Available online at
https://jmeche.uitm.edu.my/

Journal of Mechanical Engineering

e-ISSN: 2550-164X

Journal of Mechanical Engineering 22(1) 2025, 46 – 57.

The Effect of Fibre Orientation on the Density and Tensile Properties of Basalt Fibre/Epoxy Composites

Afiqah Nur Fatin Abdua[1], Nik Noor Idayu Nik Ibrahim[1,2*]

[1]*Faculty of Applied Sciences, Universiti Teknologi MARA, 40450 Shah Alam, Selangor, Malaysia.*
[2]*Center of Chemical Synthesis and Polymer Technology, Institute of Science, Universiti Teknologi MARA, 40450 Shah Alam, Selangor, Malaysia.*

ARTICLE INFO

Article history:
Received 9 October 2023
Revised 15 May 2024
Accepted 3 July 2024
Online first
Published 15 January 2025

Keywords:
Basalt fibre
Fibre orientation
Tensile properties
Density
Void content

DOI:
10.24191/jmeche.v22i1.4555

ABSTRACT

The mechanical behaviour of fibre-reinforced epoxy composites is strongly influenced by the orientation of reinforcing fibres within the epoxy matrix. Understanding the relationship between fibre orientation, void formation, density, and mechanical properties in fibre-reinforced polymer (FRP) composites is crucial for optimizing their performance. Basalt fibres, known for their superior properties, were integrated into epoxy resin to create composite materials with varied fibre orientations via the hand lay-up method. The composites were fabricated into one-ply ((0/90) and (±45)), two-plies (0/90)(±45)) and three-plies ((0/90)(±45)(0/90) and (±45)(0/90)(±45). The addition of basalt fibres increased the composite density, owing to the inherently denser nature of basalt compared to epoxy. When the number of basalt fibre plies is increased to two and three, the density of the composites decreases due to the presence of voids and the trapping of air between the layers of fibres during the process of layering and impregnation. One-ply composites with (0/90) orientation exhibited higher tensile strength and Young's modulus due to fibre alignment with the loading axis, enhancing load resistance. Conversely, (±45) orientation resulted in higher tensile strain, promoting deformation and load distribution in shear. Tensile strength and Young's modulus of two plies of basalt fibre composites lie between those of one-ply composites with (0/90) and (±45) orientations since the (0/90) fibres efficiently resist the applied load along their aligned directions, while the (±45) fibres aid in distributing and absorbing the load in shear, which enhances overall tensile strength and modulus compared to one-ply (±45) composites. In the case of three-plies composites, the composites with two plies oriented in (0,90) demonstrated higher tensile strength and Young's modulus when compared to those with two plies of fibres oriented in (±45).

INTRODUCTION

A fibre-reinforced polymer (FRP) is a composite material made up of a polymer matrix and fibre reinforcement (Congress, 1988; Wallenberger & Weston, 2004). The fibre is either made from natural sources (Chok. & Majid., 2018; Mohd Ghaztar et al., 2022) or man-made sources (Ghani & Mahmud,

[1*] Corresponding author. *E-mail address*: nikidayu@uitm.edu.my
https://doi.org/10.24191/jmeche.v22i1.4555

2018). Fibre composites have been widely used in various applications nowadays because of their superior properties. Composites typically comprise three distinct phases: the continuous phase, the dispersed phase, and the interphase (Thomas et al., 2012; Wang et al., 2011). Each phase serves a unique role in shaping the properties and behaviour of the composite material. The continuous phase is often referred to as the matrix. It forms the fundamental structure of the composite and surrounds and encases the other phases. The matrix material acts as a binder, holding the composite together and providing overall cohesion. It serves as a medium through which external forces are transmitted and distributed across the composite. The dispersed phase consists of the material that is distributed throughout the matrix. This component is also known as the reinforcement or filler. Its primary function is to enhance specific properties of the composite, such as strength, stiffness, or resistance to various environmental factors. The dispersed phase reinforces the matrix, improving the overall performance of the composite material. The interphase is a distinct region that forms at the interfaces between different layers or phases within the composite. Its purpose is to establish a bond or connection between adjacent layers, ensuring effective load transfer and enhancing the adhesion between the matrix and the dispersed phase. The interphase plays a crucial role in maintaining the integrity and performance of the composite by facilitating stress transfer and preventing delamination or separation between layers.

A class of cutting-edge materials known as synthetic fibre-reinforced composites has revolutionised a wide range of industries, including construction, sports equipment, automotive, and aerospace. These composites are engineered by combining synthetic fibres with a matrix material, typically a polymer resin, to create a material that offers a unique blend of properties and performance characteristics. Since basalt was discovered by a French scientist in 1923, it has been used widely in various applications such as automobile, aerospace, construction, etc. due to its superior properties. Because of its relatively homogenous chemical structure, large-scale availability around the world, lack of contaminants, and ability to form fibres in the molten state, basalt is an alternate raw material for fibre-making (Kumbhar, 2014). Basalt fibre has the potential to open up a whole new world of composite materials and products. Low-cost, high-performance fibres have the potential to solve the cement and concrete industry's biggest problem: concrete cracking and structural failure (Fiore et al., 2015).

Basalt fibre is a material extracted from basalt rock which is abundantly found everywhere all around the world. Basalt is formed from volcanic magma and flood volcanoes, which is an extremely hot fluid or semifluid material that solidifies in the open air underneath the earth's crust (Saravanan, 2006; Vinay et al., 2022). Basalt fibre is currently used widely due to its outstanding properties including good mechanical and chemical resistance, and excellent thermal, electric, and acoustic insulation. Basalt consists of an abundance of magnesium, calcium, sodium, potassium, silicon, and iron oxides, as well as traces of alumina. As stated by Sonnenschein et al. (2016), basalt fibre is highly resistant to alkaline, acidic, and salt attacks and it has been widely used in concrete, bridge, and shoreline structures (Branston et al., 2016).

According to Dhand et al. (2015), because of their improved mechanical qualities, basalt fibres have gotten a lot more attention than other conventional fillers like glass fibres. Basalt is widely known for its higher tensile strength and higher elongation at break. Thus, with the help of these improved properties, the impact resistance and environmental sustainability of the properties within the composite can be enhanced. Recently, Elmahdy & Verleysen (2019) in their report stated that the ultimate tensile strength, elastic modulus, and ultimate tensile strain at a lower areal weight and density of the tested woven basalt/epoxy composite are higher compared to the woven glass/epoxy composite. Other than that, the fabrication of basalt/epoxy composites with tourmaline micro (TM)/nanoparticles (0.5 wt% – 2 wt%) using the vacuum-assisted resin transfer moulding technique increased the tensile and flexural strength and modulus (Subagia et al., 2014). A study of impact strength on basalt fibre also had been conducted by Bulut (2017) who stated that the incorporation of basalt fibre-reinforced composites with graphene nanopellet filler increases the impact strength of the composites. Due to these excellent properties, basalt fibre-based composites are now widely used in structural and electro-technical applications, such as automobiles, aircraft, ships, electromagnetic shielding structures, and house-holding components.

https://doi.org/10.24191/jmeche.v22i1.4555

The orientation of the reinforcing fibres within the epoxy matrix is a crucial factor that profoundly affects the mechanical behaviour of these composites. Fibre orientation, or how the fibres are arranged in a composite, is a crucial factor in influencing important mechanical qualities like tensile strength, tensile modulus, flexural strength, and impact resistance. The selection of fibre orientation can be customised to satisfy particular design requirements, making it a crucial factor in the engineering of composite materials. The orientation of fibres can significantly impact the load-bearing capacity, stiffness, and overall performance of the composite material. Understanding the influence of fibre orientation on mechanical properties is essential for optimizing composite design and ensuring that these materials meet the demands of various applications in industries ranging from aerospace to automotive and beyond. This influence is a result of the manner in which fibres are aligned relative to the direction of applied forces, affecting how they respond to mechanical loads and distribute stresses within the composite structure.

According to Kumaresan et al. (2015), who evaluated the effect of fibre orientation on the mechanical properties of sisal fibre-reinforced epoxy composites, sisal fibre-reinforced epoxy composites with 90° orientation had better mechanical qualities than those with 0° and 45° fibre orientations. The highest tensile value is obtained when the direction of the fibre with 0° orientation is parallel to the direction of the load (Lasikun et al., 2018). Meanwhile, the strength of composites will decrease if the direction of fibre is perpendicular to the load applied as usually occurs in fibre with 15° to 90° orientation. The maximum load and the ultimate tensile strength were the highest in the sample with a 90° orientation (Lasikun et al., 2018). Fibre orientation significantly increased the impact resistance of basalt fibre-reinforced epoxy composite (Kumar & Singh, 2021). Based on a study by Yong et al. (2015), stated that when compared to composites with fibre in perpendicular or isotropic orientations, kenaf fibre in anisotropic orientation can absorb impact energy and allow the sandwich composite to sustain greater impact forces. This is possibly caused by the interfacial bond strength between the polymer and fibre which has a high influence on the impact response of the sandwich composite. According to Rao et al. (2020), bamboo fibre-reinforced composites have a maximum impact strength of 24 wt% with a 0° orientation. The woven kenaf-Kevlar composite has greater tensile and Charpy impact strength than other hybrid composites (Yahaya et al., 2016). Another mechanical property that can be affected by the fibre orientation is flexural strength. Doddi et al. (2020) in their research stated that as the fibre angle increases from 0° to 60°, the storage modulus of the specimens decreases, and as the angle increases further, the storage modulus increases, which is analogous to the results observed for flexural modulus.

Density is a crucial property for fibre-reinforced composites, especially in applications where the strength-to-weight ratio is paramount. In fibre-reinforced polymer (FRP) composites, density encompasses both the mass of the polymer matrix and the reinforcing fibres. This dual consideration is vital because fibres significantly influence mechanical properties like strength and stiffness, while the polymer matrix provides cohesion and shields the fibres. The density of a material is directly related to its void content. Void content refers to the proportion of empty spaces or voids within a material compared to its total volume. A higher density typically indicates a lower void content, meaning fewer empty spaces within the material. Conversely, a lower density suggests a higher void content, indicating more voids or empty spaces present. Lower void content generally leads to improved mechanical properties such as strength, stiffness, and durability, making density an important parameter to consider in composite material characterization and quality assessment.

Hence, this study aimed to investigate the effect of fibre orientation on the formation of voids, density, and strength of the composites. Additionally, this study also aims to understand the effect of the number of plies on void formation and the strength of the composites. The findings of this study shed light on the relationship between density, void content, and mechanical properties in FRP composites, offering insights into their performance and potential applications.

https://doi.org/10.24191/jmeche.v22i1.4555

EXPERIMENTAL

Materials

Epoxy CP362 - Diglycidyl Ether of Bisphenol A (DGEBA) in the form of a viscous liquid supplied by Vistec Technology Services was used along with the modified polyamine hardener. The modified polyamine hardener, also provided by Vistec Technology Services, was a transparent liquid with an initial viscosity of 400 cps. The hardener had a density of 0.931 g/mol and a molecular weight of 114.19 g/mol. The composite was formulated using a mixing ratio of epoxy to hardener at 2:1. To reinforce the composite, plain weave basalt fibres were utilized. These basalt fibres were chosen for their exceptional properties, including high-temperature resistance, resistance to acids and alkalis, corrosion resistance, strong resistance to ultraviolet radiation, and low moisture absorption. Before being incorporated into the composite, the basalt fibres underwent treatment with sodium hydroxide (NaOH) to enhance their compatibility with the epoxy matrix and improve the bonding between the fibres and the resin.

Method and procedures

Sodium hydroxide treatment of basalt fibre

The woven basalt fibre was initially cut into 300 x 300 mm segments using precision scissors. To eliminate contaminants, including residual oils and larger particles, the fibres underwent a thorough rinsing process using an acetone solution. Subsequently, the cleaned fibres were allowed to air dry for 24 hours at room temperature. Following this initial preparation, the basalt fibres were immersed in a 6% sodium hydroxide (NaOH) solution for 30 minutes. After the treatment, the fibres were once again dried under ambient conditions for an additional 24 hours. The purpose of this fibre treatment process was to enhance the surface texture of the fibres, promoting improved interfacial adhesion with the matrix material.

Fabrication of basalt fibre reinforced epoxy composites

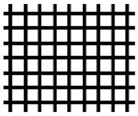
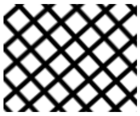
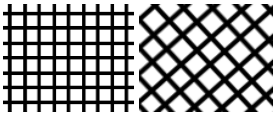
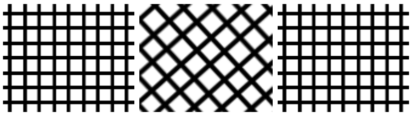
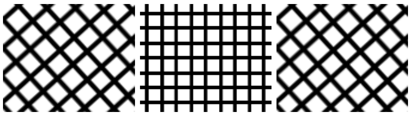
The basalt fibre-reinforced epoxy composites were fabricated using the hand lay-up method, maintaining the fibre-to-resin ratio of 40:60 (w:w) for all composites. The process commenced with the meticulous mixing of epoxy and hardener in a 100:50 ratio, respectively. To prepare the surface, a layer of this epoxy mixture was poured onto a polyvinyl chloride (PVC) sheet that had been previously waxed. Half of the epoxy mixture was then evenly spread across the sheet using a steel scraper. Next, treated basalt fibres, aligned as specified in the formulation in Table 1, were positioned on top of the epoxy layer. The remaining half of the epoxy mixture was poured over the fibres and spread to ensure thorough and uniform wetting of the fibres. To complete the assembly, another waxed PVC sheet was placed on top of the composite. This upper layer was also evenly spread and smoothed out using a combination of a steel scraper and roller. Any trapped air bubbles were gently removed from the composite during this process. For two and three-layer composites, the same sequence was followed, where the basalt fibre was sequentially added one after the other in a similar manner. One-ply composites with (0/90) and (±45) fibre orientations were fabricated to analyze the individual effects of these orientations. Additionally, a two-plies composite with (0/90)(±45) orientations was created to assess their combined effect. Conversely, three-plies composites (0/90)(±45)(0/90) and (±45)(0/90)(±45) were fabricated to study dominant fibre orientation in composites, considering the possibility of voids between plies.

Density measurement

The density of the composites was measured using 20 x 20 mm specimens via Shimadzu UX420S solid density meter. For each formulation, three separate specimens were subjected to density measurement. Subsequently, the average density value was calculated from the results of these three tests.

https://doi.org/10.24191/jmeche.v22i1.4555

Table 1. Fibre orientation of basalt fibre in epoxy composites

No.	Fibre orientation		Fibre ply
1.	(0/90)		1 ply
2.	(±45)		1 ply
3.	(0/90)(±45)		2 plies
4.	(0/90)(±45)(0/90)		3 plies
5.	(±45)(0/90)(±45)		3 plies

Tensile testing

Tensile testing was carried out in accordance with ASTM D638 standards, utilizing a Shimadzu AG-X universal testing machine operating at a crosshead speed of 5 mm/min. Each specimen was cut to dimensions of 150 x 20 mm. For each formulation, a total of five specimens underwent testing.

RESULTS AND DISCUSSION

Fig 1 illustrates the measured density of woven basalt fibre-reinforced epoxy composites fabricated with varying fibre orientations, while Table 2 lists the density values. The incorporation of basalt fibres into the epoxy resin results in composites with a higher density compared to epoxy alone, primarily because basalt fibres typically possess a higher density, ranging from 2.6 g/cm³ to 2.9 g/cm³, while epoxy typically ranges from 1.1 g/cm³ to 1.4 g/cm³. In this study, (0/90) and (±45) composites represent one-ply composites with different fibre orientations. Fig 1 reveals noticeably different density values for (0/90) and (±45) composites, even though both were one-ply composites. One plausible explanation for the density difference lies in the presence of voids or air bubbles within the composite system. In addition, the orientation of fibres can affect how epoxy resin flows and penetrates the fibre layers during the fabrication process. In some cases, certain orientations may allow for better resin infiltration, reducing the likelihood of voids forming (Doddi et al., 2020).

As the number of basalts fibre plies increases to two and three, a noticeable decline in density is observed. This decline can be attributed to increased void content and air entrapment between the fibre layers during the layering and impregnation process. This finding is agreed by Rahmani et al. (2014) and Katsiropoulos et al. (2009), where the bondlines defects such as voids and porosity tend to increase with the number of fibre plies with most of the defects occurring at the ply interface (Koushyar et al., 2012; Li et al., 2015; Liu et al., 2006; Mohd Ghaztar et al., 2022). The challenge of completely removing air bubbles or entrapped air pockets during fabrication contributes to these trapped air voids, thereby lowering the

https://doi.org/10.24191/jmeche.v22i1.4555

effective density of the composite. Additionally, the packing efficiency of the fibres may diminish as more layers are added, resulting in a less dense arrangement of fibres (Liu & Hughes, 2008).

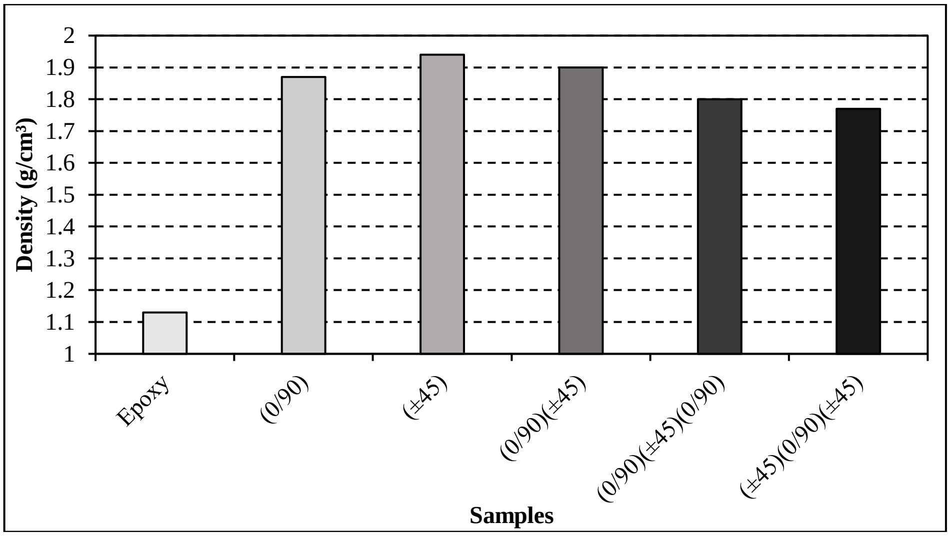


Fig. 1. Measured density of basalt fibre/epoxy composites with different fibre orientations.

Table 2. Measured density values of basalt fibre/epoxy composites with different fibre orientations

Samples	Measured density (g/cm^3)
Epoxy	1.13
(0/90)	1.87
(±45)	1.94
(0/90)(±45)	1.90
(0/90)(±45)(0/90)	1.80
(±45)(0/90)(±45)	1.77

Fig 2, Fig 3, and Fig 4 illustrate the tensile strength, tensile strain, and Young's modulus of basalt fibre/epoxy composites. (0/90) and (±45) denoted a composite with a one-ply of basalt fibre arranged at two different fibre orientations. In this context, the (0/90) orientation demonstrates higher tensile strength and Young's modulus when compared to the (±45) orientation. Conversely, the (±45) fibre orientation exhibits greater tensile strain. This behaviour is primarily attributed to the orientation of the fibres within the composite. The (0/90) orientation excels in both tensile strength and Young's modulus due to the alignment of the fibres in parallel and perpendicular directions relative to the loading axis. This alignment optimally utilizes the fibres' ability to resist applied forces, resulting in a stiffer and stronger response when subjected to tension along these specific directions (Seshaiah & Reddy, 2018; Zhang et al., 2020). On the contrary, the (±45) orientation positions the fibres at ±45 degrees relative to the loading axis. This arrangement allows for increased deformation (strain) prior to failure and is less effective at withstanding axial loads. However, it excels in its capacity to absorb and distribute loads in shear, which leads to a higher tensile strain (Chowdhury et al., 2023). The composite can deform more readily along these diagonal directions before reaching failure, contributing to the observed difference in tensile strain between the two orientations.

In theory, when the number of fibre plies is increased in a composite system, the tensile properties are anticipated to improve due to the increased reinforcement fraction (Ibrahim & Romli, 2018; Thirumalai et al., 2019). However, the final properties will also be influenced by the orientation of the fibres within the

https://doi.org/10.24191/jmeche.v22i1.4555

composites. When two layers of woven basalt fibre are used in the composites, the resulting tensile properties—tensile strength and Young's modulus—fall between the values observed for the (0/90) and (±45) one-ply composites. This behaviour can be attributed to the combined effects of the two fibre orientations. The (0/90) fibres resist the applied load efficiently along their aligned directions, while the (±45) fibres facilitate load distribution and absorption in shear, enhancing overall tensile strength and modulus compared to a one-ply composite with only (±45) orientation. This demonstrates that the combination of orientations can effectively balance load-bearing and load-distributing capabilities, resulting in improved tensile properties compared to a one-ply (±45) composite. However, it is important to note that these properties may still be lower than those of a one-ply composite with (0/90) orientation due to the inherent differences in fibre alignment and mechanical behaviour between the orientations.

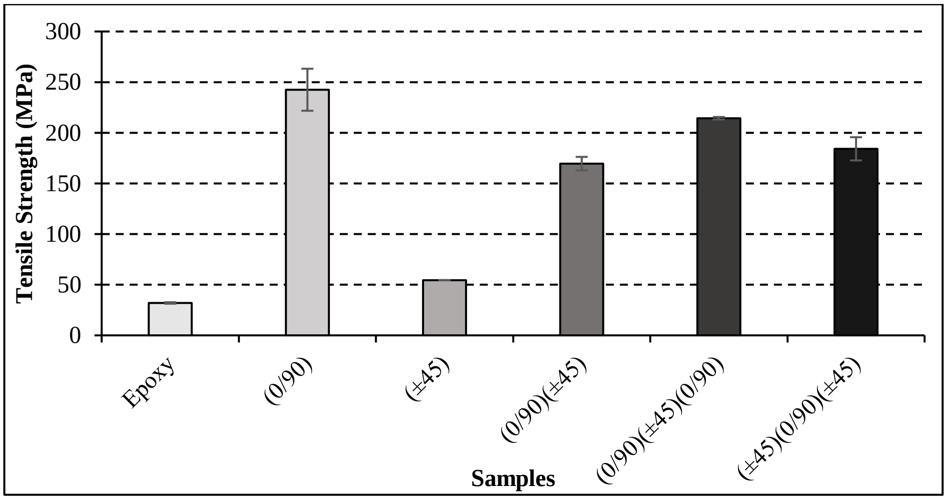


Fig. 2. Tensile strength of basalt fibre/epoxy composites with different fibre orientations.

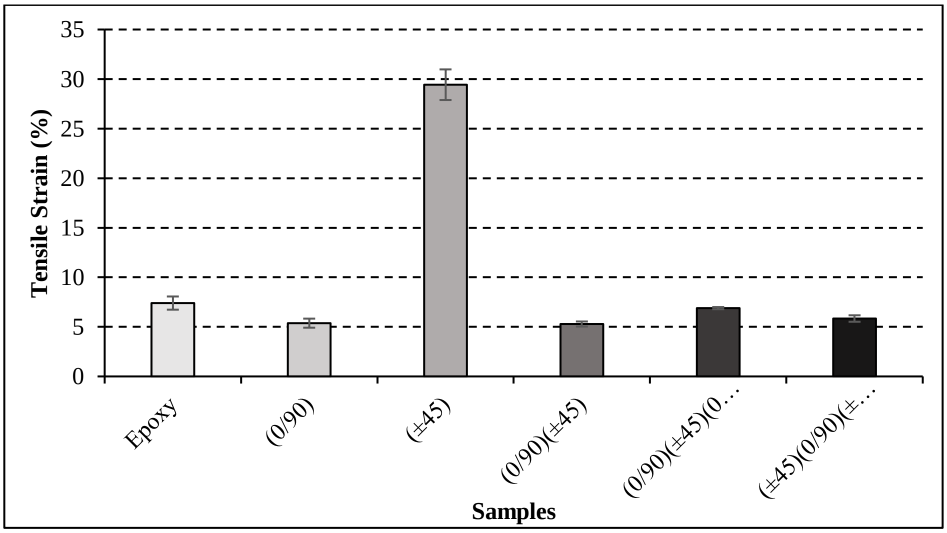


Fig. 3. Tensile strain of basalt fibre/epoxy composites with different fibre orientations.

https://doi.org/10.24191/jmeche.v22i1.4555

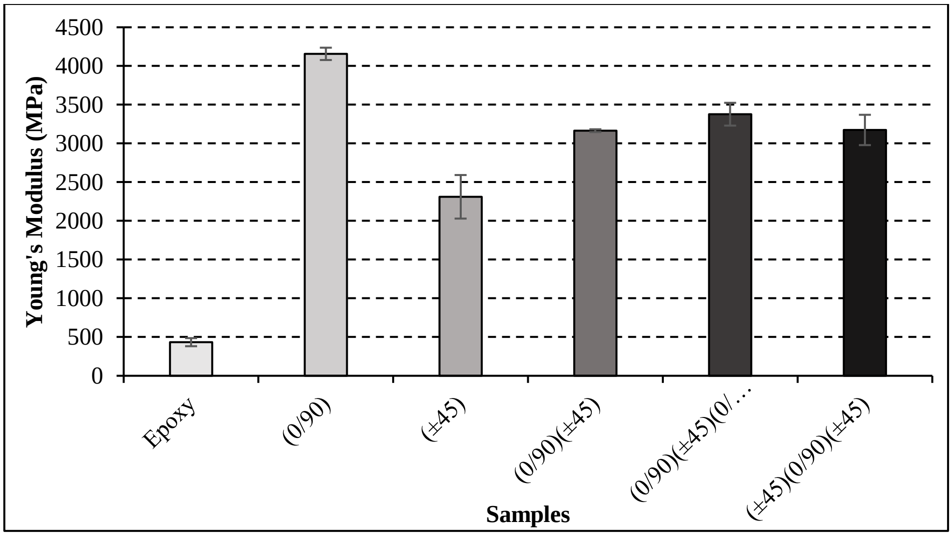


Fig. 4. Young's modulus of basalt fibre/epoxy composites with different fibre orientations.

In the case of the three-plies composites, it is observed that the tensile strength and Young's modulus surpass those of one-ply (±45) composites and two-plies (0/90)(±45) composites. This improvement can be attributed to the increased number of basalts fibre reinforcements, which enhances the composite's resistance to axial loads. The additional layers contribute to the overall stiffness and strength of the composite. However, the three-plies composites exhibit tensile strength and Young's modulus that are lower than those of one-ply (0/90) composites. This decrease in performance may be attributed to a higher percentage of void content that could become trapped between the fibre layers. This is supported by a reduction in the composite's density value, indicating the presence of voids within the material.

Voids or air pockets within a composite material create regions with no structural reinforcement. As a result, these voids do not contribute to bearing the applied load. The presence of voids inside the composite system can disrupt the continuous and uniform structure of the composite material. This material discontinuity can create stress concentration points, where stress is localized, leading to premature failure. Moreover, voids can create weak points at the interfaces between the fibres and the vicinity matrix. These weak points can result in poor stress transfer between the reinforcement and the matrix. The load applied to the composite is not uniformly transferred across these voids, causing stress concentrations in the neighbouring regions, which can lead to early failure. When the composite undergoes tensile loading, the stress at the edges of voids is typically higher due to the shear forces acting on the void boundaries. These localized high-stress regions can initiate cracks or cause deformation in the material, reducing its overall tensile strength and modulus (Abdul Malek et al., 2024; Kosmann et al., 2015; Mehdikhani et al., 2019).

It is worth noting that for the three-plies composites, two different combinations of fibre orientation were fabricated: (0/90)(±45)(0/90) and (±45)(0/90)(±45). The composites consisting of two plies oriented in (0/90) exhibited higher tensile strength and Young's modulus compared to those with two plies of fibres oriented in (±45). This variation in performance can be attributed to the specific combination of orientations, with the (0/90) orientation contributing to better load resistance in tension (Biswas et al., 2023).

https://doi.org/10.24191/jmeche.v22i1.4555

CONCLUSIONS

This study explores the tensile properties and density of woven basalt fibre-reinforced epoxy composites, focusing on the influence of varying fibre orientations. The incorporation of basalt fibres into epoxy resin results in composites with higher density, attributed to the inherently denser nature of basalt fibres compared to epoxy. Distinct density variations are observed between (0/90) and (±45) one-ply composites, which might be attributed to the presence of voids or air bubbles within the composite. Tensile testing reveals significant differences between (0/90) and (±45) composites. (0/90) composites exhibit higher tensile strength and Young's modulus due to fibre alignment with the loading axis, optimizing load resistance. In contrast, (±45) composites exhibit higher tensile strain due to their diagonal fibre orientation, which facilitates deformation and load distribution in shear. When two layers of basalt fibre are incorporated into the composites, tensile properties fall between those of one-ply (0/90) and (±45) composites, reflecting the combined effects of both orientations. Three-plies composites, however, exhibit increased tensile strength and modulus compared to one-ply (±45) composites but lower values than one-ply (0/90) composites. This decrease may be attributed to higher void content between fibre layers, supported by reduced composite density. Despite the existence of voids inside the fabricated composites, the tensile strength of the composites, specifically (0/90) and (±45) one-ply composites, values were still within the range found by Varley et al. (2013) and Liu et al. (2006).

ACKNOWLEDGEMENTS/ FUNDING

The authors extend their profound gratitude to the Institute of Science and the Faculty of Applied Sciences at Universiti Teknologi MARA for generously providing the research materials and facilities essential for this study.

CONFLICT OF INTEREST STATEMENT

The authors confirm that this research was conducted without any personal, commercial, or financial interests and declare no conflicts of interest.

AUTHORS' CONTRIBUTIONS

The authors confirm their contribution to the paper as follows: **Samples fabrication, experimental work and data collection:** Afiqah Nor Fatin Abdua; **Study concept and design, experimental and results verification, manuscript preparation, and manuscript revision:** Nik Noor Idayu Nik Ibrahim. All authors reviewed the results and approved the final version of the manuscript.

REFERENCES

Abdul Malek, N. S. N., Engku Zawawi, E. Z., Romli, A. Z., & Nik Ibrahim, N. N. I. (2024). Epoxy filled with nylon powder—An approach to reduce void formation via fused particle method. Journal of Applied Polymer Science, 141(13), e55164.

Biswas, R., Sharma, N., & Singh, K. K. (2023). Influence of fiber areal density on mechanical behavior of basalt fiber/epoxy composites under varying loading rates: An experimental and statistical approach.

https://doi.org/10.24191/jmeche.v22i1.4555

Polymer Composites, 44(4), 2222-2235.

Branston, J., Das, S., Kenno, S. Y., & Taylor, C. (2016). Mechanical behaviour of basalt fibre reinforced concrete. Construction and Building Materials, 124, 878-886.

Bulut, M. (2017). Mechanical characterization of Basalt/epoxy composite laminates containing graphene nanopellets. Composites Part B: Engineering, 122(6), 71-78.

Chok., E. Y. L., & Majid., D. L. A. A. (2018). Low cycle fatigue of hybrid woven kenaf fiber reinforced epoxy composite with 1% addition of silica aerogel. Journal of Mechanical Engineering, 15(2), 73-89.

Chowdhury, I. R., O'Dowd, N. P., & Comer, A. J. (2023). Failure prediction in a non-crimp basalt fibre reinforced epoxy composite. Composite Structures, 322, 117413.

Dhand, V., Mittal, G., Rhee, K. Y., Park, S.J., & Hui, D. (2015). A short review on basalt fiber reinforced polymer composites. Composites Part B: Engineering, 73, 166-180.

Doddi, P. R. V., Chanamala, R., & Dora, S. P. (2020). Effect of fiber orientation on dynamic mechanical properties of PALF hybridized with basalt reinforced epoxy composites. Materials Research Express, 7(1), 015329.

Elmahdy, A., & Verleysen, P. (2019). Mechanical behavior of basalt and glass textile composites at high strain rates: A comparison. Polymer Testing, 81, 106224.

Fiore, V., Scalici, T., Di Bella, G., & Valenza, A. (2015). A review on basalt fibre and its composites. Composites Part B: Engineering, 74, 74-94.

Ghani, A. F. A., & Mahmud, J. (2018). Hardness, tensile and microstructure assessment of carbon/glass hybrid composite laminate. Journal of Mechanical Engineering, 15(2), 91-105.

Katsiropoulos, C. V., Pantelakis, S. G., & Meyer, B. C. (2009). Mechanical behavior of non-crimp fabric PEEK/C thermoplastic composites. Theoretical and Applied Fracture Mechanics, 52(2), 122-129.

Kosmann, N., Karsten, J., Schuett, M., Karl, S., & Fiedler, B. (2015). Determining the effect of voids in GFRP on the damage behaviour under compression loading using acoustic emission. Composites Part B: Engineering, 70, 184–188.

Koushyar, H., Alavi-Soltani, S., Minaie, B., & Violette, M. (2012). Effects of variation in autoclave pressure, temperature, and vacuum-application time on porosity and mechanical properties of a carbon fiber/epoxy composite. Journal of Composite Materials, 46(16), 1985-2004.

Kumar, N., & Singh, A. (2021). Study the effect of fiber orientation on mechanical properties of bidirectional basalt fiber reinforced epoxy composites. Materials Today: Proceedings, 39(4), 1581-1587.

Kumaresan, M., Sathish, S., & Karthi, N. (2015). Effect of fiber orientation on mechanical properties of sisal fiber reinforced epoxy composites. Journal of Applied Science and Engineering, 18(3), 289-294.

Kumbhar, V.P. (2014). An overview: Basalt rock fibres - New construction material. Acta Engineering International, 2(1), 11-18.

Lasikun, Ariawan, D., Surojo, E., & Triyono, J. (2018). Effect of fiber orientation on tensile and impact properties of Zalacca Midrib fiber-HDPE composites by compression molding. In J. P. Davim, R. Keshavamurthy & V. Tambrallimath (Eds.), AIP Conference Proceedings (p. 030060). AIP Publisher.

Li, Y., Li, Q., & Ma, H. (2015). The voids formation mechanisms and their effects on the mechanical properties of flax fiber reinforced epoxy composites. Composites Part A: Applied Science and

https://doi.org/10.24191/jmeche.v22i1.4555

Manufacturing, 72(3), 40-48.

Liu, L., Zhang, B.M., Wang, D.F., & Wu, Z. J. (2006). Effects of cure cycles on void content and mechanical properties of composite laminates. Composite Structures, 73(3), 303-309.

Liu, Q., & Hughes, M. (2008). The fracture behaviour and toughness of woven flax fibre reinforced epoxy composites. Composites Part A: Applied Science and Manufacturing, 39(10), 1644-1652.

Liu, Q., Shaw, M. T., Parnas, R. S., & McDonnell, A. M. (2006). Investigation of basalt fiber composite mechanical properties for applications in transportation. Polymer Composites, 27(1), 41-48.

Mehdikhani, M., Gorbatikh, L., Verpoest, I., & Lomov, S. V. (2019). Voids in fiber-reinforced polymer composites: A review on their formation, characteristics, and effects on mechanical performance. Journal of Composite Materials, 53(12), 1579-1669.

Mohd Ghaztar, M. M., Nik Ibrahim, N. N. I., & Romli, A. Z. (2022). Sodium hydroxide/silane treated kenaf fibre in unsaturated polyester matrix: Effects of fibres length and fibres loading towards the composites flexural and morphological properties. Journal of Mechanical Engineering 19(2), 147-167

Nik Ibrahim, N. N. I., & Romli, A. Z. (2018). Mechanical properties of one layer and seven layer glass fibre reinforced unsaturated polyester filled with P84 polyimide. AIP Conference Proceedings (p. 030008), AIP Publisher.

Rahmani, H., Mahmoudi Najafi, S. H., Saffarzadeh-Matin, S., & Ashori, A. (2014). Mechanical properties of carbon fiber/epoxy composites: Effects of number of plies, fiber contents, and angle-ply layers. Polymer Engineering and Science, 54(11), 2676-2682.

Rao, H. R., Reddy, K. M., Reddy, P. V., & Reddy, R. M. (2020). Effect of fibre orientation on mechanical properties of Hardwickia binata and bamboo fibre reinforced epoxy composites. Materials Today: Proceedings, 21(10), 1265-1269.

Saravanan, D. (2006). Spinning the rocks - Basalt fibres. Journal of the Institution of Engineers (India), Part TX: Textile Engineering Division, 86, 39-45.

Seshaiah, T., & Reddy, K. V. K. (2018). Effect of fiber orientation on the mechanical behavior of e-glass fibre reinforced epoxy composite materials. International Journal of Mechanical and Production Engineering Research and Development, 8(4), 379-396.

Sonnenschein, R., Gajdosova, K., & Holly, I. (2016). FRP Composites and their using in the construction of bridges. Procedia Engineering, 161, 477-482.

Subagia, A., D, T. L., Yonjig, K., Sang, K. C., P., V. I. F., & Kyong, S. H. (2014). Mechanical performance of multiscale basalt fiber–epoxy laminates containing tourmaline micro/nano particles. Composites Part B: Engineering, 58(13), 611-617.

Thirumalai, R., Prakash, R., Ragunath, R., & Senthil Kumar, K. M. (2019). Experimental investigation of mechanical properties of epoxy based composites. Materials Research Express, 6(7), 075309.

Thomas, S., Joseph, K., Malhotra, S. K., Goda, K., & Sreekala, M. S. (2012). Polymer composites: Macro- and microcomposites. John Wiley & Sons.

U.S. Congress (1988). Advanced materials by design. In Office of Technology Assesment (Ed.), Polymer Matrix Composites (pp. 71 - 95). U.S. Government Printing Office.

Varley, R. J., Tian, W., Leong, K., Leong, A. Y., Fredo, F., & Quaresimin, M. (2013). The effect of surface treatments on the mechanical properties of basalt-reinforced epoxy composites. Polymer Composites, 34(3), 320-329.

https://doi.org/10.24191/jmeche.v22i1.4555

Vinay, S. S., Sanjay, M. R., Siengchin, S., & Venkatesh, C. V. (2022). Basalt fiber reinforced polymer composites filled with nano fillers: A short review. Materials Today: Proceedings, 52(5), 2460-2466.

Wallenberger, F. T., & Weston, N. E. (2011). Natural fibers, plastics and composites. (1st Ed.). Springer US.

Wang, R. M., Zheng, S. R., & Zheng, Y. G. (2011). Polymer matrix composites and technology. (1st Ed.). Woodhead Publisher.

Yahaya, R., Sapuan, S., Jawaid, M., Leman, Z., & Zainudin, E. (2016). Effect of fibre orientations on the mechanical properties of kenaf–aramid hybrid composites for spall-liner application. Defence Technology, 12(1), 52-58.

Yong, C. K., Ching, Y. C., Chuah, C. H., & Liou, N.S. (2015). Effect of fiber orientation on mechanical properties of kenaf-reinforced polymer composite. BioResources, 10(2), 2597-2608.

Zhang, Z., Hou, S., Mao, Y., He, L., & Han, X. (2020). Rate-related study on the ply orientation of carbon fiber reinforced epoxy composite laminates. International Journal of Mechanical Sciences, 188, 105968.

https://doi.org/10.24191/jmeche.v22i1.4555