Mugla Journal of Science and Technology

MECHANICAL PROPERTIES OF CNTS INTEGRATED PP/GLASS FIBER REINFORCED BIAXIAL WEFT-KNITTED THERMOPLASTIC COMPOSITES WITH DIFFERENT KNITTING STRUCTURES

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Received: 19.01.2024, Accepted: 26.03.2024 Research Article
*Corresponding author DOI: 10.22531/muglajsci.1422587

Abstract

In this study, four types of biaxial weft-knitted (BWK) fabrics (polypropylene (PP) resin yarn/glass fiber (GF) with different knitting structures such as plain (P), interlock (INT), tuck (T) and tuck&miss (TM) and multi-walled carbon nanotubes (MWCNTs) (0.4 wt%) were used as reinforcements to produce thermoplastic laminates with MWCNTs. In order to study the mechanical characteristics of the laminates, the flexural, short beam and Charpy impact tests on the samples were performed. In preliminary studies, the BWK fabrics with the plain knittings were used to produce the thermoplastic laminates with and without MWCNTs and positive effect of MWCNTs on the laminates were found out by performing the flexural tests on the specimens. The BWK laminates with the INT and TM knitting types with 0.4 wt% MWCNTs had almost same bending modulus and strength. 5% and 41% higher bending modulus and strength were gained with the BWK laminates with the interlock knitting type with 0.4-wt% MWCNTs compared to that was with the tuck type. 28.2% higher short beam strength and 57% higher Charpy impact energy were obtained with tuck&miss with 0.4-wt% MWCNTs (21.02 MPa and 6.34 Joule) compared to that was with the tuck knitting (16.39 MPa and 4.04 Joule).
Keywords: Plain, Interlock, Tuck and Tuck&miss knitting, Commingled fibers, Carbon nanotubes, Thermoplastic laminates, Flexural, short beam and Charpy impact test characteristics

FARKLI ÖRME YAPILARINA SAHİP KNT İLAVELİ PP/CAM ELYAF TAKVİYELİ ÇİFT EKSENLİ ATKI ÖRME TERMOPLASTİK KOMPOZİTLERİNİN MEKANİK ÖZELLİKLERİ

Özet

Bu çalışmada düz (P), interlok (INT), askı (T) ve askı&atlama (TM) gibi farklı örgü yapılarına sahip dört tip çift eksenli atkılı örme (BWK) kumaş (polipropilen (PP) reçine iplik/cam elyaf (GF)) ve çok duvarlı karbon nanotüpler (ÇDKNT'ler) (ağırlıkça %0,4) ÇDKNT ilaveli termoplastik laminantlar üretmek için takviye olarak kullanıldı. Laminantların mekanik özelliklerini incelemek için, eğilme, kısa kiriş ve Charpy darbe testleri numunelere uygulandı. Ön çalışmalarda, ÇDKNT'li ve ÇDKNT'siz termoplastik laminantların üretilmesi için düz örgülü BWK kumaşlar kullanılmış ve numuneler üzerinde eğilme testleri yapılarak ÇDKNT 'lerin laminantlar üzerindeki olumlu etkisi ortaya çıkarılmıştır. Ağırlıkça %0,4 ÇDKNT'li INT ve TM örgü tipleri neredeyse aynı bükülme modülüsü ve mukavemetine sahiptir. Ağırlıkça %0,4 ÇDKNT'li interlok örgü tipine sahip BWK laminantlarla askı tipi ile olanlarına göre %5 ve %41 daha yüksek bükülme modülü ve mukavemeti elde edildi. Ağırlıkça %0,4 ÇDKNT'li askı&atlama örgülü (21,02 MPa ve 6,34 Joule) ve askı örgülü (16,39 MPa ve 4,04 Joule) plakalar karşılaştırıldığında %28,2 daha yüksek kısa kiriş mukavemeti ve %57 daha yüksek Charpy darbe enerjisi elde edildi.
Anahtar Kelimeler: Düz, İnterlok, Askı ve Askı&atlama örgü, Karışık elyaflar, Karbon nanotüpler, Termoplastik laminantlar, Eğilme, Kısa kiriş ve Charpy darbe testi özellikleri

Cite

Demircan, Ö., Yıldız, A., (2024). "Mechanical Properties of CNTs Integrated PP/Glass Fiber Reinforced Biaxial Weft-Knitted Thermoplastic Composites with Different Knitting Structures", Mugla Journal of Science and Technology, 10(1), 33-41.

1. Introduction

Mass production of reinforced composites with low cost is possible using thermoplastics [1].

Some researchers used carbon nanotubes (CNTs) in nanocomposites [2–12]. Nanocomposites with thermoplastic matrix can be effectively produced by compression moulding method which was reported by Quadrini et al. [2].

Multi-walled carbon nanotubes (MWCNTs) have been used in many studies due to their high mechanical characteristics. The effect of MWCNT content on the mechanical characteristics of polypropylene (PP) was presented by Teng et al. [3]. The thermal properties of PP-MWCNTs materials were reported by Zhou et al. [4]. Park et al. [5] investigated interfacial behaviors of PP composites reinforced with MWCNTs. Mechanical and structural studies of PP-MWCNTs composite sheets was studied by Sánchez et al. [6].

Some researchers used CNTs and other nanomaterials in the fiber reinforced thermoplastic composites [7–29]. Papageorgiou et al. [13] studied hybrid multifunctional graphene/glass-fibre polypropylene composites. Liu et al. [14] presented that the tensile performance of the GFRP was enhanced by up to ~120 MPa (95%), by the integration of up to ~ 1.7 vol% of the graphene nanoplatelet (GNP), to the composite. Aytac et al. [15] studied effect of hybrid CNT/short GF reinforcement on the properties of PP composites. Balancing the toughness and strength in PP composites was reported by Naebe et al. [16]. Lee et al. [17] reported an 109 % enhancement in tensile strength in hybrid GNP reinforced polymer composites. Ramesh et al. [18] reported a review of influence of filler material on properties of FRPCs. Yum et al. [19] showed that CNTs enhanced the mechanical properties of CFRPs with PA6/PP resin. Rajesh et al. [20] reported that composite fabricated using co-cure producing technique with 1 wt% CNT adding enhanced the tensile strength by 22.8% compared to co-bonded composites. Tang et al. [21] studied preparation of multiscale CNT/GF reinforcements. Rasana et al. [22] reported that the improvements on the ultimate tensile strength by 76% and tensile modulus by 127% with comparison to neat PP in the hybrid filler-reinforced laminates.

In the literature, thermoplastic composites with knitted commingled fibers were reported [30–36]. Biaxial weft-knitted (BWK) fabrics have some of the extra yarns which can enhance the mechanical characteristics of the knitted fabrics [1].

From the above literature, MWCNTs loading in the mechanical characteristics of the thermoplastic laminates were presented. However, it was found no work the characteristics of the MWCNTs added thermoplastic composites reinforced with different BWK fabrics such as plain (P), interlock (INT), tuck (T) and tuck&miss (TM). In this research, the flexural, short beam and Charpy impact characteristics of the MWCNTs reinforced BWK laminates with different knitting structures were studied.

2. Experimental

2.1. Composite Constituents

In this research, P, INT, T and TM types of fabrics were used as a reinforcement. The knitting characteristics and photographs of these fabrics are different [1]. MWCNTs (Ege Nanotek Limited Şirketi, TURKEY) were used in the study (Figure 1 and Table 1).

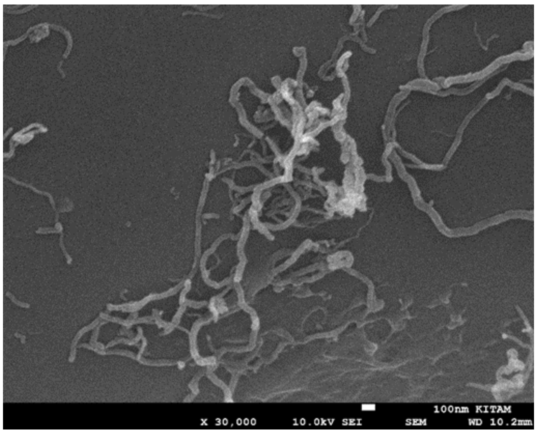

Figure 1. SEM photograph of MWCNTs

Table 1. Properties of MWCNTs

Parameter	Value
Outer diameter (nm)	10-20
Interior diameter (nm)	5-10
Length (μm)	10-30
Surface area (m^2/g)	>200
Colour	Black

2.2 Fabrication Method

The solution of the MWCNTs and ethanol were used in order to coat of the BWK fabrics [37] (Figure 2a-d). Later, the BWK reinforcements were cut in the weft way and put in the molding die. The eight layers of the composite panels were produced in the hot press machine and they had symmetric laminate sequence $[90_{we}/0_{wa}/90_{we}/0_{wa}/90_{we}/0_{wa}/90_{we}/0_{wa}]_s$ (Figure 3a and b). Fiber volume fractions (V_fs) were calculated by conducting the burn-out tests (Table 2).

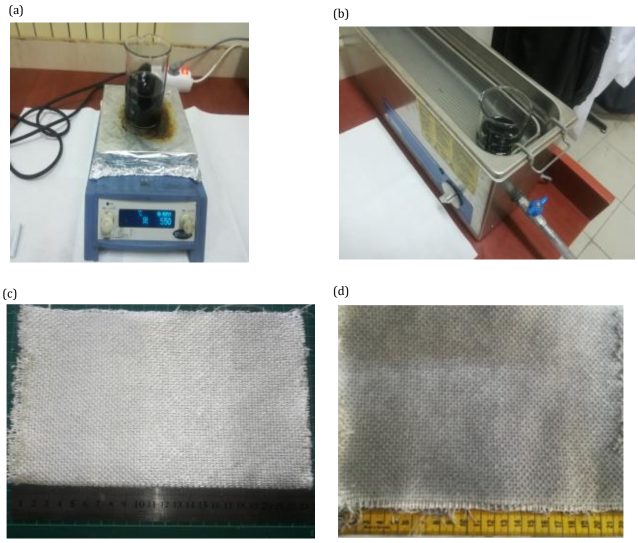

Figure 2. Processing of coating of the BWK fabrics with the solution of the MWCNTs and ethanol. (a) magnetic stirrer device; (b) ultrasonic bath device; (c) uncoated BWK fabric; (d) coated BWK fabric

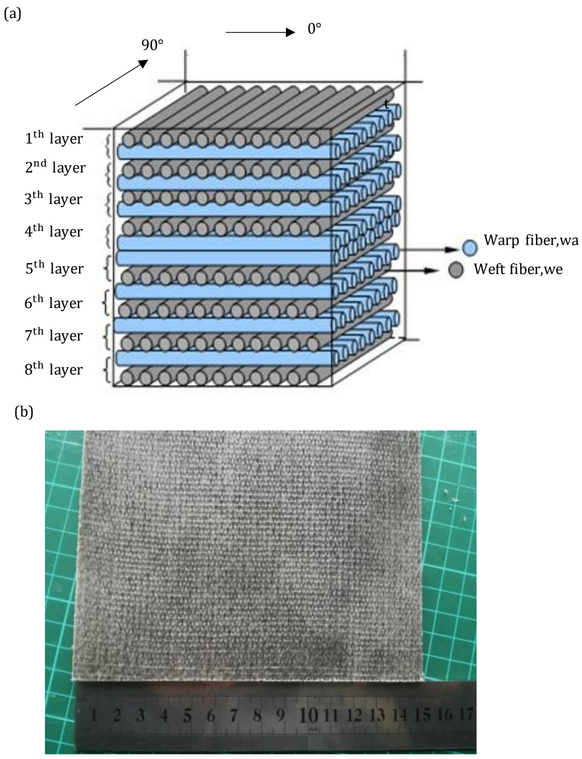

Figure 3. (a) Schematic drawing of the BWK fabrics representation of symmetric stacking; (b) photograph of fabricated laminate

2.3. Characterization

The INSTRON 5982 100KN type of test machine with the bending test apparatus was used to test the fabricated specimens at Ondokuz Mayıs University (OMU) Central Laboratory (KITAM) (Figure 4a and b). In the preliminary studies, in the bending tests, three samples were tested in the warp direction for the P type of the laminates. After that, the produced INT, T and TM plates with 0.4 wt% MWCNTs were cut in 80 mmx15 mm x thickness mm dimensions and three samples were tested in the weft way.

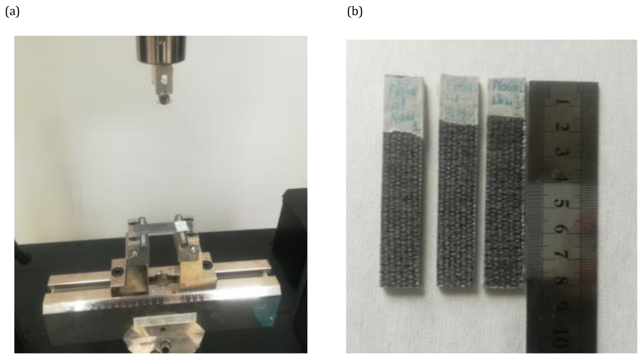

Figure 4. (a) Bending test apparatus; (b) photograph of specimens of bending test

In the short beam tests, the INSTRON 5982 100KN type of test machine with short beam testing apparatus was used with displacement speed of 1 mm/min according to ASTM D2344-13 procedure. The dimensions of the samples were 7 mm (width) x 25 mm (length) x thickness mm. Three samples were tested in the weft direction.

In the Charpy impact (CI) tests, the three samples were cut in the dimensions of 10 mm x 80 mm x thickness mm. ALSA ZBC 2000, Turkey test machine was used to conduct the Charpy impact tests at Ondokuz Mayıs University.

Table 2. Fiber volume fractions and thickness of composites

Samples	Weft V_f(%)	Warp V_f(%)	Stitch V_f(%)	Total V_f(%)	Thickness (mm)
Plain neat	10.35	14.02	17.41	41.78	1.93
Plain with 0.4-wt% MWCNTs	10.21	13.83	17.17	41.20	2.08
Interlock with 0.4-wt% MWCNTs	18.31	7.89	14.16	40.37	3.11
Tuck with 0.4-wt% MWCNTs	9.08	8.21	14.69	31.99	3.48
Tuck-miss with 0.4-wt% MWCNTs	12.31	7.03	17.2	36.55	3.68

3. Results and Discussion

3.1. Flexural Test

Figure 5(a) and (b) show the results of the bending tests of the BWK laminates with plain type with and without MWCNTs from the preliminary studies. According to these results, it was seen that addition of 0.4-wt% MWCNTS improved both bending modulus and strength from 4.75 GPa to 5.62 GPa and from 149 MPa to 176 MPa of the plain type of the BWK composites. Later on, it was decided to fabricate the BWK laminates of the INT, T and TM knitting types with the integration of the MWCNTs.

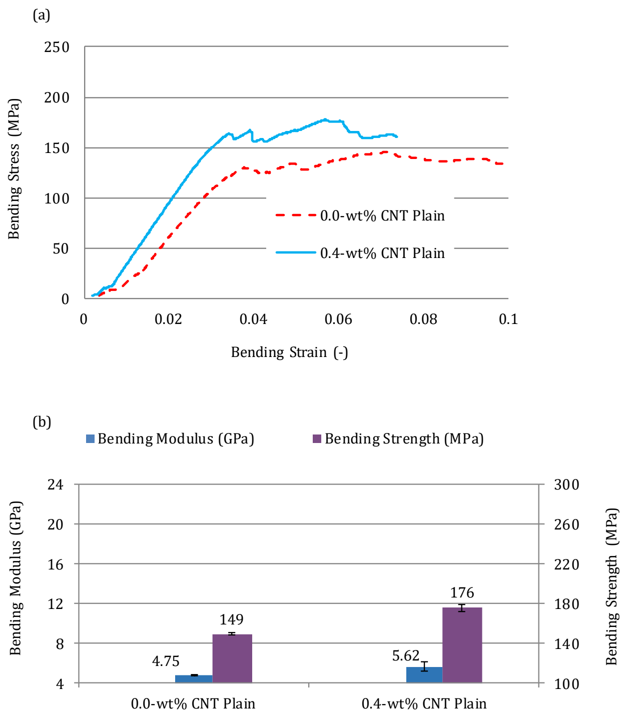

Figure 5. The results of the bending tests of the BWK laminates with plain type with and without MWCNTs. (a) stress and strain curve; (b) modulus and strength

Figures 6 (a), (b) show the results from the flexural tests with the different knitting types and MWCNTs. The INT and TM laminates with 0.4 wt% MWCNTs had 8.89 GPa, 8.46 GPa and 199.9 MPa, 199.6 MPa bending performance. The T composite with 0.4 wt% MWCNTs had 5.85 GPa and 141.8 MPa bending performance. The INT type BWK laminates with 0.4-wt% MWCNTs demonstrated 5% and 41% higher bending modulus and strength than that was with the tuck type. The higher fiber V_f of the laminates with the INT and TM with 0.4 wt% MWCNTs (18.3% and 12.3%) might be reason of the higher bending characteristics compared to the that was with the T laminates (9.08%).

Although the interlock composites had higher weft fiber V_f than that was with the tuck&miss composites, the bending properties of the interlock and tuck&miss was almost same. This was due to the different knitting structures of interlock and tuck&miss. In previous report [1], it was shown that length of the straight part of the loop shape in the knitting structures of the interlock and tuck&miss were longer than the tuck.

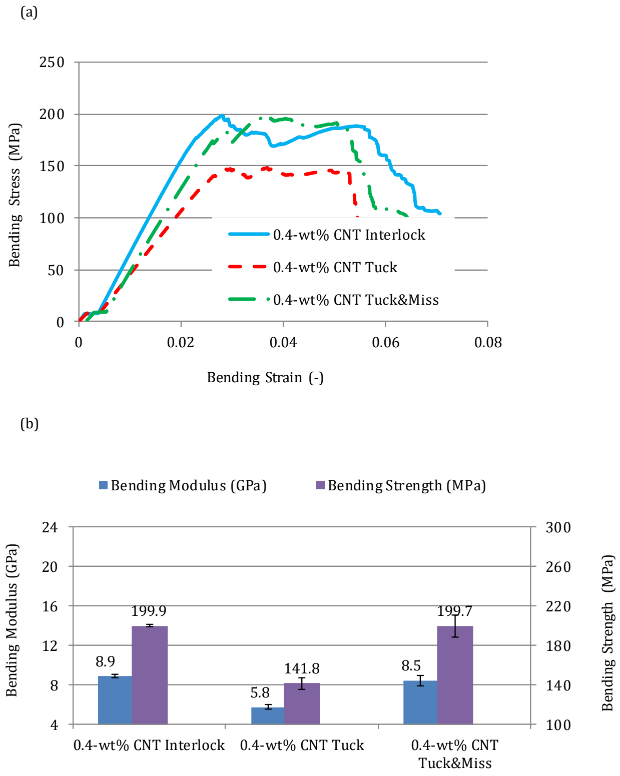

Figure 6. The results of the bending tests of the BWK laminates with interlock, tuck and tuck&miss types with MWCNTs. (a) stress and strain curve; (b) modulus and strength

The straight part of the loop shape would possibly improve bending properties of the interlock and tuck&miss compared to the tuck knitting.

In Table 3, bending test results of the BWK laminates with and without MWCNTs (1) were shown. The addition of MWCNTs enhanced 8.8% the bending strength of the BWK laminates with the tuck&miss from 183.4 MPa [1] to 199.6 MPa. The bending characteristics of the BWK laminates with the interlock without MWCNTs (9.9 GPa and 203.7 MPa) [1] was little bit higher than those with MWCNTs (8.8 GPa and 199.9 MPa). Our study showed that very close bending strength results from ten layers of the interlock BWK composites (203.7 MPa) [1] and from eight layers of the MWCNTs integrated interlock BWK composites (199.9 MPa).

Table 3. Bending test results with standard deviation of composites

Specimen types	Bending strength (MPa)	Bending modulus (GPa)
Interlock with 0-wt% MWCNT [1]	203.7 ± 3.10	9.85 ± 0.07
Tuck with 0-wt% MWCNT [1]	172.7 ± 1.20	6.90 ± 0.0
Tuck&miss with 0-wt% MWCNT [1]	183.4 ± 0.80	8.90 ± 0.0
Interlock with 0.4-wt% MWCNTs	199.9 ± 0.95	8.89 ± 0.2
Tuck with 0.4-wt% MWCNTs	141.8 ± 5.75	5.85 ± 0.2
Tuck&miss with 0.4-wt% MWCNTs	199.6 ± 11.0	8.46 ± 0.5

Table 4 presents maximum load and total absorbed energies from bending tests. The total absorbed energy of the specimens of the BWK laminates with the tuck&miss knitting structure with 0.4-wt% MWCNTs was highest (3.28 J) compared to that was with the interlock and tuck knitting structures (2.38 J and 1.98 J). This was due to small increase in elongation at failure point with the specimens with the tuck&miss knitting structure compared to the interlock and tuck knitting structures.

Table 4. Maximum load and total absorbed energies from bending tests

Specimen types	Maximum load (kN)	Total absorbed energy (J)
Interlock with 0.4-wt% MWCNTs	0.38±0.02	2.38±0.33
Tuck with 0.4-wt% MWCNTs	0.31±0.01	1.93±0.08
Tuck&miss with 0.4-wt% MWCNTs	0.47±0.01	3.28±0.08

3.2. Short Beam Test

Figure 7 represents the results of the short beam tests of the laminates with different knitting types and with MWCNTs. The highest load was obtained with the tuck&miss knitting structure with 0.4-wt% MWCNTs (735.17 N), the sample followed by the interlock and tuck knitting structures (657.96 N and 550.90 N).

The thermoplastic composites with the tuck&miss knitting structure exhibited highest short beam strength values (21.02 MPa) and 28.2% higher short beam strength than that was with the tuck knitting (16.39 MPa) as shown in Figure 8.

3.3. Charpy Impact (CI) Test

Figure 9 demonstrates the results of the CI tests of the laminates with different knitting types and with MWCNTs. By changing the knitting types, the impact absorbed energies of the laminates were enhanced.

The BWK laminates with the tuck&miss knitting and 0.4-wt% MWCNTs showed higher impact absorbed energy (6.34 Joule) compared to the other tested samples. The second higher Charpy impact absorbed energy was obtained from the BWK laminates with the interlock and 0.4-wt% MWCNTs (5.51 Joule). The lowest Charpy impact absorbed energy was obtained from the BWK laminates with the tuck and 0.4-wt% MWCNTs (4.04 Joule). The BWK composites with the tuck&miss and 0.4-wt% MWCNTs exhibited 57% higher improvement of impact energy compared to that was with the tuck knitting.

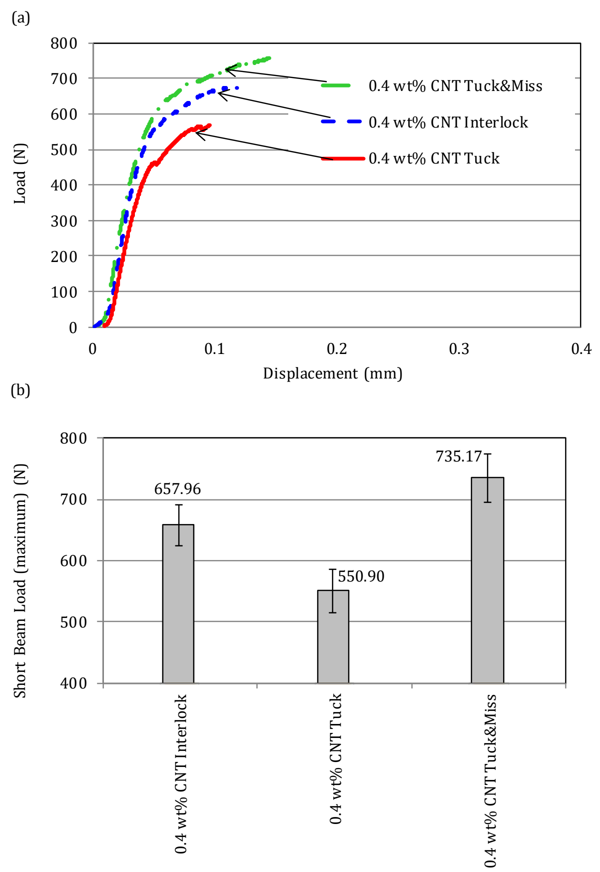

Figure 7. (a) Load-displacement graphs and (b) short beam load of the BWK laminates with INT, T and TM types with MWCNTs

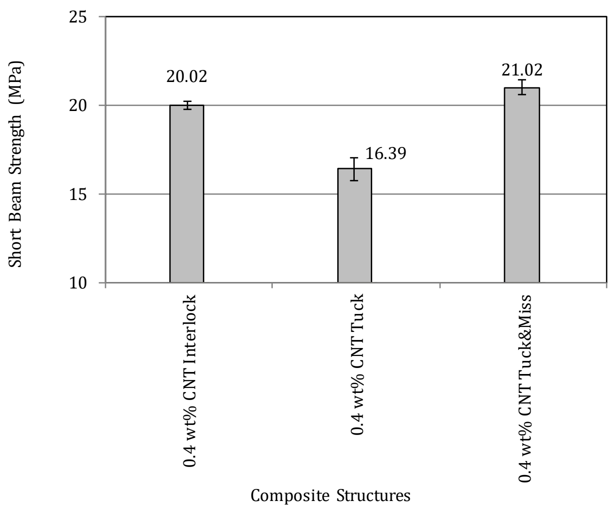

Figure 8. The results of the short beam strength of the BWK laminates with INT, T and TM types with MWCNTs

As mentioned earlier, due to lower weft fiber V_f of the laminates with the tuck knitting (9.08 %) compared to that was with the interlock (18.3 %) and tuck&miss (12.3 %) would be reason of the higher CI characteristics of the laminates with the interlock and tuck&miss compared to the tuck knitting. The second reason of the higher CI characteristics of the laminates with the interlock and tuck&miss would be the longer length of straight part of the loop shape in the tuck&miss and interlock compared to the tuck knitting.

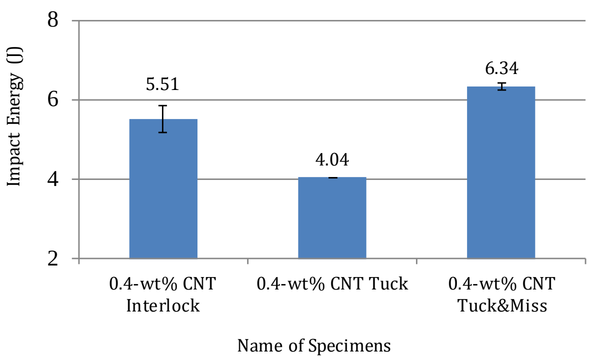

Figure 9. The results of the CI tests of the BWK laminates with different knitting types and with MWCNTs

3.4. Total Absorbed Energies from Bending and from CI Tests

Figure 10 demonstrates the graph of the total absorbed energies from bending and Charpy impact tests. There was a good relationship between both test results was obtained. The total absorbed energies from bending tests rise with rising the total absorbed energy from CI tests.

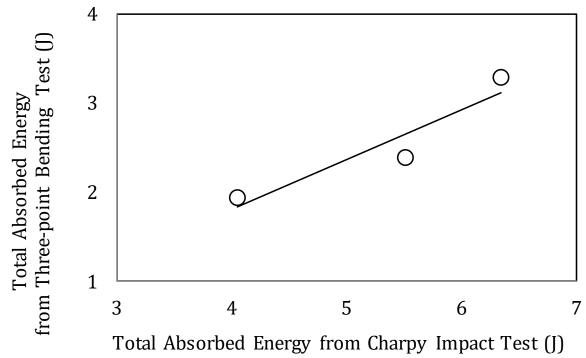

Figure 10. The relationship of the total absorbed energies from bending and from Charpy impact tests

Our mechanical test results showed good agreement with the results of Bilişik et al. [38, 39], Demircan et al. [37] and Papilla et al. [40]. In the work of Bilişik at al. [38], the addition of the few percent stitching fiber (1.81%) and nanotubes (0.03125%) in the baseline structure improved the interlaminar strength. In another work of Bilişik at al. [39], the addition of stitching and multiwall carbon nanotubes to the base structures slightly increased the flexure strength, modulus and strain of all the stitched and stitched/nano composites. Specimens with 0.9-wt% MWCNTs in 90° direction showed the highest values of tensile and flexural properties with an improvement of about 7% and 33% in tensile and flexural modulus and about 3% and 65% in tensile and flexural strength in the work of Ozgur et al. [37]. 20 % increase in the Charpy impact energy absorbance in the presence of 0.2 wt% MWCNTs interlayers of carbon fiber/epoxy composites was obtained in the work of Papilla et al. [40].

3.5. Results of Fracture Aspects

Figure 11 presents the SEM images of fractured specimens of interlock and tuck&miss with MWCNTs from bending test. Figure 11b and d was magnified view of the Figure 11a and c. The bonded MWCNTs between glass fiber surface and PP polymer were observed in both interlock and tuck&miss knitting structures. The CNTs on the fiber surface bridge the crack in nanoscale and enhance the toughness as well as other mechanical characteristics (bending, short beam and impact energy) of the laminates during crack growth.

The good agreements between the results of the three different tests (bending, short beam and CI) have approved the reliability of our performed mechanical tests.

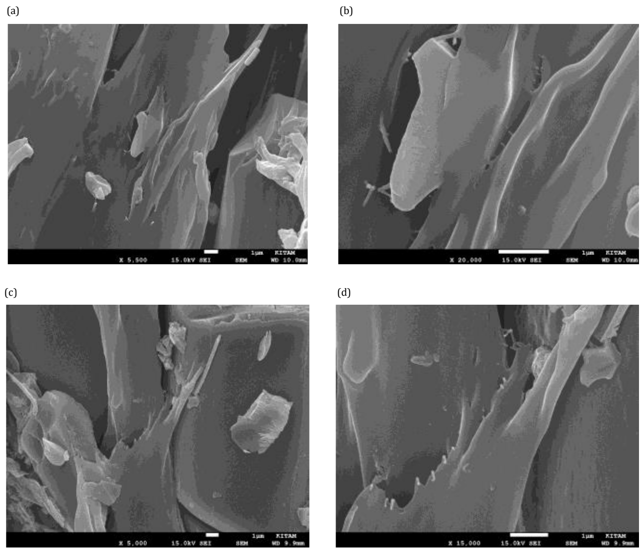

Figure 11. The SEM images of fractured specimens with MWCNTs from bending test. (a) and (b) interlock specimens; (c) and (d) tuck&miss specimens

4. Conclusions

In our research, we investigated the bending, short beam and CI characteristics of BWK reinforced laminates with different knitting types (plain, interlock, tuck, tuck&miss) and 0.4-wt% MWCNTs. The effect of fiber volume fraction and different knitting structures on the mechanical characteristics of the composites were studied as a result of the flexural, short beam and Charpy impact tests and the interesting results were summarized as follow:

1. In the preliminary studies, the BWK fabrics with the plain knitting types were used to fabricate the thermoplastic composites with and without MWCNTs and positive effect of MWCNTs on the composites were found out by conducting the flexural tests on the specimens.

2. 5% and 41% higher bending modulus and strength were obtained with the BWK laminates with the interlock knitting type with 0.4-wt% MWCNTs compared to that was with the tuck type.

3. 28.2% higher short beam strength was obtained with tuck&miss with 0.4-wt% MWCNTs (21.02 MPa) compared to that was with the tuck knitting (16.39 MPa).

4. The highest bending, short beam and CI resistances of the laminates with 0.4-wt% MWCNTs were obtained with the INT and TM compared to the tuck knitting, according to the result of the bending, short beam and impact tests of the samples.

5. The total absorbed energy of the specimens of the BWK laminates with the tuck&miss knitting structure with 0.4-wt% MWCNTs was highest compared to that was with the interlock and tuck knitting structures.

6. A good relationship between both total absorbed energies from flexural and Charpy impact tests were obtained from our study.

5. Acknowledgment

We wish to acknowledge company of Shima Seiki Mfg. Ltd., Japan to supply BWK fabrics. This work was supported by the Research fund of Ondokuz Mayıs University (Project Numbers: PYO.MUH.1901.16.001 and PYO.MUH.1901.18.008).

6. References

[1] Demircan, Ö., Ashibe, S., Kosui, T. and Nakai, A., “Effect of various knitting techniques on mechanical properties of biaxial weft-knitted thermoplastic composites”, *Journal of Thermoplastic Composite Materials*, 28(6), 896–910, 2014.

[2] Quadrini, F., Bellisario, D., Santo, L., Stan, F. and Catalin, F., “Compression moulding of thermoplastic nanocomposites filled with MWCNT”, *Polymers & Polymer Composites*, 25(8), 611–620, 2017.

[3] Teng, C.C., Ma, C.C.M., Huang, Y.W., Yuen, S.M., Weng, C.C., Chen, C.H. and Su S.F., “Effect of MWCNT content on rheological and dynamic mechanical properties of multiwalled carbon nanotube/polypropylene composites”, *Composites Part A: Applied Science and Manufacturing*, 39(12), 1869–1875, 2008.

[4] Zhou, T.Y., Tsui, G.C.P., Liang, J.Z., Zou, S.Y., Tang, C.Y. and Mišković-Stanković V., “Thermal properties and thermal stability of PP/MWCNT composites”, *Composites Part B: Engineering*, 90, 107–114, 2016.

[5] Seo, M.K., Lee, J.R. and Park, S.J., “Crystallization kinetics and interfacial behaviors of polypropylene composites reinforced with multi-walled carbon nanotubes”, *Materials Science and Engineering: A*, 404(1–2), 79–84, 2005.

[6] Lozano-Sánchez, L.M., Sustaita, A.O., Soto, M., Biradar, S., Ge, L., Segura-Cárdenas, E, Diabb J., L.E., Elizalde, Barrera E.V. and Elías-Zúniga A., “Mechanical and structural studies on single point incremental forming of polypropylene-MWCNTs composite sheets”, *Journal of Materials Processing Technology*, 242, 218–227. 2017.

[7] Bikiaris, D., “Microstructure and properties of polypropylene/carbon nanotube nanocomposites”, *Materials*, 3(4), 2884, 2010.

[8] Ezenkwa, O.E., Hassan, A. and Samsudin, S.A., “Comparison of mechanical properties and thermal stability of graphene-based materials and halloysite nanotubes reinforced maleated polymer compatibilized polypropylene nanocomposites”, *Polymer Composites*. 43(3), 1852–1863, 2022.

[9] Abubakre, O.K., Medupin, R.O., Akintunde, I.B., Jimoh, O.T., Abdulkareem, A.S., Muriana, R.A, James J.A., Ukoba KO., Jen T.C. and Yoro K.O., “Carbon nanotube-

reinforced polymer nanocomposites for sustainable biomedical applications: A review", *Journal of Science: Advanced Materials and Devices*, 8(2), 100557, 2023.

[10] Yousefi, A.A., Rezaei, M. and Naderpour, N., "Hybrid multiwalled-carbon nanotube/ nanosilica/ polypropylene nanocomposites: Morphology, rheology, and mechanical properties", *Polymer Composites*, 44(9), 5464–5479, 2023.

[11] Mi, D., Zhao, Z. and Bai, H., "Effects of orientation and dispersion on electrical conductivity and mechanical properties of Carbon Nanotube/Polypropylene composite", *Polymers (Basel),* 15(10), 2370, 2023.

[12] Raja, G.M., Vasanthanathan, A. and Selvabharathi, R., "Effect of one-step dipping coating process on microstructure and tribology of polypropylene/graphene oxide/carbon nanotube nanocomposites", *Iranian Polymer Journal*, 32(6), 739–748, 2023.

[13] Papageorgiou, D.G., Kinloch, I.A. and Young, R.J., "Hybrid multifunctional graphene/glass-fibre polypropylene composites". *Composites Science and Technology*, 137, 44–51, 2016.

[14] Liu, M., Lin, K., Yao, X., Vallés, C., Bissett, M.A., Young, R.J. and Kinloch I.A., "Mechanics of reinforcement in a hybrid graphene and continuous glass fibre reinforced thermoplastic", *Composites Science and Technology*. 237,110001, 2023.

[15] Gamze, Karsli, N., Yesil, S. and Aytac, A., "Effect of hybrid carbon nanotube/short glass fiber reinforcement on the properties of polypropylene composites", *Composites Part B: Engineering,* 63, 154–160, 2014.

[16] Shirvanimoghaddam, K., Balaji, K.V., Yadav, R., Zabihi, O., Ahmadi, M., Adetunji, P. and Naebe M., "Balancing the toughness and strength in polypropylene composites", *Composites Part B: Engineering*, 223, 109121, 2021.

[17] Salari, M., Sansone, N.D., Razzaz, Z., Taromsori, S.M., Leroux, M., Park, C.B. and Lee, PC., "Insights into synergy-induced multifunctional property enhancement mechanisms in hybrid graphene nanoplatelet reinforced polymer composites", *Chemical Engineering Journal*, 463, 142406, 2023.

[18] Ramesh, M., Rajeshkumar, L.N., Srinivasan, N., Kumar, D.V. and Balaji, D., "Influence of filler material on properties of fiber-reinforced polymer composites: A review", *E-Polymers*, 22(1), 898–916, 2022.

[19] Nguyen-Tran, H.D., Hoang, V.T., Do V.T., Chun, D.M. and Yum Y.J., "Effect of multiwalled carbon nanotubes on the mechanical properties of carbon Fiber-Reinforced Polyamide-6/Polypropylene composites for lightweight automotive parts". *Materials*, 11(3), 2018.

[20] Dhilipkumar, T. and Rajesh, M., "Effect of manufacturing processes and multi-walled carbon nanotube loading on mechanical and dynamic properties of glass fiber reinforced composites", *Polymer Composites*, 43(3), 1772–1786, 2022.

[21] Peng, K., Wan, Y.J., Ren, D.Y., Zeng, Q.W. and Tang, L.C., "Scalable preparation of multiscale carbon nanotube/glass fiber reinforcements and their application in polymer composites", *Fibers and Polymers*.;15(6):1242–1250, 2014.

[22] Rasana, N., Jayanarayanan, K. and Ramachandran, K.I., "Experimental, analytical and finite element studies on nano(MWCNT) and hybrid (MWCNT/glass fiber) filler reinforced polypropylene composites", *Iranian Polymer Journal*, 29(12), 1071–85, 2020.

[23] Mäder, E., Rausch, J. and Schmidt, N., "Commingled yarns – Processing aspects and tailored surfaces of polypropylene/glass composites", *Composites Part A: Applied Science and Manufacturing*, 39(4), 612–623, 2008.

[24] Fang, J., Zhang, L. and Li, C., "The combined effect of impregnated rollers configuration and glass fibers surface modification on the properties of continuous glass fibers reinforced polypropylene prepreg composites", *Composites Science and Technology*.;197:108259, 2020.

[25] Díez-Pascual, A.M., Naffakh, M., Marco, C, Gómez-Fatou, M.A. and Ellis, G.J., "Multiscale fiber-reinforced thermoplastic composites incorporating carbon nanotubes: A review", *Current Opinion in Solid State & Materials Science*, 18(2), 62–80, 2014.

[26] Pedrazzoli, D. and Pegoretti, A., "Hybridization of short glass fiber polypropylene composites with nanosilica and graphite nanoplatelets", *Journal of Reinforced Plastics and Composites*, 33(18), 1682–1695, 2014.

[27] Rausch, J., Zhuang, R.C. and Mäder, E., "Application of nanomaterials in sizings for glass fibre/polypropylene hybrid yarn spinning", *Materials Technology*, 24(1), 29–35, 2009.

[28] Mäder, E., Rothe, C. and Gao, S.L., "Commingled yarns of surface nanostructured glass and polypropylene filaments for effective composite properties", *Journal of Materials Science*, 42(19), 8062–8070, 2007.

[29] Rasana, N. and Jayanarayanan, K., "Polypropylene/short glass fiber/nanosilica hybrid composites: evaluation of morphology, mechanical, thermal, and transport properties", *Polymer Bulletin*, 75(6), 2587–2605, 2018.

[30] Qi, Y., Li, J. and Liu, L., "Tensile properties of multilayer-connected biaxial weft knitted fabric reinforced composites for carbon fibers", *Materials & Design*, 54, 678–685, 2014.

[31] Khondker, O.A., Leong, K.H. and Herszberg, I., "Effects of biaxial deformation of the knitted glass preform on the in-plane mechanical properties of the composite", *Composites Part A: Applied Science and Manufacturing*, 32(10), 1513–1523, 2001.

[32] Abounaim, M, Diestel, O, Hoffmann, G and Cherif, C., "High performance thermoplastic composite from flat knitted multi-layer textile preform using hybrid yarn", *Composites Science and Technology*, 71(4), 511–519, 2011.

[33] Hamada, H., Sugimoto, K., Nakai, A., Takeda, N., Gotoh, S. and Ishida, T., "Mechanical properties of knitted fabric composites", *Journal of Reinforced Plastics and Composites*, 19(5), 364–376, 2000.

[34] Kiss, P., Stadlbauer, W., Burgstaller, C. and Archodoulaki, V.M., "Development of high-performance glass fibre-polypropylene composite laminates: Effect of fibre sizing type and coupling agent concentration on mechanical properties", *Composites Part A: Applied Science and Manufacturing*, 138, 106056, 2020.

[35] Hufenbach, W., Böhm, R., Thieme, M., Winkler, A, Mäder, E., Rausch, J. and Schade. M., "Polypropylene/glass fibre 3D-textile reinforced composites for automotive applications", *Materials & Design*, 32(3), 1468–1476, 2011.

[36] Liu, M.H., Li, R., Wang, G., Hou, Z.Y. and Huang, B., "Morphology and dynamic mechanical properties of long glass fiber-reinforced polyamide 6 composites", *Journal of Thermal Analysis and Calorimetry*, 126(3), 1281–1288, 2016.

[37] Demircan, O., Al-darkazali, A., İnanç, I. and Eskizeybek, V. "Investigation of the effect of CNTs on the mechanical properties of LPET/glass fiber thermoplastic composites", *Journal of Thermoplastic Composite Materials*, 33(12), 1652–1673, 2019.

[38] Bilisik, K, Erdogan, G and Sapanci, E., "Interlaminar shear properties of nanostitched/nanoprepreg aramid/phenolic composites by short beam method", *Journal of Composite Materials*, 53(21), 2941-2957, 2019.

[39] Bilisik, K, Erdogan, G and Sapanci, E. "Flexural behavior of 3D para-aramid/phenolic/nano (MWCNT) composites", *RSC Adv*ances, 8, 7213-7224, 2018.

[40] Papila, M. Bilge, K., Yenigün, E. O., Şimşek, E. and Menceloğlu, Y. Z., "Structural composites hybridized with epoxy compatible polymer/MWCNT nanofibrous interlayers", *Composites Science and Technology*, 72, 1639, 2012.