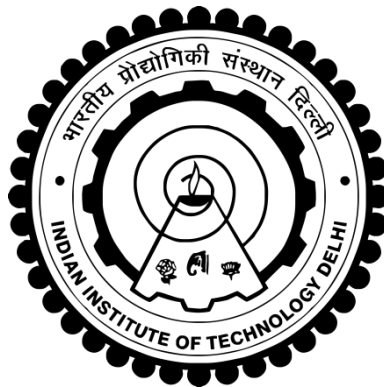


**DEVELOPMENT AND CHARACTERIZATION OF COMPOSITES
REINFORCED WITH TEXTILE WASTE**

ZUNJARRAO BAPUSO KAMBLE



**DEPARTMENT OF TEXTILE AND FIBRE ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI
JUNE 2021**

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by

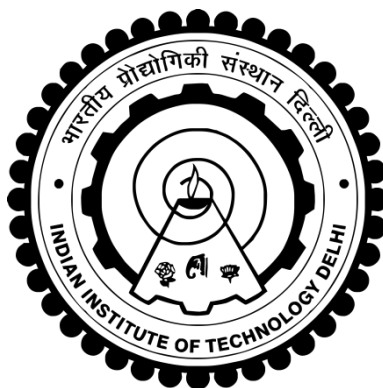
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Department of Textile and Fibre Engineering

Submitted

in fulfilment of the requirement of the degree of Doctor of Philosophy

to the



**DEPARTMENT OF TEXTILE AND FIBRE ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI**

JUNE 2021

Dedicated To My Parents

CERTIFICATE

This is to certify that the thesis entitled “**Development and characterization of composites reinforced with textile waste**” being submitted by **Mr. Zunjarrao Bapuso Kamble** to the Indian Institute of Technology Delhi for the award of the degree of **Doctor of Philosophy** is a record of bonafide research work carried out by him. Mr. Zunjarrao Bapuso Kamble has worked under my guidance and supervision and fulfilled the requirements for the submission of the thesis. The results contained in the thesis have not been submitted, in part or full, to any other university for the award of any degree or diploma.

Date:

Prof. B. K. Behera

Place: New Delhi

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New Delhi – 110016.

ACKNOWLEDGEMENTS

Words of appreciation and gratitude fall short of acknowledging the inspiring guidance, valuable suggestions, constant encouragement, and liberty provided by Prof. B. K. Behera at every stage of this research. I enjoyed and learned a lot working under him throughout my Ph.D.

I gratefully acknowledge the help and suggestions by my SRC members Prof. R. Alagirusamy, Prof. Samrat Mukhopadhyay, Prof. B. K. Satapathy (Department of Material Science and Engineering), and other faculty members of the department. I also wish to thank ex-Head of the Department, Prof. A. K. Agrawal, for encouragement and support.

I gratefully acknowledge the help and support of Prof. Rajesh Mishra (Czech University of Life Sciences Prague, Czech Republic) and Dr. Promoda Behera (Technical University of Liberec, Czech Republic). I acknowledge the help & cooperation of the lab staff, especially Mr. M. Kundu, Mr. M. Singh, and Mr. Vikas Khatkar. I am thankful to all my friends, especially Dr. Ghanshyam Neje, Mr. Ashraf Khan, Mr. Nagender Jangra, Mr. Rupesh Ganvir, Ms. Shikha Yadav, Mr. Omender Kumar, Mr. Soumya Choudhary, Ms. Lekhani Tripathi, Ms. Meenakshi Ahirwar, Mr. Sandeep Olhan, for their help, support, and encouragement.

I express my sincere gratitude to my mother, brothers, sisters and friends for their motivation, moral support, and understanding.

Date :

Zunjarrao Bapuso Kamble

Place : New Delhi

Abstract

The ever-increasing population and, most importantly, ‘fast fashion’ has put the demand for clothing high. The increased consumption of textiles led to increased waste. The textile waste, if not appropriately managed it can cause serious health hazards. The conventional methods of textile waste management, such as landfilling and burning, are not environmentally friendly. Therefore, it is necessary to develop new ways to recycle or reuse waste textiles and new applications.

In this research, in the first section, thermoset epoxy and thermoplastic polypropylene (PP) composites with four different fibre volume fractions (0.1, 0.2, 0.3, and 0.4) were developed using cotton fibres extracted from waste textiles and waste polyester fibres generated during polyester staple yarn manufacturing. The fibres extracted from waste textiles are called shoddy. The cotton shoddy and polyester fibres were processed on carding machines to produce oriented fibre web. This oriented fibre web was used as a preform. The thermoset resin mixed with the curing agent was applied uniformly on the fibre web. The thermoset composites were developed using a compression moulding machine. The mechanical performance in terms of tensile, flexural, and impact properties of cotton and polyester fibre epoxy composites with 0.3 fibre volume fraction was found better. The average tensile, impact, and pinned joint strength of polyester/epoxy composites was higher than cotton/epoxy composites. However, the average flexural strength of cotton/epoxy composites was found higher than polyester/epoxy composites. The water absorption causes a notable change in the mechanical properties of these composites. Further, the tensile strength of cotton/PP composites decreases with an increase in fibre loading. In contrast, the izod impact strength increases with an increase in cotton fibre loading. The flexural strength of cotton/PP composite increases with an increase in cotton loading from 20 to 40wt% and decreases when

cotton loading increases to 50wt%. The tensile, flexural, and izod impact strength of polyester/PP composites increases with polyester fibre loading.

An effort has been made to enhance the mechanical properties of the cotton/epoxy composites by incorporating reduced graphene oxide (rGO) nanoparticles in four different weight percentages (0.1, 0.3, 0.5, and 1wt%) and enzyme-treated hemp fibre (HF) microparticles in four different weight percentages (1, 2, 3, and 5wt%). The compression moulding technique was used to produce the composite specimens. It has been found that the mechanical properties of composites loaded with 0.3wt% of rGO and 3wt% of HF microparticles show enhancement in mechanical properties, namely, tensile, flexural, izod impact, and pinned joint strength. The dynamic mechanical properties of the composites improve upon rGO and HF particles loading. However, the water absorption properties are not influenced by rGO and HF particle filler loading.

The yarn produced using fibres extracted from waste textiles were used to produce the 2D fabric, 3D homogeneous, and 3D hybrid orthogonal woven preforms. The 3D hybrid preform consists of glass yarn as a stuffer and wastes cotton yarn as a binder and filler. The four-layer 2D laminate and 3D composite specimens were developed using the vacuum-assisted resin infusion technique. The tensile and flexural properties composites were in order of 3D hybrid > 2D laminate > 3D homogeneous. In comparison, the impact strength was in the order of 3D hybrid > 3D homogeneous > 2D laminate.

The mechanical properties of textile waste-based composites can be improved by engineering the preform structure. Nine different types of preforms, namely, carded cotton web (SH), cotton nonwoven laminate (Nw), stitched cotton nonwoven laminate (NwSt), cotton web sandwiched between woven fabrics (Wb), cotton web sandwiched between woven fabrics, and stitched (WbSt), nonwoven sandwiched between woven fabrics (Wn), nonwoven

sandwiched between woven fabrics and stitched (WnSt), cotton web sandwiched between waste cotton yarn UD preform (WbUD), cotton web sandwiched between hybrid woven fabrics (WbH) were developed. These preforms were then converted to composites having ~0.3 fibre volume fraction using the compression moulding technique. The composite specimen WbH exhibited a notable improvement of mechanical properties, namely, tensile, flexural, impact, and pinned joint strength, than all other composite specimens, followed by composite specimen WbUD. The mechanical properties of composite specimens Wb, WbSt, Wn, WnSt were approximately the same. The tensile and flexural properties of composite specimens Nw, NwSt, Wb, WbSt, Wn, WnSt are lower than SH. However, izod impact strength of SH was lower than composite specimens Nw, NwSt, Wb, WbSt, Wn, WnSt. The equilibrium water content of composite specimen Wb was substantially lower than SH.

In the last section, hybrid composites of carded cotton web laminated with unidirectional (UD) glass preform (in four weight percentages, namely, 7.64, 14.83, 21.59, and 27.96%) and jute nonwoven (in four weight percentages, namely, 3.59, 7.17, 10.76, and 14.34%) were developed. The tensile, flexural, impact, and pinned joint strength of hybrid composite specimens increases with UD glass preform loading. However, tensile and flexural properties of hybrid composites increased with an increase in jute nonwoven loading from 3.59 to 7.2wt%, and jute nonwoven loading beyond 7.2wt% does not help to improve these properties. However, the izod impact strength of the hybrid composites increased with an increase in jute nonwoven loading. The equilibrium water content decreases with UD glass loading, but it was approximately the same in jute nonwoven loaded composites.

The comparative analysis of specific mechanical properties of all the different types of composites reveals that the specific tensile strength and specific flexural strength of composite specimen WbH were highest among all the developed composites. The specific impact strength of hybrid composite loaded with 7.64wt% of UD glass was the highest

among all the composites. It has also been found that the equilibrium water content of cotton web reinforced composite was highest and polyester web reinforced composites was lowest.

सार

लगातार बढ़ती आबादी और, सबसे महत्वपूर्ण बात, 'फास्ट फैशन' ने कपड़ों की मांग को बढ़ा दिया है। वस्त्रों की बढ़ती खपत के कारण अपशिष्ट में वृद्धि हुई। कपड़ा अपशिष्ट, यदि उचित रूप से प्रबंधित नहीं किया गया तो यह गंभीर स्वास्थ्य खतरों का कारण बन सकता है। कपड़ा अपशिष्ट प्रबंधन के पारंपरिक तरीके, जैसे जमीन में गढ़ना या जलाना पर्यावरण के अनुकूल नहीं हैं। इसलिए, अपशिष्ट वस्त्रों के पुनर्चक्रण या पुनः उपयोग के नए तरीकों को विकसित करना और नए अनुप्रयोगों को विकसित करना आवश्यक है।

इस शोध में, पहले खंड में, चार अलग-अलग फाइबर आयतन अंशों (0.१, 0.२, 0.३ और 0.४) के साथ थर्मोसेट एपॉक्सी और थर्मोप्लास्टिक पॉलीप्रोपाइलीन कंपोजिट को अपशिष्ट वस्त्रों से निकाला गया कपास फाइबर तथा पॉलिएस्टर धागा विनिर्माण के दौरान उत्पन्न अपशिष्ट पॉलिएस्टर फाइबर से विकसित किया गया है। बेकार वस्त्रों से निकाले गए फाइबर को शोड़ी कहा जाता है। उन्मुख फाइबर वेब का उत्पादन करने के लिए कपास शोड़ी और अपशिष्ट पॉलिएस्टर फाइबर को कार्डिंग मशीन पर संसाधित किया गया है। इस उन्मुख फाइबर वेब को प्रीफॉर्म के रूप में इस्तेमाल किया गया है। क्युरिंग एजेंट के साथ मिश्रित थर्मोसेट रेसिन फाइबर वेब पर समान रूप से लागू किया गया है। थर्मोसेट कंपोजिट को कम्प्रेसन मोल्डिंग मशीन का उपयोग करके विकसित किया गया है। 0.३ फाइबर आयतन अंश के साथ कपास और पॉलिएस्टर फाइबर एपॉक्सी कंपोजिट के तन्यता, फ्लेक्सुरल और प्रभाव गुणों के संदर्भ में यांत्रिक प्रदर्शन बेहतर पाया गया। पॉलिएस्टर/एपॉक्सी कंपोजिट की औसत तन्यता, प्रभाव और पिन की गई संयुक्त ताकत कपास/एपॉक्सी कंपोजिट की तुलना में अधिक थी। हालांकि, कपास/एपॉक्सी कंपोजिट की औसत फ्लेक्सुरल ताकत पॉलिएस्टर/एपॉक्सी कंपोजिट की तुलना में अधिक पाई गई। जल अवशोषण इन कंपोजिट के यांत्रिक गुणों में उल्लेखनीय परिवर्तन का कारण बनता है। इसके अलावा, फाइबर लोडिंग में वृद्धि के साथ कपास/पॉलीप्रोपाइलीन कंपोजिट की तन्य शक्ति कम पाई गई। इसके विपरीत, कपास फाइबर लोडिंग में वृद्धि के साथ आईजोड प्रभाव शक्ति बढ़ जाती है। कॉटन/पॉलीप्रोपाइलीन कंपोजिट की फ्लेक्सुरल स्ट्रेंथ कॉटन लोडिंग में २० से ४० वजन प्रतिशत की वृद्धि के साथ बढ़ जाती है और कॉटन लोडिंग ५० तक बढ़ने पर घट जाती है। पॉलिएस्टर/पॉलीप्रोपाइलीन कंपोजिट की तन्यता, फ्लेक्सुरल और आईजोड प्रभाव शक्ति पॉलिएस्टर फाइबर लोडिंग के साथ बढ़ जाती है।

कपास/एपॉक्सी कंपोजिट के यांत्रिक गुणों को बढ़ाने के लिए चार अलग-अलग वजन प्रतिशत में रीडूसड ग्राफीन ऑक्साइड (rGO) नैनोकणों (0.१, 0.३, 0.५, और १ वजन प्रतिशत) और एंजाइम-उपचारित हेम्प फाइबर (HF) माइक्रोपार्टिकल्स (१, २, ३, और ५ वजन प्रतिशत) को शामिल किया गया है। कंपोजिट नमूनों के उत्पादन के लिए कम्प्रेसन मोल्डिंग तकनीक का उपयोग किया गया है। यह पाया गया है कि 0.३ वजन प्रतिशत rGO और ३ वजन प्रतिशत HF माइक्रोपार्टिकल्स के साथ लोड किए गए कंपोजिट के यांत्रिक गुण, अर्थात् तन्यता, फ्लेक्सुरल, आईज़ोड प्रभाव और पिन किए गए संयुक्त शक्ति में वृद्धि दिखाते हैं। कंपोजिट के गतिशील यांत्रिक गुणों में rGO और HF कणों के लोड होने पर सुधार होता है। हालाँकि, जल अवशोषण गुण rGO और HF कण भराव लोडिंग से प्रभावित नहीं होते हैं।

अपशिष्ट वस्त्रों से निकाले गए फाइबर का उपयोग करके उत्पादित धागे से २डी कपड़े, ३डी सजातीय, और ३डी हाइब्रिड ऑर्थोगोनल बुने हुए प्रीफॉर्म के उत्पादन किया गया है। ३डी हाइब्रिड प्रीफॉर्म में स्टर के रूप में ग्लास धागा और बाइंडर और फिलर के रूप में शोडि का धागा है। चार परतों का २डी लैमिनेट और ३डी कंपोजिट नमूनों को वैक्यूम-असिस्टेड रेजिन इन्फ्यूजन तकनीक का उपयोग करके विकसित किया गया था। तन्यता और फ्लेक्सुरल गुण कंपोजिट ३ डी हाइब्रिड > २ डी लैमिनेट > ३ डी सजातीय के क्रम में पाया गया है। इसकी तुलना में, प्रभाव शक्ति ३डी हाइब्रिड > ३डी सजातीय > २डी लैमिनेट के क्रम में पाया गया है।

टेक्सटाइल अपशिष्ट-आधारित कंपोजिट के यांत्रिक गुणों को इंजीनियरिंग संरचना द्वारा सुधारा जा सकता है। नौ विभिन्न प्रकार के प्रीफॉर्म विकसित किए गए हैं, वे इस प्रकार हैं: कार्डेड कपास वेब (SH), कपास नॉनवॉवन लैमिनेट (Nw), सिला हुआ कपास नॉनवॉवन लैमिनेट (NwSt), बुने हुए कपड़ों के बीच कपास वेब (Wb), बुने हुए कपड़ों के बीच कपास वेब डालकर सिला हुआ प्रीफॉर्म (WbSt), बुने हुए कपड़ों के बीच नॉनवॉवन (Wn), बुने हुए कपड़ों के बीच नॉनवॉवन डालकर सिला हुआ प्रीफॉर्म (WnSt), अपशिष्ट कपास धागे का यूनिडायरेक्शनल कपड़े के बीच सैंडविच किए गए कॉटन वेब (WbUD), हाइब्रिड बुने हुए कपड़े के बीच कपास वेब (WbH)। इन प्रीफॉर्म्स को कम्प्रेसन मोल्डिंग तकनीक का उपयोग करके ~0.३ फाइबर आयतन अंश वाले कंपोजिट में बदल दिया गया। कंपोजिट नमूना WbH ने अन्य सभी मिश्रित नमूनों की तुलना में यांत्रिक गुणों, अर्थात् तन्यता, फ्लेक्सुरल, प्रभाव, और पिन की गई संयुक्त शक्ति के उल्लेखनीय सुधार का प्रदर्शन किया, इसके बाद समग्र नमूना WbUD। कंपोजिट नमूनों Wb, WbSt, Wn, WnSt के यांत्रिक गुण लगभग समान हैं। कंपोजिट नमूनों Nw, NwSt, Wb, WbSt, Wn, WnSt के तन्यता और फ्लेक्सुरल गुण SH से कम हैं। हालाँकि, SH की आईज़ोड

प्रभाव शक्ति कंपोजिट नमूनों Nw, NwSt, Wb, WbSt, Wn, WnSt से कम है। कंपोजिट नमूने Wb की संतुलन जल सामग्री SH की तुलना में काफी कम है।

अंतिम खंड में, कार्डेड कपास वेब के हाइब्रिड कंपोजिट, जो यूनिडायरेक्शनल (UD) ग्लास प्रीफॉर्म (चार वजन प्रतिशत में, अर्थात् ७.६४, १४.८३, २१.५९, और २७.९६%) और जूट नॉनवॉवन (चार वजन प्रतिशत में, ३.५९, ७.१७, १०.७६ और १४.३४%) के साथ लैमिनेट करके विकसित किए गए हैं। यूनिडायरेक्शनल ग्लास प्रीफॉर्म लोडिंग के साथ हाइब्रिड कंपोजिट नमूनों की तन्यता, फ्लेक्सुरल, प्रभाव और पिन की गई संयुक्त ताकत बढ़ जाती है। हालांकि, हाइब्रिड कंपोजिट के तन्यता और फ्लेक्सुरल गुणों में ३.५९ से ७.२ वजन प्रतिशत जूट नॉनवॉवन डालने से वृद्धि हुई है, और जूट नॉनवॉवन लोडिंग ७.२ वजन प्रतिशत से अधिक होने पर गुणों को बेहतर बनाने में मदद नहीं करता है। हालांकि, जूट नॉनवॉवन लोडिंग में वृद्धि के साथ हाइब्रिड कंपोजिट की आईज़ोड प्रभाव शक्ति में वृद्धि हुई। यूनिडायरेक्शनल ग्लास लोडिंग के साथ संतुलन पानी की मात्रा कम हो जाती है, लेकिन जूट नॉनवॉवन लोडेड कंपोजिट में यह लगभग समान था।

सभी विभिन्न प्रकार के कंपोजिट के विशिष्ट यांत्रिक गुणों के तुलनात्मक विश्लेषण से पता चलता है कि विशिष्ट तन्य शक्ति और समग्र नमूना WbH की विशिष्ट फ्लेक्सुरल ताकत सभी विकसित कंपोजिट में सबसे अधिक थी। ७.६४ वजन प्रतिशत यूनिडायरेक्शनल ग्लास के साथ लोड किए गए हाइब्रिड कंपोजिट की विशिष्ट प्रभाव शक्ति सभी कंपोजिट में सबसे अधिक थी। यह भी पाया गया है कि कपास वेब रीइन्फोर्स्ड कंपोजिट की संतुलन जल सामग्री उच्चतम थी और पॉलिएस्टर वेब प्रबलित कंपोजिट न्यूनतम थी। सभी कंपोजिट के थर्मोग्रैविमेट्रिक विश्लेषण से पता चलता है कि वे पर्याप्त रूप से तापीय रूप से स्थिर हैं।

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