

**INVESTIGATION ON MECHANICAL & IMPACT
PROPERTIES OF KEVLAR/POLYPROPYLENE
COMPOSITES MADE WITH COMMINGLED TOWPREGS**

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**Investigation on Mechanical & Impact Properties of Kevlar/Polypropylene Composites
Made with Commingled Towpregs**

by

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Submitted

In fulfillment of the requirements of the degree of Doctor of Philosophy
to the



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**Dedicated Gratefully
To My Gurus, Parents, Extended
Family & Friends**

CERTIFICATE

This is to certify that the thesis entitled “**Investigation on Mechanical & Impact Properties of Kevlar/Polypropylene Composites Made with Commingled Towpregs**” submitted by **Mr. Ganesh Jogur** to the **Indian Institute of Technology Delhi** for the award of the degree of **Doctor of Philosophy** in the **Department of Textile and Fibre Engineering**, is a record of bonafide research work carried out by him. Mr. Ganesh Jogur has worked under our guidance and supervision.

The results contained in this thesis are original and have not been submitted in partial or full, to any other university or institute for the award of any degree or diploma.

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ABSTRACT

The present study investigates the importance of commingled towpregs and their effect on Kevlar/PP composites. A commingling machine was fabricated in-house for the towpregs' production. The study begins with optimising nozzle design geometry using 3D CFD simulation and experimental testing. Three different nozzle geometries were analysed to understand their airflow behaviour and commingling efficiency in terms of fluid parameters vorticity magnitude (VM), turbulent kinetic energy (TKE), turbulent intensity (TI) and radial velocity (RV). Among the chosen nozzle designs, configurations I and II work on backwards airflow principles, while configuration (CONF) III functions with forwarding airflow principles. To gain a comprehensive insight into the airflow dynamics within distinct nozzle sections, an analysis is conducted on the contours of 3D and surface streamlines. Subsequently, COM towpregs are manufactured employing these three nozzles under the same processing conditions. The structural properties of the resulting COM towpregs, including nip frequency, nip stability, yarn regularity, and mingling tendency, are then evaluated to determine the effectiveness of the simulated nozzle designs.

Further, the pre-opening behaviour of nozzles was analysed by recording/capturing the commingling process during the production. Among the studied nozzles, the nozzle Configuration III with forward airflow principle can produce towpregs with compact structure, high nip frequency, and mixing quality at lower pressure (4.5 bar) compared to other nozzle designs. Nozzle CONF III have the excellent ability to mix both reinforcement and matrix filaments across the yarn structure. The nozzle can also form stable nips in the yarn structure, making the textile's performance effortless.

Nozzle CONF III diameter was optimised, and commingling process parameters were conducted through 3D CFD simulations and Box-Behnken design studies. Simulations were performed for nozzles with cylindrical diameters of 3, 5, 7, and 9 mm, and towpregs were subsequently manufactured at these diameters to assess the effect on the quality properties of Kevlar®/PP commingled towpregs. Among the studied diameters, the 7 mm nozzle diameter yielded towpregs of exceptional quality compared to others. The available empty space for commingling individual Kevlar® and PP filaments reached an optimal level at the 7 mm nozzle, offering improved fibre displacement within and between the Kevlar® and PP filament bundles. The Box-Behnken design study highlighted that air pressure can significantly influence the formation of higher stable nips.

Furthermore, interaction parameters such as delivery speed and overfeed of fibre bundles should be minimal to enhance fibre-air interaction and to increase stable nip frequency in towpregs. The optimal processing parameters for quality towpregs were arrived at an air pressure of 4.5 bar, delivery speed of 2 m/min, and overfeed of 3% and 1% for Kevlar and PP filaments, respectively. Towpregs produced under these conditions using a 7 mm nozzle diameter exhibited the highest nip frequency, nip stability, weavability, and homogeneous fibre-matrix mixing quality.

The consolidation quality of the unidirectional (UD) composites made with commingled (COM) Kevlar®/pp towpregs produced at the optimised conditions were compared with UD composites of friction spun (FS) and braided (BR) towpregs. The composites were produced with 50 % fibre volume using unidirectional layer wrapping technique under compression moulding machine at constant consolidation parameters. Among these composites, UD-COM composites outperformed other composites in terms of lowest void, higher flexural, interlaminar shear and Izod notch impact properties. The towpregs' structure and the fibre-matrix distribution within the towpregs' cross-section significantly affect the consolidation quality and composite properties. The COM towpregs offered a homogenous distribution of fibre and matrix, reducing melt flow distance, eventually reducing the void and increasing the composite mechanical and impact properties.

The current study investigated the influence of woven textile preforms using COM towpregs on consolidation quality and composite performance. Woven preforms, including UD, Satin/Sateen, and 3D orthogonal structures, were manufactured using Kevlar®/PP COM towpregs with a fibre volume close to 50%. To ensure a fair comparison, the areal density of these composites was kept constant. The evaluation was done in terms of void content, flexural strength, modulus, interlaminar shear strength, Izod notch impact, and dynamic impact resistance properties. Remarkably, 3DO-WC outperformed UD-WC and SA-WC across all these mechanical and impact properties. The study underscored the importance of through-thickness directional towpregs in enhancing the absorption of higher impact energy. The combinational effect of parameters such as fibre orientation, fibre volume in the loading direction, increased structural integrity and stability played a crucial role in influencing the mechanical and impact properties of the composites.

सारांश

वर्तमान अध्ययन कोमिंगल टोप्रेग्स के महत्व और उनके केवलर/पीपी सम्मिश्रण पर प्रभाव की जांच करता है। टोप्रेग्स के उत्पादन के लिए इन-हाउस एक कोमिंगल मशीन तैयार की गई थी। अध्ययन की शुरुआत 3D CFD सिमुलेशन और प्रयोगात्मक परीक्षण का उपयोग करके नोजल डिज़ाइन ज्यामिति को अनुकूलित करने से होती है। तीन विभिन्न नोजल ज्यामितियों का विश्लेषण किया गया ताकि उनके वायुप्रवाह व्यवहार और मिश्रण दक्षता को समझा जा सके, जिनमें तरल मापदंडों वॉर्टिसिटी मैग्निट्यूड (VM), टर्बुलेंट काइनेटिक एनर्जी (TKE), टर्बुलेंट इंटेन्सिटी (TI) और रेडियल वेग (RV) शामिल हैं। चुनी गई नोजल डिज़ाइनों में से, कॉन्फ़िगरेशन I और II पिछड़े वायुप्रवाह सिद्धांतों पर काम करते हैं, जबकि कॉन्फ़िगरेशन (CONF) III अग्र वायुप्रवाह सिद्धांतों के साथ काम करता है। विभिन्न नोजल अनुभागों के भीतर वायुप्रवाह गतिकी में व्यापक अंतर्दृष्टि प्राप्त करने के लिए, 3D और सतह स्ट्रीमलाइनों के कंटूर का विश्लेषण किया जाता है। इसके बाद, इन तीन नोजलों का उपयोग करके समान प्रसंस्करण स्थितियों में COM टोप्रेग्स का निर्माण किया जाता है। परिणामी COM टोप्रेग्स के संरचनात्मक गुणों का मूल्यांकन किया जाता है, जिसमें निप फ्रीक्वेंसी, निप स्थिरता, यार्न नियमितता, और मिश्रण प्रवृत्ति शामिल हैं, ताकि अनुकरण किए गए नोजल डिज़ाइनों की प्रभावशीलता को निर्धारित किया जा सके।

इसके अतिरिक्त, नोजलों के पूर्व-खोलने के व्यवहार का विश्लेषण किया गया और उत्पादन के दौरान मिश्रण प्रक्रिया को रिकॉर्ड/कैप्चर किया गया। अध्ययन किए गए नोजलों में, आगे वायुप्रवाह सिद्धांत के साथ नोजल कॉन्फ़िगरेशन III अन्य नोजल डिज़ाइनों की तुलना में कम दबाव (4.5 बार) पर कॉम्पैक्ट संरचना, उच्च निप फ्रीक्वेंसी और मिश्रण गुणवत्ता वाले टोप्रेग्स का उत्पादन कर सकता है। नोजल CONF III यार्न संरचना में स्थिर निप्स भी बना सकता है, जिससे कपड़ा प्रदर्शन सरल हो जाता है। नोजल CONF III व्यास को अनुकूलित किया गया, और मिश्रण प्रक्रिया मापदंडों को 3D CFD सिमुलेशन और बॉक्स-बेन्केन डिज़ाइन अध्ययन के माध्यम से संचालित किया गया। नोजलों के लिए 3, 5, 7, और 9 मिमी के सिलेंडर व्यास के लिए सिमुलेशन किया गया, और इन व्यासों पर टोप्रेग्स का निर्माण किया गया ताकि केवलर®/PP मिश्रित टोप्रेग्स की गुणवत्ता गुणों पर प्रभाव को आंका जा सके। अध्ययन किए गए व्यासों में, 7 मिमी नोजल व्यास ने अन्य की तुलना में उत्कृष्ट गुणवत्ता वाले टोप्रेग्स का उत्पादन किया। व्यक्तिगत केवलर® और पीपी फिलामेंट्स के मिश्रण के लिए उपलब्ध खाली स्थान 7 मिमी नोजल पर एक इष्टतम स्तर तक पहुँच गया, जिससे केवलर® और पीपी फिलामेंट बंडलों के भीतर और बीच में फाइबर विस्थापन में सुधार हुआ। बॉक्स-बेन्केन डिज़ाइन अध्ययन ने रेखांकित किया कि उच्च स्थिर निप्स के गठन को महत्वपूर्ण रूप से प्रभावित कर सकता है।

इसके अतिरिक्त, वितरण गति और फाइबर बंडलों के ओवरफीड जैसे अंतःक्रियात्मक मापदंडों को न्यूनतम रखा जाना चाहिए ताकि फाइबर-वायु संपर्क में वृद्धि हो सके और टोप्रेग्स में स्थिर निप फ्रीक्वेंसी बढ़ाई जा सके। गुणवत्ता टोप्रेग्स के लिए इष्टतम प्रसंस्करण मापदंडों का निर्धारण 4.5 बार वायु दबाव, 2 मी/मिनट वितरण गति, और केव्लर और पीपी फिलामेंट्स के लिए क्रमशः 3% और 1% ओवरफीड पर किया गया। इन परिस्थितियों में 7 मिमी नोजल व्यास का उपयोग करके उत्पादित टोप्रेग्स ने सबसे उच्च निप फ्रीक्वेंसी, निप स्थिरता, बुने जाने की क्षमता, और समान फाइबर-मैट्रिक्स मिश्रण गुणवत्ता का प्रदर्शन किया।

संपीड़न मोल्लिंग मशीन पर निरंतर समेकन मापदंडों पर 50% फाइबर मात्रा के साथ एक दिशात्मक परत लपेटने की तकनीक का उपयोग करके उत्पादित टॉप्रेग्स के साथ बनाए गए समेकित यूनिडायरेक्शनल (UD) सम्मिश्रण की गुणवत्ता की तुलना FS (फ़िक्शन स्पिन) और BR (ब्रेइडेड) टोप्रेग्स के UD सम्मिश्रणों के साथ की गई। इन सम्मिश्रणों में, UD-COM सम्मिश्रण ने न्यूनतम शून्यता, उच्चतम फ्लेक्सुरल, इंटरलामिनार शीयर और इज़ोड नॉच इम्पैक्ट गुणों के संदर्भ में अन्य सम्मिश्रणों से बेहतर प्रदर्शन किया। टोप्रेग्स की संरचना और टोप्रेग्स के क्रॉस-सेक्शन के भीतर फाइबर-मैट्रिक्स वितरण ने समेकन गुणवत्ता और सम्मिश्रण गुणों को महत्वपूर्ण रूप से प्रभावित किया। COM टोप्रेग्स ने फाइबर और मैट्रिक्स का समान वितरण प्रदान किया, जिससे पिघल प्रवाह दूरी में कमी आई, और अंततः शून्यता में कमी और सम्मिश्रण के यांत्रिक और प्रभाव गुणों में वृद्धि हुई।

वर्तमान अध्ययन ने COM टोप्रेग्स का उपयोग करके बुने हुए वस्त्र पूर्वप्रारूपों के समेकन गुणवत्ता और सम्मिश्रण प्रदर्शन पर प्रभाव की जांच की। COM टोप्रेग्स का उपयोग करके निर्मित बुने हुए पूर्वप्रारूपों, जिसमें UD, सैटिन/सतीन, और 3D ऑर्थोगोनल संरचनाएँ शामिल थीं, का उत्पादन 50% के निकट फाइबर मात्रा के साथ किया गया था। निष्पक्ष तुलना सुनिश्चित करने के लिए, इन सम्मिश्रणों का क्षेत्रीय घनत्व स्थिर रखा गया था। मूल्यांकन शून्यता सामग्री, फ्लेक्सुरल ताकत, माडुलस, इंटरलामिनार शीयर ताकत, इज़ोड नॉच इम्पैक्ट, और गतिशील प्रभाव प्रतिरोध गुणों के संदर्भ में किया गया। आश्चर्यजनक रूप से, 3DO-WC ने सभी यांत्रिक और प्रभाव गुणों में UD-WC और SA-WC को बेहतर प्रदर्शन दिया। अध्ययन ने उच्च प्रभाव ऊर्जा अवशोषण को बढ़ाने में थ्रू-थिकनेस दिशात्मक टोप्रेग्स के महत्व को रेखांकित किया। फाइबर अभिविन्यास, भार दिशा में फाइबर मात्रा, संरचनात्मक अखंडता और स्थिरता जैसे मापदंडों का संयोजनात्मक प्रभाव सम्मिश्रण के यांत्रिक और प्रभाव गुणों को प्रभावित करने में महत्वपूर्ण भूमिका निभाता है।

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Abbreviation and Symbols

%	Percentage
°C	Degree Celsius
K	Kelvin
°C/min	Degree Celsius per minute
V _f	Fibre volume
V _m	Matrix volume
ρ_f	Fibre density
ρ_m	Matrix density
μm	Micro-meter
tpm	Twist per meter
MPa	Mega pascal
GPa	Giga pascal
mm	Millimetre
cm	Centimetre
m	Meter
N	Newton force
kN	Kilo newton force
g	Gram
kg	Kilo gram
kg/m ³	Kilo grams per cubic meter
g/m ²	Grams per square meter
ktex	Kilo tex
g/den	Grams per denier
g/10 min	Grams per 10 minutes
g.cm ²	Gram centimetre square
Dyn.cm ²	Dynes per square centimetre
J	Joule
J/g	Joule per gram
N-ms	Newton per millisecond
J-ms	Joule per millisecond
mm/min	Millimetre per minute
m/s	Meter per second

m/min	Meter per minute
rev/min	Revolutions per minute
D _{com}	Degree of commingling
T _m	Melting temperature
TP	Thermoplastic
COM	Commingled
FS	Friction spun
BR	Braided
CFD	Computational fluid dynamics
3D	Three-dimensional/directional
2D	Two-dimensional/directional
UD	Unidirectional
CONF	Configuration
VM	Vorticity magnitude
TKE	Turbulent kinetic energy
TI	Turbulent intensity
RV	Radial velocity
FPI	First perpendicular inlet
FOI	First oblique inlet
SPI	Second perpendicular inlet
MOI	Middle oblique inlet
1/s	Swirl per second
m ² /s ²	Square Meter per Square Second
MFI	Melt flow index
NF	Nip frequency
RD	Relative decay
OF	Overfeed
AP	Air pressure
DS	Delivery speed
dpf	Denier per filament
UD-WC	Unidirectional woven composite
SA-WC	Satin/Sateen woven composite
3DO-WC	3D orthogonal woven composite