Research Article

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Characterization of Mechanical Properties of Ramie/SiO_2 Hybrid Composite by Incorporation of Kenaf Fiber

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ABSTRACT

This study examines the mechanical characteristics of a novel hybrid composite consisting of 25% ramie fiber, 15% kenaf fiber, and 2% titanium dioxide particles. Ramie fiber is known for its tensile rigidity and durability, while kenaf fiber is valued for its availability and biodegradability. Titanium dioxide particles are included to enhance the composite's mechanical properties. Mechanical tests—including tensile, bending, impact, and hardness—were conducted, revealing an average tensile strength of 66.14 MPa, a flexural strength of 86.46 MPa, an impact strength of 35.88 kJ/m², and a hardness of 181.8 HV. The significance of this study lies in its innovative combination of natural fibers with inorganic particles, addressing the demand for high-performing yet eco-friendly materials. The novelty of the composite is reflected in the strategic integration of ramie and kenaf fibers, which offer complementary mechanical properties, with titanium dioxide particles to enhance overall performance. This approach achieves a balance between strength, rigidity, and impact resistance while maintaining environmental sustainability. The inclusion of titanium dioxide boosts mechanical performance without compromising the material's eco-friendly nature. These findings suggest that this composite is suitable for technical applications requiring exceptional strength, rigidity, and impact resistance. This research contributes to the advancement of composite materials technology, showing potential for the development of sustainable and effective materials across various industries.

Keywords: Titanium dioxide; Nanoparticle; Mechanical properties; Fiber; Composite.

1. INTRODUCTION

Fiber-reinforced composites (FRC) have experienced a surge in popularity across several industries such as automotive, aircraft, building, wrapping, railroad, sports equipment, and storage systems over the past few years (Zelalem and Sirahbizu, 2022; Li *et al.* 2023). Natural and synthetic fibres are the major fibres utilized in advanced FRC (Jothi *et al.* 2024)). Natural fibre composites possess numerous advantages compared to synthetic fibres, such as their lightweight nature, cost-effectiveness, biodegradability, and eco-friendliness (He *et al.* 2020; Xie *et al.* 2020). An important advantage of natural fibres is their favourable carbon footprint on the environment (Yao *et al.* 2022). As a result, numerous scholars and professionals in academia and industry are actively investigating environmentally friendly resources as alternatives to conventional ones (Thanikodi *et al.* 2024). The environmental and financial advantages of natural fibre composites have contributed to their increased popularity over synthetic fiber-reinforced composites in modern applications (Khan *et al.* 2021; Topkaya *et al.* 2020).

Guo *et al.* (2022) investigated complete strain throughout the entire field was quantified via the digital image correlation technique in order to reveal the hybrid process. The investigation revealed that mechanical characteristics were considerably influenced by the type of fibre hybridised. The addition of carbon fibres evenly distributed among glass fibres resulted in a maximum strength increase for ILSS, tensile strength (TS), and flexural strength. The carbon fiber's TS was effectively harnessed, resulting in improved mechanical qualities. Nevertheless, using larger carbon fibre tows can result in a less robust interface layer between the carbon/glass fiber/resin components. This can cause uneven distribution of stress at the interface when subjected to external forces, ultimately reducing the shear strength of the interface.

Bekele *et al.* (2022) investigate the effects of NaOH on the chemical composition content of fibres. Additionally, the durability of both fibres was assessed. The findings demonstrated that enset and sisal fibres treated with 5% NaOH displayed superior tenacity, suggesting a greater TS of individual fibres, in comparison to untreated fibres and those treated with 10% NaOH. Increasing the moisture content, size, and hemicellulose and lignin content of the fibres enhances the adhesion with matrix materials, thereby improving the mechanical characteristics of the laminated. Gudayu *et al.* (2022) investigates the impact of different approaches for modifying sisal fibre on its moisture absorption, thermal characteristics, and mechanical characteristics. The specimens that underwent acetylation exhibited a notable decrease in TS. Nevertheless, the tensile tests conducted on the specimens treated with alkaline solution showed a negligible reduction in TS and an enhancement in the modulus for all processed specimens. Structural changes were identified through the use of Fourier-transform infrared spectroscopy and scanning electron microscopy investigations, providing support for the findings. Bahja *et al.* (2021) examines the effects of integrating sisal fibres into cement mortar. The inclusion of 4% sisal fibres by weight of cement led to a reduction in density and an increase in porosity. Although the compressive and flexural strength decreased, the composite including treated sisal fibres soaked in paraffin oil demonstrated acceptable outcomes for the elastic modulus. Arumugam *et al.* (2020) examine the mechanical characteristics of a hybrid composite material composed of glass fibre (GF), sisal fibre (SF), and chitosan (CTS) to use it in orthopedic long bone plates. The mechanical testing results indicated that the GF/SF/CTS hybrid composites exhibited enhanced properties in terms of bending strength, tensile strength, compression strength, and Young's modulus. Teklu *et al.* (2022) assessed the efficacy of several extraction techniques on the physico-chemical, thermal, and mechanical characteristics of sisal fibres. Thermal analysis (TGA) identified two distinct degradation peak levels, indicating the liberation of retained moisture and the breaking of glycosidic bonds in the chemical constituents of sisal fibres. The chemical extract approach exhibited higher TS in comparison to fibres obtained from retting. Sathees *et al.* (2021) deals with natural fibre composites (NFC) stems from the substantial variability in their characteristics and features. The experimental results demonstrated a consistent pattern of enhanced mechanical properties when natural fibres or fillers were added. The improved capacity to connect and interact between the NFC and the polyester matrix also played a role in their successful ability to resist certain forces. Composite materials have significant value for a wide range of engineering uses. Zuccarello *et al.* (2021) indicate that the close-knit structure of sisal fibre is associated with significant anisotropy, which impacts both the elastic properties and the occurrence of damage, such as fibre breaking. These parameters have a substantial impact on the strength of the biocomposite when subjected to transverse tensile/compressive and longitudinal compressive pressures. Boopathi *et al.* (2022) investage FRC material employing an epoxy resin matrix, along with kenaf, Grewia, and hair fibres. The compression moulding process was employed to improve mechanical properties. The findings demonstrated that kenaf had a notably greater impact on the TS, FS, and IS in comparison to the other two fibres. Moreover, the weight of the hair fibre had a substantial impact on improving both the flexural and impact characteristics. Malik *et al.* (2023) investigates the physical and mechanical characteristics of hybrid composites made of epoxy reinforced with kenaf and flax natural fibres. The objective is to analyse the impact of hybridization on the mechanical and physical characteristics of the composites. The mechanical characteristics of these mixed composites were significantly influenced by the placement of fibre stacking sequences.

In its most fundamental form, this study is an example of a multidisciplinary approach that incorporates ideas from materials science, mechanical engineering, and environmental sustainability to make progress in the field of composite materials technology. The objective is to build composite materials that not only match the high-performance demands of current technological uses but also encourage a more resilient and environmentally friendly future. This will be accomplished by utilizing the one-of-a-kind qualities of natural fibres and combining innovative additives such as TiO_2 particles.

2. MATERIALS AND METHODS

The primary aim of this research is to create and analyse a hybrid composite material that combines coir fibers derived from kenaf fibre, ramie fibres obtained from the plants, and TiO2 particles. An appropriate matrix material was employed to incorporate these fibres and particles into the composite. The composite was manufactured using the hand lay-up process, in which fibres and particles were methodically arranged in a mould with a specific orientation. TiO_2 particles were positioned between the layers. The fibres and particles were thoroughly impregnated with the selected matrix material using a brush or roller to achieve complete wetting. Compression moulding was subsequently utilized to cure and consolidate the composite framework while maintaining precise control over the pressure and temperature parameters. Fig. 2 depicts the sample for the testing.

The process of creating composite specimens entails various stages, such as mould fabrication, material slicing and forming, and surface refinement. This study examines the mechanical characteristics of a novel hybrid composite consisting of 25% ramie fiber, 15%

kenaf fiber, and 2% titanium dioxide particles. Ramie fiber is known for its tensile rigidity and durability, while kenaf fiber is valued for its availability and biodegradability. Titanium dioxide particles are included to enhance the composite's mechanical properties.

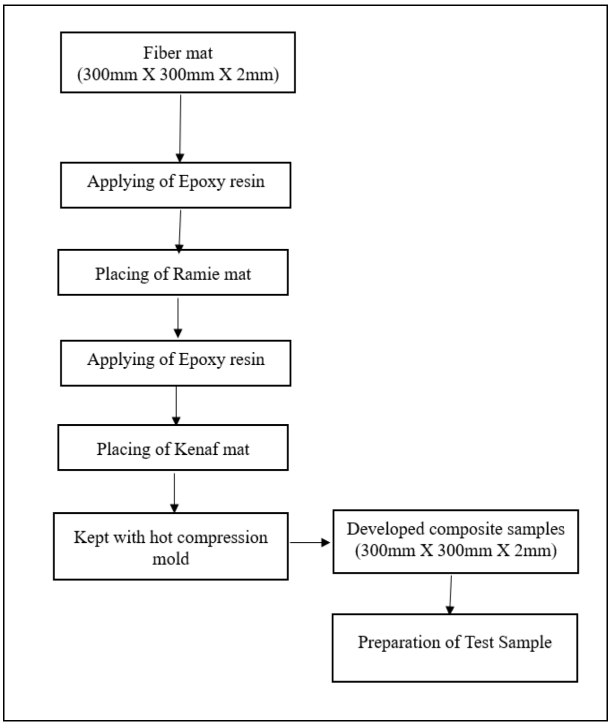

Fig. 1: Experimental process flow

Mechanical tests—including tensile, bending, impact, and hardness—were conducted to evaluate the material's behavior. The results revealed an average tensile strength of 66.14 MPa, a flexural strength of 86.46 MPa, an impact strength of 35.88 kJ/m², and a hardness of 181.8 HV. The data obtained were analyzed using response surface methodology (RSM), a robust statistical tool that facilitated the optimization of the composite's properties. The significance of this study lies in its innovative combination of natural fibers with inorganic particles, addressing the demand for high-performing yet eco-friendly materials. The novelty of the composite is reflected in the strategic integration of ramie and kenaf fibers, which offer complementary mechanical properties, with titanium dioxide particles to enhance overall performance. This approach achieves a balance between strength, rigidity, and impact resistance while maintaining environmental sustainability. The inclusion of titanium dioxide boosts mechanical performance without compromising the material's eco-friendly nature. These findings suggest that this composite is suitable for technical applications requiring exceptional strength, rigidity, and impact resistance. This research contributes to the advancement of composite materials technology, showing potential for the development of sustainable and effective materials across various industries.

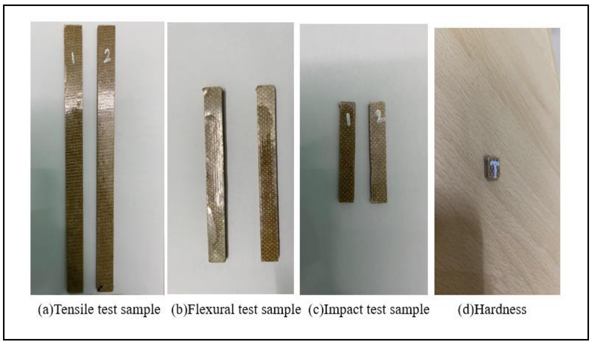

Fig.2: Testing sample (a) Tensile (b) Flexural (c) Impact (d) Hardness

3. RESULT AND DISCUSSION

3.1 Tensile Strength (TS)

The examination of the tensile test data reveals that the combined composite laminate possesses a mean TS of 64.66 MPa, with particular specimen values varying from 63.2 MPa to 67.1 MPa, as depicted in Fig. 3. The composite material exhibits a mean Young's modulus of 4.1 GPa, indicating its high resistance to deformation when subjected to tensile forces. Moreover, the composite material exhibits a mean elongation at break of 2.8%, which signifies its capacity to undergo deformation before failure. Table 1 displays the findings from the tensile tests performed on the nanocomposite laminates, comprising of kenaf fibers, ramie fibres, and TiO_2 nanoparticles.

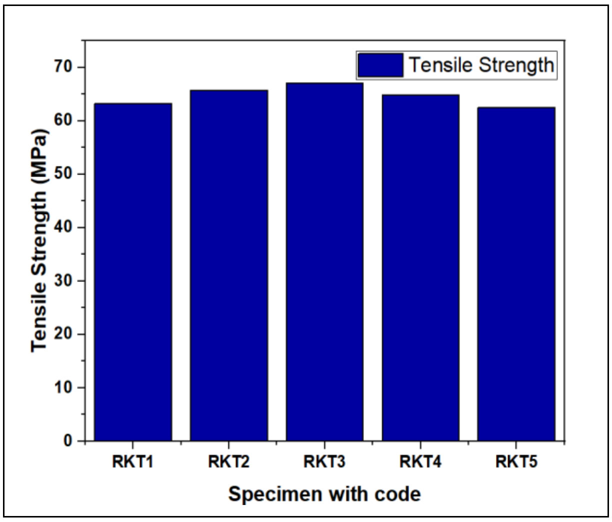

Fig. 3: Tensile strength of the different specimens

Table 1. Tensile specimen outcomes of the nanocomposite

Specimen	Ramie Fiber %	Kenaf fiber %	Titanium dioxide %	Epoxy %	Tensile Strength (MPa)	Young modulus (GPa)	Elongation @ break %
RKT1	25	20	2	53	63.2	4.1	2.7
RKT2	25	19	2	54	65.7	4.4	2.9
RKT3	25	18	2	55	67.1	4.9	3.1
RKT4	25	17	2	56	64.8	3.9	2.8
RKT5	25	16	2	57	62.5	3.6	2.6
		Average			64.66	4.1	2.8
		Standard Deviation			1.66	0.41	0.16

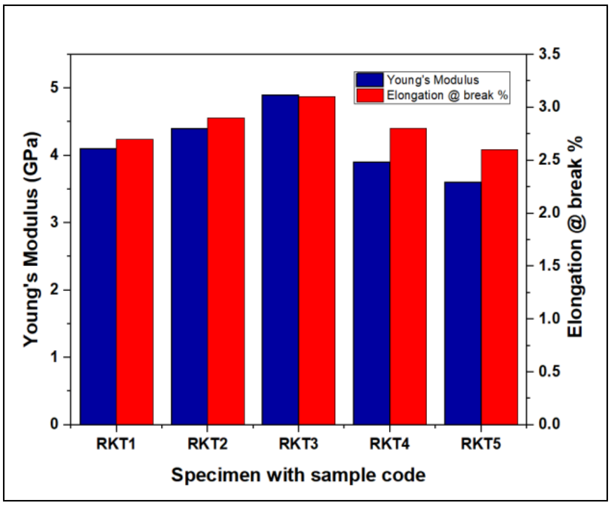

Fig. 4: depicts young's modulus and Elongation @break of the hybrid composite

The measured SD values for TS, Young's modulus, and elongation at break are 1.66 MPa, 0.41 GPa, and 0.16%, respectively. These metrics demonstrate the range of values within the specimen set, suggesting the uniformity of material characteristics between various samples.The TS of the composite laminates is attributed to the combined reinforcing of kenaf fibres, ramie fibres, and titanium dioxide nanoparticles, which work together synergistically. The natural TS and stiffness of kenaf and ramie fibres play a key role in the total strength of the laminated material. Additionally, the TiO_2 nanoparticles function as reinforcing agents, further improving the material's mechanical characteristics. Fig. 3 depicts the Young's Modulus of the samples.

Moreover, the strong adhesion between fibres and the matrix is crucial for transmitting stress and avoiding the separation of layers, hence improving the TS of the laminated composite. Fig. 4 depicts the extent to which the samples elongate before breaking. In summary, the findings from the tensile tests demonstrate the hybrid composite's capacity for use in situations that require both exceptional strength and rigidity. The fact that it can resist deformation until it breaks shows that it has ductile properties. By further refining the composite formulation through processing parameters, there is potential to enhance its mechanical qualities, tailoring it for specific technical applications.

3.2 Flexural Strength (FS)

The results of the FS test, shown in Fig. 5, reveal that the hybrid composite material exhibits a mean FS of 90.2 MPa, with each sample that vary from 88.2 MPa to 93.7 MPa. Moreover, the mean flexural modulus, which indicates the stiffness of the material when subjected to bending, is determined to be 4.5 GPa, as depicted in Fig. 6. Table 2 presents a summary of the FS test findings for the nanocomposite laminate consisting of kenaf fibres, ramie fibres, and TiO_2 nanoparticles.

Table 2. Flexural specimen outcomes of the nanocomposite

Sample	Ramie %	Kenaf %	TiO_2 %	Epoxy %	Flexural Strength (MPa)	Flexural Modulus (GPa)
RKT 1	25	20	2	53	88.2	4.4
RKT 2	25	19	2	54	91.1	4.7
RKT 3	25	18	2	55	93.7	4.9
RKT 4	25	17	2	56	90.4	4.6
RKT 5	25	16	2	57	87.7	4.2
		Average			90.2	4.5
		Standard Deviation			2.16	0.31

The reported standard deviation values for FS and FM of rupture are 2.16 MPa and 0.31 GPa, respectively. These statistics demonstrate the degree of variance detected in the test findings across the specimens, emphasizing the uniformity of material characteristics across different samples. The observed FS properties of the nanocomposite laminate are likely attributable to the synergistic reinforcing impact of

Kenaf fibres, ramie fibres, and TiO_2 nanoparticles. The intrinsic robustness and rigidity of these fibres, along with the reinforcing characteristics of TiO2 nanoparticles, greatly enhance the material's capacity to endure bending loads. Moreover, the robust bonding between the fibres and the matrix material improves the FS of the composite by facilitating the efficient transfer of stress and avoiding the separation of layers.

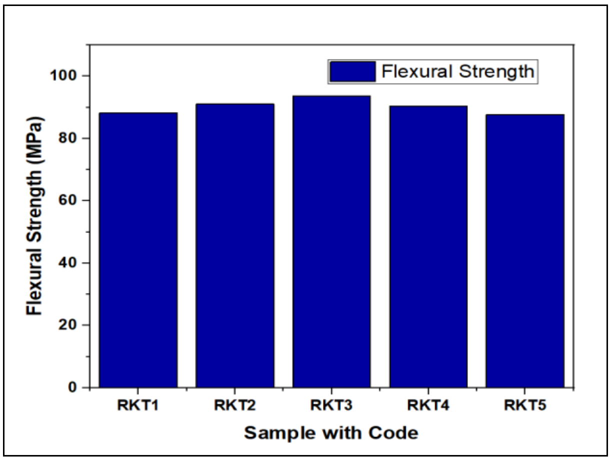

Fig. 5: Flexural strength of the different specimens

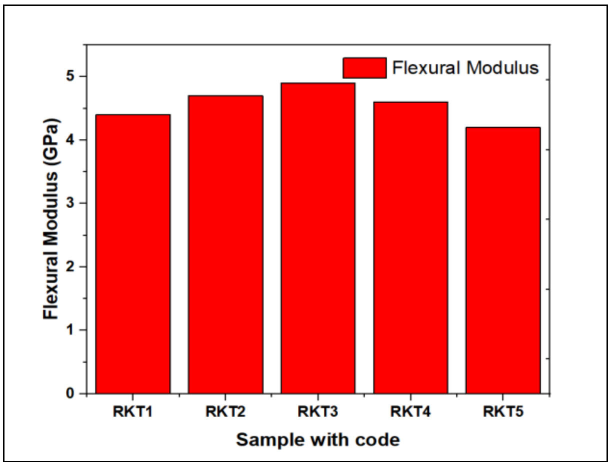

Fig. 6: Flexural modulus of the different specimens

In conclusion, the findings from the FS test highlight the hybrid composite material's suitability for structural applications that demand robust resistance against bending loads. There is promising potential for improving its mechanical performance through continued optimization of composite formulation and processing parameters.

3.3 Impact Strength

The hybrid composite material, as shown in Fig. 7, has a mean impact strength of 38.8 kJ/m², with each specimen varying from 38.1 to 40.8 kJ/m², according to the findings of the impact test. Furthermore, 35.8 kJ/m² is the computed mean impact toughness of the material. The results of the impact test for the hybrid composite material, which consists of TiO_2 nanoparticles, ramie fibres, and kenaf fibres, are summarised in Table 3.

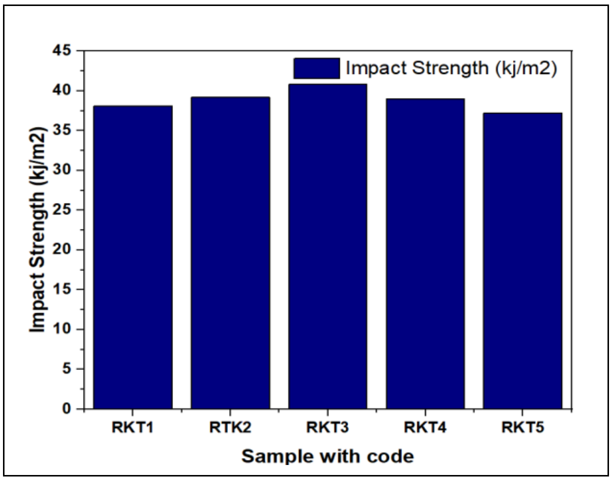

Fig. 7: Impact strength of the different specimens

Table 3. Impact test specimen outcomes of the nanocomposite

Sample	Ramie %	Kenaf %	TiO_2 %	Epoxy %	Impact Strength (kj/m²)	Impact toughness (kj/m²)
RKT 1	25	20	2	53	38.1	35.3
RKT 2	25	19	2	54	39.2	36.1
RKT 3	25	18	2	55	40.8	37.4
RKT 4	25	17	2	56	39	35.5
RKT 5	25	16	2	57	37.2	34.7
		Average			38.8	35.8
		Standard Deviation			1.20	0.92

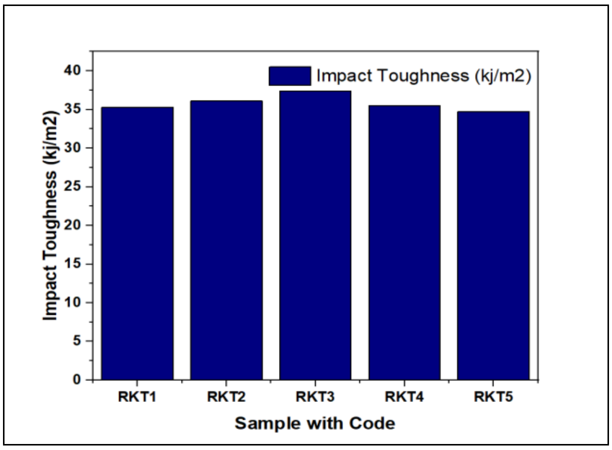

Fig. 8: Impact toughness of the different specimens

IS and impact toughness (IT) had standard deviation values of 1.20 kJ/m² and 0.92 kJ/m², respectively. These numbers highlight the consistency of material qualities across various samples by indicating the degree of variability seen in the test findings between the specimens. The samples' impact toughness is shown in Fig. 8. The combination reinforcing actions of

TiO_2 nanoparticles, ramie fibres, and kenaf fibres are responsible for the material's reported IS and IT. The fibres fortify the framework against breakage and growth of cracks by absorbing and distributing impact energy, and the TiO_2 nanoparticles improve the matrix. In addition, the stability of the composite framework under impact stress is greatly dependent on the strong adherence between the fibres and the matrix layer.

In summary, the findings from the impact tests highlight the nanocomposite materials capability for applications requiring high-impact resistance. There is potential for further enhancing its performance through continued optimization of composite formulation and processing parameters.

Table 4. Hardness test specimen outcomes of the nanocomposite

Sample	Ramie %	Kenaf %	TiO_2 %	Epoxy %	Hardness (HRC)
RKT 1	25	20	2	53	190
RKT 2	25	19	2	54	195
RKT 3	25	18	2	55	202
RKT 4	25	17	2	56	193
RKT 5	25	16	2	57	188
		Average			193.6
		Standard Deviation			4.84

3.4 Hardness

The hybrid composite laminate has a mean hardness measurement of 193.6 HRC, according to the findings of the hardness test, each of the samples ranges in hardness from 190 to 202 HRC. The reported 4.84 standard deviation highlights the constant material qualities across numerous specimens by illustrating the diversity in hardness levels between the specimens. The results of the laminated material's hardness test are summarised in Table 4.

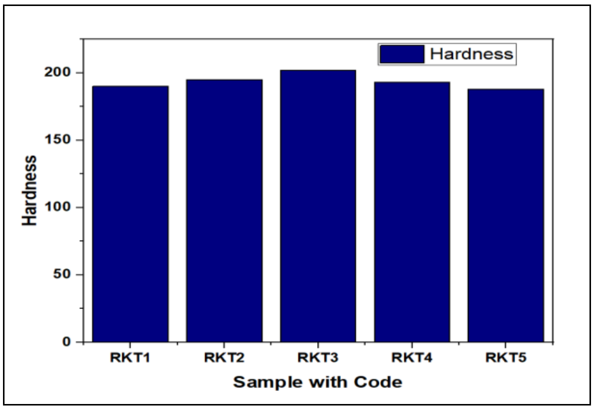

Fig. 9: Hardness of the different specimens

Fig. 9 illustrates, the addition of TiO_2 nanoparticles, which are recognized for their hardness, significantly raises the material's total hardness. Furthermore, the arrangement and dispersion of fibres inside the matrix might affect the hardness of the material. Essentially, the hardness test findings offer insightful data regarding the material's capacity to withstand deformation and indentation important characteristics for determining the material's applicability for a range of technical applications.

4. CONCLUSION

In summary, the development and evaluation of the hybrid composite material incorporating kenaf fibers, ramie fibers, and titanium dioxide nanoparticles have yielded promising results across a range of mechanical tests, including tensile, flexural, impact, and hardness assessments. The mechanical tests revealed that the hybrid composite material has an average tensile strength of 64.66 MPa, indicating its ability to withstand tensile stresses. Flexural strength testing demonstrated the material's resistance to bending forces, with an average strength of 90.2 MPa. Impact assessments showed a mean impact strength of 38.8 kJ/m², confirming the material's capacity to absorb impact energy. The hardness tests recorded a mean hardness of 193.6 HRC, indicating its strong resistance to deformation and impact. These results underscore the potential of hybrid composite materials in various technical applications that demand high levels of hardness, impact resistance, stiffness, and toughness. The mechanical properties of the material are significantly enhanced by the synergistic reinforcement provided by TiO_2 nanoparticles, ramie fibers, and kenaf fibers, offering a well-balanced combination of sustainability and performance.

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CONFLICT OF INTEREST

The authors declared no conflict of interest in this manuscript regarding publication.

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