1	3401	21,8
	Half-cardigan	3688	22

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