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Original Article

The hydroscopic effect on dynamic and thermal properties of woven jute, banana, and intra-ply hybrid natural fiber composites

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A B S T R A C T

The effect of reinforcing natural fiber in the form of woven fabric on dynamic mechanical and thermogravimetric analysis was investigated. Further the influence of water molecule interaction on dynamic mechanical analysis of natural fiber composite were studied. Results revealed that basket type and intra-ply hybridized composites enhances the dynamic mechanical properties of the composites due to the enhancement in modulus by the reinforcement, whereas herringbone composites enhance the loss factor of the composites. It was noticed that, irrespective of the weaving architecture and intra-ply hybridization, composite samples immersed in the water for 45 days affects the storage and loss modulus of the composite and to enhance the loss factor. Thermogravimetric analysis carried out on composites revealed that, compared to weaving architecture, the presence of cellulose and hemicellulose in the fiber cell wall influences the thermal properties of the composites.

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1. Introduction

Over the past few decades, the use of conventional materials have reduced drastically, and been replaced with natural fiber-reinforced composites, especially plant wastage for low and medium load structural applications. In general, materials used for structural applications have good strength, stiffness, along with energy dissipation properties [1,2]. Most conventional materials provide high strength and stiffness, but exhibit poor damping behavior. On the other hand, natural fiber composites provide good damping properties due to their viscoelastic nature, but show less strength and stiffness [3]. Hence, it is important to enhance the strength and stiffness of the natural fiber composites. Most researchers have developed natural fiber composites by reinforcing natural fibers in the polymer matrix in the short form, with random distribution (SNFRC) [4,5]. Reinforcing with natural fibers in short form enhanced the strength of the composites, compared to the neat polymer composites. SNFRCs fail under loading due to the non-uniform distribution of the fiber in the matrix. Hence, it is important to find an alternative for reinforcement of the enhanced strength, and energy dissipation properties, which can, in turn, increase the use of NFRCs for many practical applications.

Nagaraj et al. [6] reported the significance of natural fiber-reinforced composites and proved that NFRCs could be used as a good alternative for conventional materials. Fazita et al. [7] found that reinforcement of a higher weight percentage of short natural fiber in polymer matrix decreases the strength of the composites. Similarly, Shekeil et al. [8] observed that reinforcement of kenaf fiber by more than 30 wt% affected the strength of the composite. Habibi et al. [9] developed the novel flax natural fiber reinforcement with combination of short flax fibers and unidirectional flax yarns using paper-making process. Results revealed that the presence of short flax natural fiber decreases the tensile strength and modulus in the longitudinal direction. Similar observation was observed for compressive strength. Further, they alter the orientation of natural fiber and increased the properties of composite. They found that for [±45 orientation] composite laminate short flax natural fiber showed the positive effect [10]. Rayyaan et al. [11] found that the weaving architecture influenced the strength and stiffness of the NFRCs. Other reseachers also found that plain woven banana composite enhanced the mechanical properties compared to basket and twill woven composites. It further enhanced the storage and loss modulus of the composites [12]. Song et al. [13] carried out dynamic mechanical analysis (DMA) of twill and plain-woven hemp fiber-reinforced composites. They found that twill woven composites enhanced the modulus value of the composites. Pothan et al. [14] found that fiber loading influenced the energy dissipation behavior of the composites. Higher fiber loading increased the loss factor of the composites. The hydrophilic nature associated with natural fibers affected the interfacial bonding between the fibers and matrix [15]. King et al. [16] found that the interaction of bagasse fiber with water molecules decreased the tensile and flexural strength of the composites due to the weak adhesive nature of the fiber and the matrix.

Similarly, Gupta and Srivastava [17] observed that the interaction of water molecules decreased the mechanical properties of the hybrid sisal/jute composite. It was inferred that the moisture absorption by the natural fibers affected its hybridization. Almansour et al. [18] observed a reduction in the toughness of hybrid the flax/basalt reinforced vinyl ester composites due to the water molecule interaction with the fibers [18]. Hence, it is essential to increase the fiber-matrix adhesion by minimizing the interaction of the natural fibers with water molecules.

Manimaran et al. [19] explored the thermal properties of *Furcraea Foetida*,a natural fiber using Thermogravimetric Analysis (TGA) analysis. The authors found that the thermal stability of the fiber stood at 320.5 °C, with a kinetic activation energy of 66.64 kJ/mol. It increased the thermal stability of the composites. Kiziltas et al. [20] analyzed the visco-elastic, and thermal behavior of flax, kenaf, and hemp fiber reinforced polyamide composites. DMA tests revealed that the addition of natural fiber reinforcement in the matrix enhanced the modulus and glass transition temperature of the composites. The authors also inferred that higher loading (wt%) of natural fiber in the matrix decreased the thermal stability of the composites. Khalili et al. [21] reinforced expandable graphite with natural fiber in the epoxy matrix, and found that the reinforcement of expandable graphite enhanced the thermal resistivity and fire retardation characteristics of the composites. Xia et al. [22] found that the addition of boron nitride in the natural fiber composite enhanced the thermal conductivity of the composites. Amorim et al. [23] reinforced *Curaua* fiber in the epoxy matrix and reported that the addition of the fiber enhanced the modulus value of the composites.

The disadvantages associated with short natural fiber reinforcement (SNFRC) can be improved by reinforcing natural fiber with woven form in the polymer matrix. Also, SNFRCs make the composite bulky, and offer weak resistance against failure. Few researchers explored the enhanced the mechanical properties of NFRCs by reinforcing them in woven form. However, detailed investigation is required to analyze the effect of fiber yarn movement in the warp and weft direction, nature of weaving pattern, intra-ply hybridization on dynamic properties of a polymer composite is yet to be explored. Rajesh et al. [24,25] carried out an experimental investigation on the mechanical properties of jute and banana fiber-reinforced composite with different weaving patterns, such as plain, basket, twill, satin, and herringbone. The authors reported that the strength and modulus of composites reinforced with plain and basket weave patterns were high compared to other weave patterns. Based on the experimental results obtained from previous studies conducted by the author [24,25] it was decided to use different weave patterns, such as plain, basket, herringbone, jute-banana intra-ply hybridization, and sandwich composites to enhance the dynamic properties of the NFRCs. In continuation, effect of water immersion on dynamic properties of the composites were carried out to understand the effect of reinforcement. Further the thermal properties of

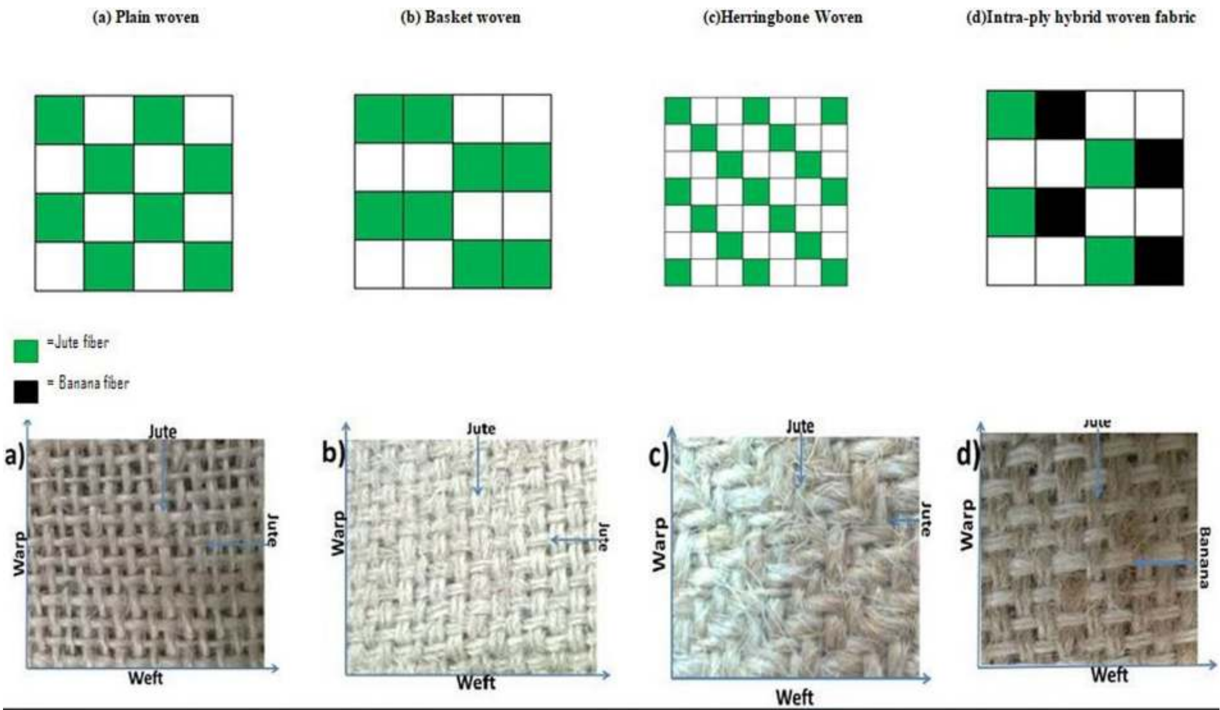

Fig. 1 – Schematic diagram and original image of woven fabrics used in the study.

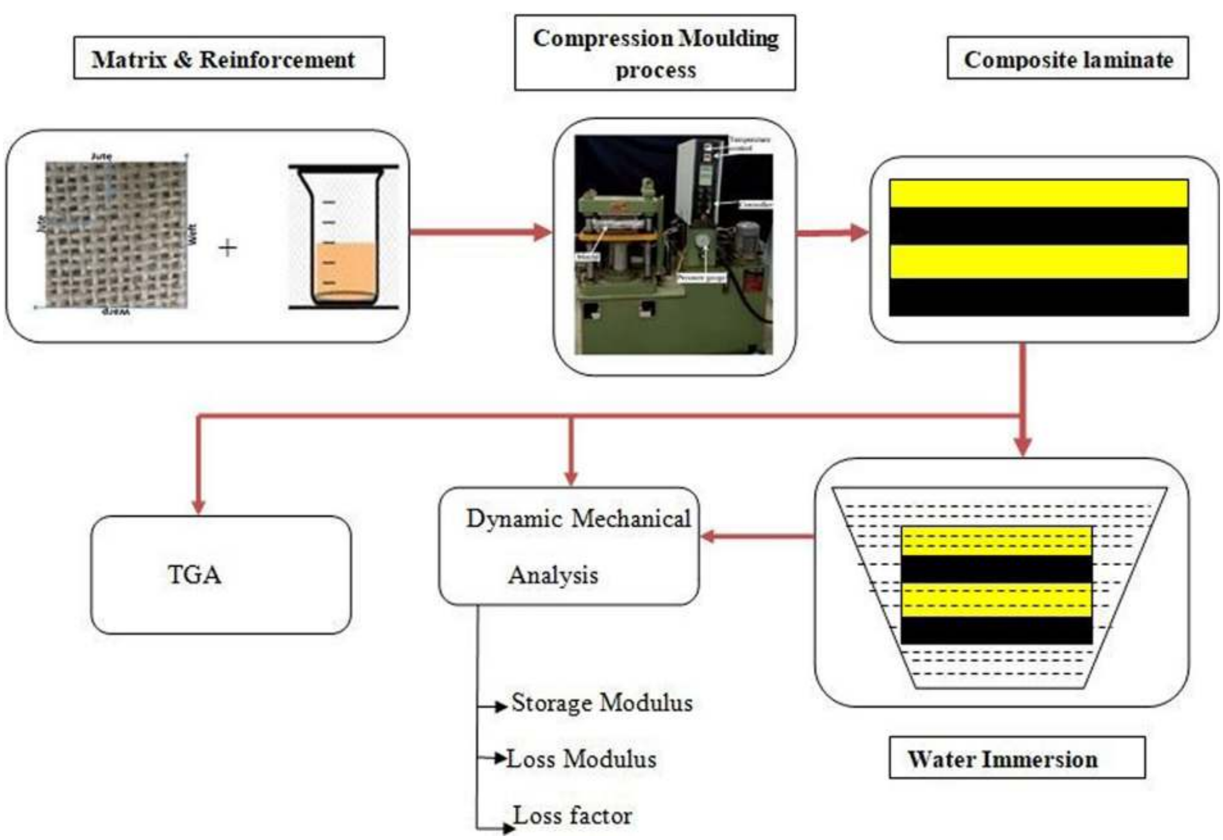

Fig. 2 – Schematic diagram of composite laminate preparation.

the composites were analyzed using Thermogravimetric analysis (TGA).

2. Experiment

2.1. *Woven reinforcement and matrix preparation*

In this study, jute and banana fibers were used as a reinforcement in the woven form. Unsaturated polyester resin, methyl ethyl ketone peroxide (MEKP), and cobalt naphthenate were used as the matrix, catalyst, and accelerator, respectively. As a first step, 100–150 loose jute and banana natural fibers were converted into continuous yarn, which was further weaved into plain, basket, herringbone woven fabric. The intra-ply hybrid woven fabric was prepared by keeping relatively strong jute yarn in the warp direction, and relatively weak banana fiber in the weft direction. Woven fabrics used in this study was manufactured with the help of a power loom to attain the required stiffness with a thickness of 0.8–0.9 mm. The matrix material was prepared using unsaturated isophthalic polyester resin, methyl ethyl ketone peroxide (MEKP), and cobalt naphthenate, with a weight ratio of 100:1:1. The banana and jute fibers were procured from M/s. Jothi Fabric, Madurai, Tamil Nadu, India, and M/s. Kiran Jute Industry, Kolkata, West Bengal, India, respectively. The resin, the catalyst, and the accelerator, were purchased from M/s. Vasavibala Resins Ltd., Chennai, Tamil Nadu, India.

2.2. *Fabrication of composites*

Four layered composite laminates were prepared with different woven fabric reinforcements using the compression moulding technique, with a size of 250 mm × 250 mm × 4 mm. Stainless steel was used to make the mould, with a dimension of 250 mm × 250 mm × 4 mm, in order to fabricate the composite laminates. Before initiating the fabrication of the WNFRCs, the natural fiber fabrics were soaked in an epoxy bath to make them wet. It helped to enhance the interfacial bonding between the fiber and the matrix under dry conditions. After the wetting process, excess epoxy resin present in the fabrics was removed, and a known quantity of matrix was poured into the mould cavity. Subsequently, the woven fabrics were placed in the mould cavity, and a roller was used to remove the voids in the composite laminates. Schematic diagram of fiber reinforcement and manufacturing process used in the study is shown in Figs. 1 and 2. Table 1 shows the fiber volume fraction of composites used in this study.

The remaining amount of matrix was poured in the mould cavity, and the steel plates were placed over the cavity. It was then compressed with a pressure of 150 kgf/cm^2 for 1 h at 80 °C curing temperature, to prepare uniform composite laminates. After curing for 24 h at room temperature, the composite laminates were removed from the mould cavity, and the samples were prepared for the TGA and DMA to find the storage modulus, loss modulus and loss factor, in order to understand the effects of the weaving pattern, intra-ply hybridization, and the sandwich effect. The composites prepared in this study were marked as SW, BB, BJ, KJ, and IP. SW represents for the sandwich composite, made of two basket jute woven fabrics as facing layers, and two plain jute fabric layers as the core layers. BB represents the composite made of banana fiber via basket weaving, BJ denotes the composite with jute fiber via basket weaving, KJ represents the herringbone woven jute composite, and IP represents the intra-ply composite.

Table 1 – Fiber weight and void fraction of composites used in this study.

Composite	Weight fraction (%)	Void fraction (%)
BB	45.0	0.19
PJ	43.2	0.18
IP	48.0	0.24
KB	68.8	0.57
BJ	70.4	0.59
SW	53.6	0.33

2.3. *Dynamic mechanical analysis (DMA)*

To study the effect of weaving pattern and intra-ply hybridization on the dynamic properties such as storage modulus (E’), loss modulus (Ë̤), and damping factor (Tanδ), DMA was carried out. TA Instrument Model Q800 dynamic mechanical analyzer was used. It was used in dual cantilever mode, at a temperature range from 25 °C to 150 °C, and heating rate of 5 °C/min. The frequency was maintained at 1 Hz for all the composites. Samples were prepared with a dimension of 50 mm × 13 mm × 4 mm. To understand the effect of water molecules interaction with the natural fibers reinforced in the polymer matrix, the samples were immersed in water for 15 days, 30 days, and 45 days separately.

2.4. *Thermogravimetry analysis (TGA)*

The influence of banana and jute natural fiber reinforcement and intra-ply hybridization on the thermal stability properties were analyzed using a thermogravimetric analyzer (Model: Mettler Toledo TGA, Mettler Toledo, Columbus, OH, USA) as per the ASTM E1131-03 standard. For TGA analysis, 10 mg powdered composites were loaded into an alumina crucible and underwent pyrolysis in a nitrogen filled environment.

3. Results and discussion

3.1. *Dynamic mechanical analysis*

Several researchers have investigated the influence of temperature on the storage modulus, loss modulus, and loss factor for SNFRCs. It was reported that, the dynamic behavior of the SNFRCs depended on the fiber’s length, aspect ratio, distribution, fiber/matrix interaction, and hybridization effect of the natural fiber. In this study, banana and jute natural fibers were reinforced in the polyester matrix with the plain, basket, and herringbone weaving patterns to help understand the effect of reinforcement on the storage modulus, loss modulus and loss factor. The intra-ply hybridization of the natural fibers helped by keeping the jute in the warp direction, and banana fiber in the weft direction for developing the required dynamic properties. In continuation, results of various reinforcement effects were compared with that of the sandwich composites.

3.2. Storage modulus

Types of fiber, the effect of weaving pattern, its hybridization, and sandwich effect on the storage modulus are shown in Fig. 3. From Fig. 3, it can be inferred that BJ and SW composites exhibited an enhanced storage modulus, as compared to BB, KJ, and IP reinforced composites. In the glassy region, the SW composites showed an enhanced storage modulus as compared to other composites, whereas in the rubbery region, BJ composites showed an enhanced storage modulus value instead. The enhancement in stiffness of the SW is due to the arrangement of the stiff braided jute fabric as the facing layer. In contrast, the arrangement of the relatively strong jute fiber in the warp and weft directions offered more resistance against the free molecular movement of the polymer chain in the rubbery region for the BJ composite. It also enhanced the tensile and flexural modulus of the composite, compared to the natural fibers reinforced with plain and herringbone patterns, as reported in previous studies [24]. The primary reason for the enhancement of the modulus of the SW and BJ composites was due to the arrangement of the jute fabric in the warp and weft directions with the basket pattern, therefore enhancing its rigidity, which further increased the load carrying capacity of the composite and making them much more rigid.

From Fig. 3a, it can be observed that, other than the type of fiber, the weaving pattern influenced considerably the stiffness of the composite. Compared to JP, KJ, and IP composites, the relatively low strength of the banana fiber compared to the jute enhanced the storage modulus of the composite up to 70 °C. It was revealed that the basket weaving pattern increased the modulus of the banana fabric, which in turn increased the load carrying capacity, compared to the relatively stronger jute fiber with plain and herringbone patterns. Hence, it provided much more resistance against free molecular movement, and increased the interfacial bonding between the fiber and matrix. Post 70 °C, the effects of the fiber's strength influenced the storage modulus much more than the weaving pattern itself. While increasing the temperature from 70 °C to 100 °C, relatively strong jute fiber offered higher resistance against free molecular movement, compared to BB composites. Hence, it can be concluded that the fiber strength, and the basket weaving pattern, helped to increase the stiffness of the composites, and delayed the failure of the composites when subjected to high temperatures. In the case of the IP composite, the increment of the storage modulus compared to BB, PJ, KJ, and SW composites was not significant. Although IP composites exhibited an enhanced tensile and flexural modulus value [24], the arrangement of both strong and weak jute, banana fibers in the warp, and weft directions failed to provide resistance against free molecular movement, which increased the molecular mobility of the polymer chain. The main reason for this was that under a thermal environment, the high strength of the jute fiber offered much more resistance against molecular movement, compared to the banana fibers. The storage modulus of different composites used in this study revealed that the basket weave pattern (from the rubbery region) and the high strength jute fiber enhanced the storage modulus much more, compared to SW, and other weaving patterns. It showed that the arrangement of the high strength jute fiber yarns in the warp and weft direction of the basket weave increased the rigidity of the fabric, as compared to both plain and herringbone patterns. In the BJ composite, the load carrying capacity increased, and the stress transformation from the matrix to the fiber was much more effective. The reason for the high storage modulus of the BJ composite in the rubbery region was the low crimp, and the gap between two successive fiber yarns in the warp and weft directions, therefore minimizing the stress concentration levels. The plain and herringbone weave patterns had much higher crimp and gap between the yarns in the warp and weft directions.

Figs. 4a, 5a & 6a revealed that the interaction of the natural fiber with water molecules decreased the stiffness of the composites, which was reflected by the decrease in the storage modulus of the composites used in this study. The results also revealed that the storage modulus of the specimens used in this study fell in the range of 3000–5000 MPa in the glassy region under a normal environment. In contrast, the storage modulus fell between 2000–4000 MPa for composites immersed in water. This revealed that the interaction of water molecules with natural fibers affected the interfacial bonding between the fiber and the matrix, which reduced the load carrying behavior of the composites under dynamic loading. The presence of a higher amount of cellulose and hemicellulose increased the interaction rate with water particles. The abundance of hydroxyl groups of cellulose and hemicellulose increased the interaction with water molecules through the amorphous region [26]. The absorbed water molecules occupied the space between the microfibril, and acted as a natural plasticizer [27], affecting the weaving pattern, fiber strength, intra-ply hybridization, and sandwich effect, by reducing its rigidity, as compared to the dry condition. This further affected the storage modulus of the composites.

From Figs. 4a, 5a & 6a, it can be observed that the SW composite had a higher storage modulus compared to the other composites, over 15, 30, and 45 days of water immersion, respectively. But, this value is still much lower compared to dry composites. This revealed that, the water interaction reduced the storage modulus due to the penetration of water molecules between the cracks and the debonding of the fiber-polymer interface. The arrangement of high stiff braided jute fabric in the outer layer delayed the failure of the composite, due to the much higher rigidity of the composites. From Figs. 4a, 5a & 6a, it was found that the SW composite with 45 days had a much lower storage modulus in the glassy region, as compared to samples from 15 days and 30 days, respectively. This was due to the combined eff ;ects of hydrolysis on the polyester matrix, and the degradation of the fiber/matrix interface, as well as leaching of the fiber. The other reason for the low value of the composites with water immersion was due to the hydrolysis of the ester linkages, breaking down the long macromolecular chains. It led to the formation of additional voids in the composites filled with water. A similar observation can be made for other composites used in this study, across the glassy region. After 100 °C, in the rubbery region, the storage modulus of all composites used in this study decreased drastically. This was due to the high-stress concentration and poor fiber/matrix interfacial bonding. It further affected the

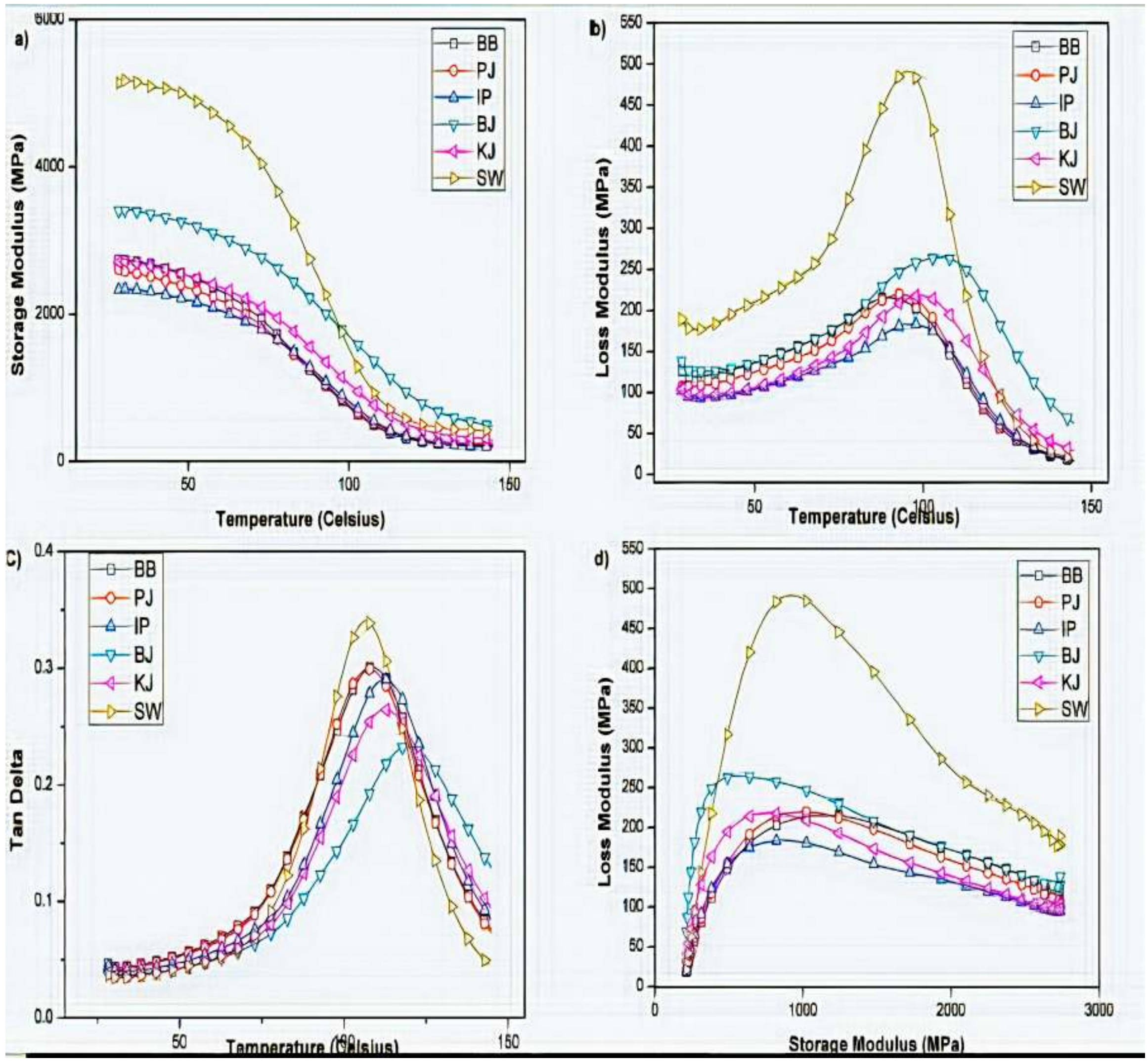

Fig. 3 – Nature of weaving pattern on a) Storage modulus, b) Loss modulus, c) Damping factor, d) Cole–Cole plot.

strength and stiffness of the composites drastically, due to the reduction of the adhesion between the fiber and matrix.

3.3. *Loss modulus*

From Figs. 3b, 4b, 5b & 6b, it can be noticed that the loss modulus variation of the WNFEC was similar to the storage modulus variation. From Fig. 3b, it can be observed that the SW composite had a higher loss modulus than other composites used in this study. It reflected the combination of the basket and plain-woven jute fabric in the SW composite, which enhanced the loss modulus value of the composite by providing much more resistance against the free molecular movement of the polymer chain. It also revealed that the reinforcement of the stiff and strong fabric in the polymer matrix increased the frictional resistance, which in turn increased the energy dissipation behavior of the composites. This was the reason for the SW composite to have a much higher loss modulus than the BJ, IP, and KJ composites. Although the BJ and KJ composites were fabricated using relatively strong jute fiber, the SW composite exhibited an enhanced loss modulus. This was due to the combined effects of the basket and plain-woven jute fabric, which increased the interaction between the fiber yarns in the particular fabric, and between the basket and plain woven fabric in the SW composite. It further increased the energy dissipation properties of the SW composite. Another reason was the lower gap associated with basket weaving patterns, which increased the interaction between the fiber yarns.

From Fig. 3b, it can be observed that, compared to the SW composite BB, BJ, KJ & IP composites has a much wider loss modulus curve. It also revealed that the fabrics available in these composites increased the energy-absorbing behavior of the composites, and moved the curve into a much higher temperature region. Irrespective of the fiber type, the strength and the arrangement of the fabric's stresses shifted from the matrix to the reinforcement uniformly, due to the good adhesion between the fiber and matrix. It also increased the interaction between the fabric and matrix, and the fiber yarns in the reinforcement. It also increased the frictional resistance of these composites. Fig. 3b revealed that the BJ composite had a higher glass transition temperature (T_g) than other composites, as shown in Table 2.

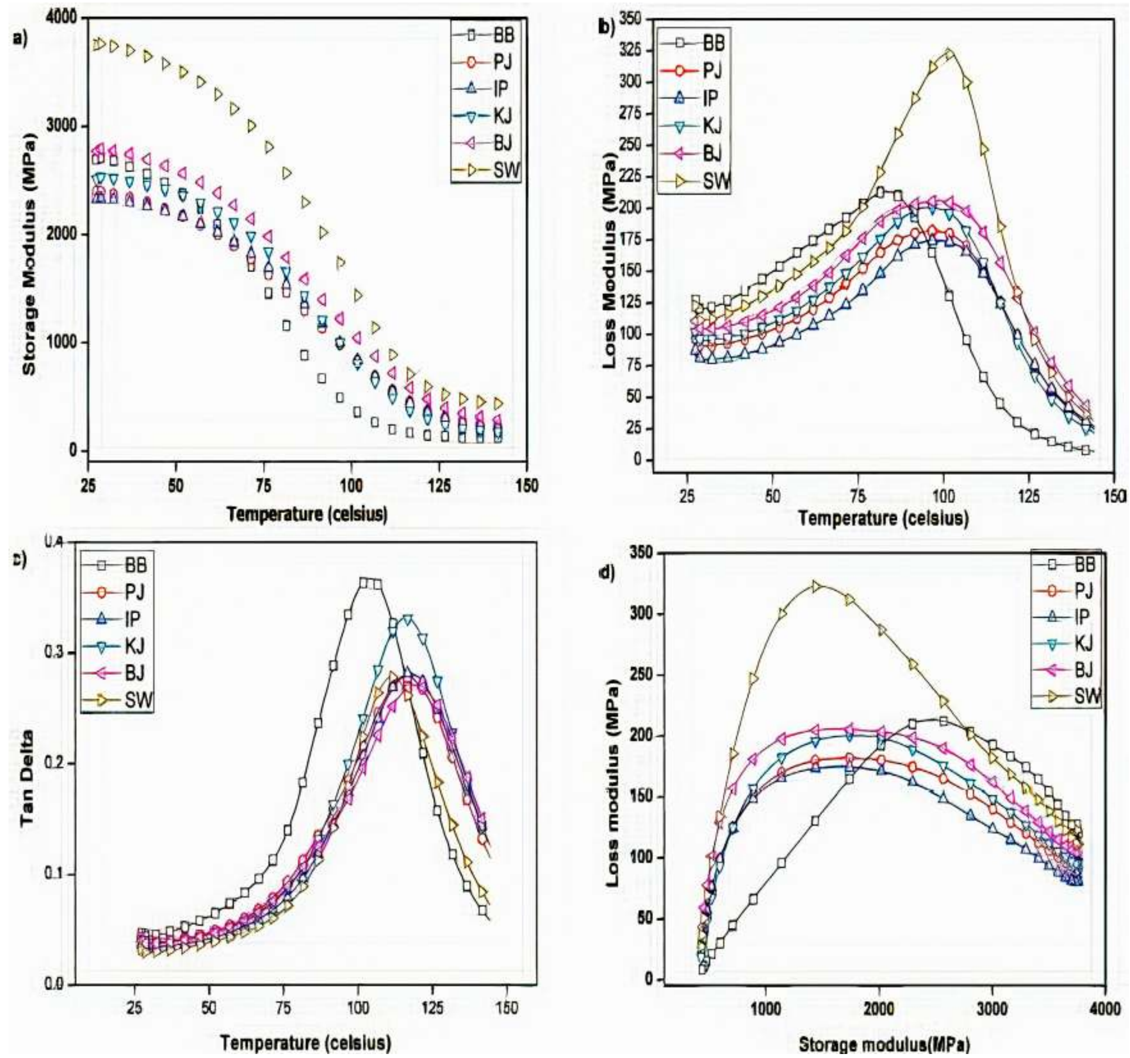

Fig. 4 – Influence of 15 days water immersion on a) Storage modulus, b) Loss modulus, c) Damping factor, d) Cole–Cole plot.

Table 2 – Glass transition temperature of different composites.

Composites	Glass transition temperature (°C)											
	From storage modulus curve				From loss modulus curve				From tan delta curve			
	0 Day	15 Day	30 Day	45 Day	0 Day	15 Day	30 Day	45 Day	0 Day	15 Day	30 Day	45 Day
BB	62.04	60.75	58.59	59.00	90.08	83.27	89.15	88.96	108.57	103.95	107.40	102.00
PJ	62.05	60.67	61.93	61.29	93.20	96.33	96.67	95.33	107.44	115.84	115.04	114.23
IP	63.05	61.30	62.88	62.76	91.84	93.68	92.84	88.61	108.07	112.90	110.52	106.62
KJ	63.14	64.19	62.86	63.89	95.61	92.78	99.68	95.56	109.10	113.52	118.52	119.80
BJ	64.24	63.08	63.80	61.80	100.63	99.66	98.64	93.37	115.11	120.84	119.40	118.25
SW	68.09	65.36	70.01	64.88	95.46	98.08	101.22	96.85	106.69	115.84	110.97	108.36

It also revealed that the basket woven composite enhanced the load carrying capacity of the composite, and increased its resistance against deformation and failure. It also provided resistance against the free molecular movement in the polymer chain. Composites made of the basket-type banana woven fabric (BB) reinforcement increased the glass transition temperature, but slightly less than the jute fiber composites. Although the strength of the banana fiber was less than jute fiber, the basket weaving architecture enhanced the loss modulus and T_g values of the composite. A similar observation could be observed from the storage modulus value of the BB composite (Fig. 3a). Other than the fiber type, the weaving pattern influenced the rigidity of the composite, which helped to enrich the inherent properties of the composite. Although the T_g value of the IP composite was slightly higher compared to the BB composite, the effect of both relatively strong and weak fibers present in the fabric did not influence the inherent properties of the composite under thermal conditions. In contrast,

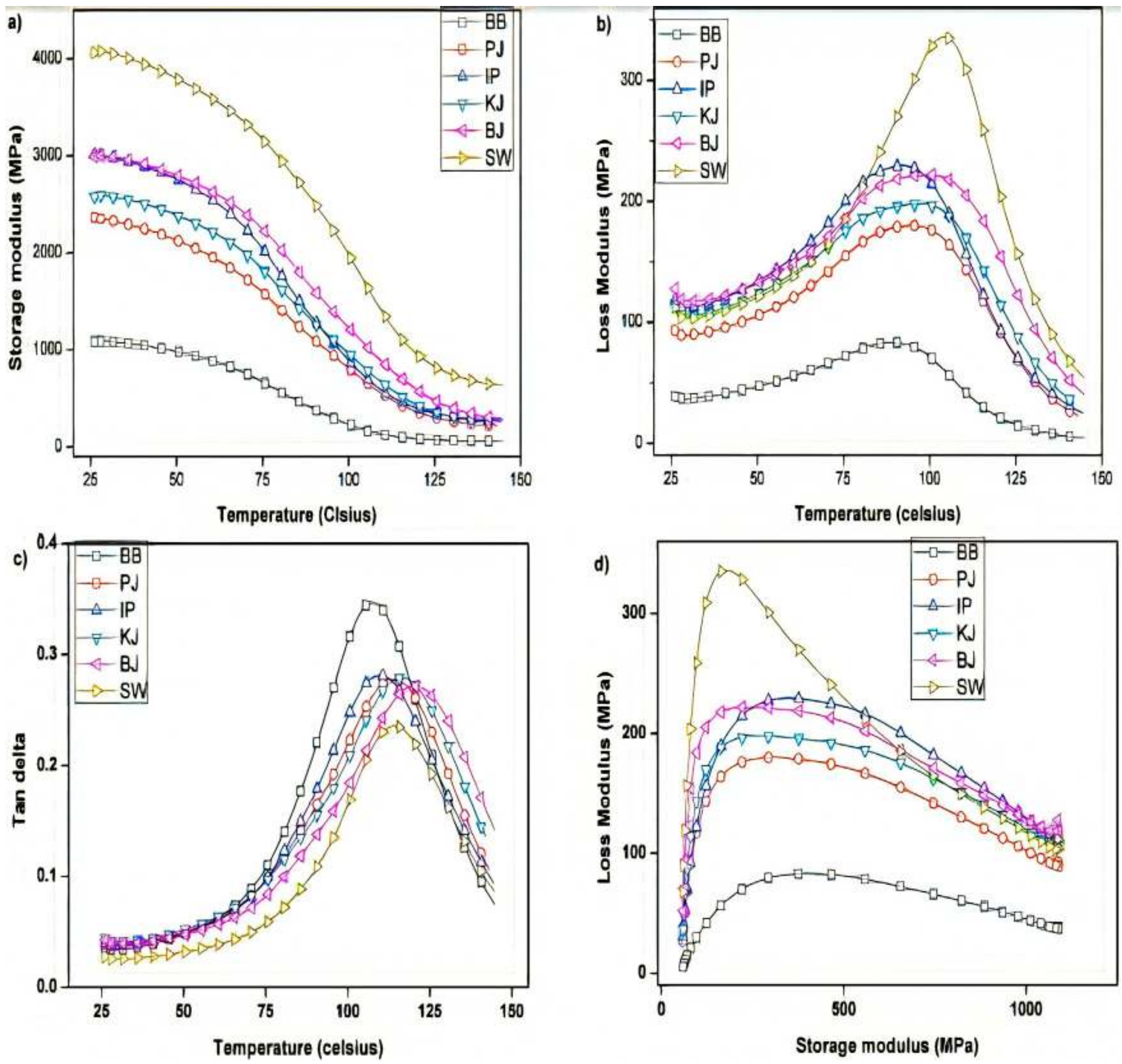

Fig. 5 – Influence of 30 days water immersion on a) Storage modulus, b) Loss modulus, c) Damping factor, d) Cole–Cole plot.

under a normal environment, the modulus value increased [24].

Figs. 3b, 4b & 5b revealed that the water molecule absorption of the NFRC decreased the loss modulus value drastically, from 100–500 MPa to 75–350 MPa. The effect of water interaction on the loss modulus variation was similar to storage modulus variation. An interesting observation made with respect to the loss modulus variation is that the BB composite face suddenly changed after T_g. The main reason behind this loss modulus variation of the BB composite was the presence of a high volume of hemicellulose in the banana fiber cell wall. The presence of a huge volume of hemicellulose allowed more water molecules into the fiber, due to the interaction of a huge amount of hydroxyl groups in that region. It increased the fiber-matrix damage due to the formation of microcracks followed by debonding due to weak fiber-matrix adhesion. It also affected the inherent properties of the BB composites, and minimized the resistance against free molecular movement of the polymer chain. As compared to BB, BJ, KJ & IP, the SW composite showed an enhanced loss modulus value in the glassy region, irrespective of the number of days immersed in water. This was still less than the composite under dry conditions. It indicated that the weave pattern influenced the modulus improvement of the composites. As the number of days of water immersion of composite samples used in the study is increased, it was observed that there was a decrease in the broadening of the loss modulus curve. It revealed that the water immersion of the natural fiber made it lose its strength, which decreased the stiffness of the reinforcement, and affected the strength of the composites.

3.4. *Material loss factor*

Fig. 3c shows the loss factor variation within the thermal environment for different composite samples used in this study. It revealed that the BJ composite has a low loss factor, and the SW composite had a higher loss factor, while the IP fell in between. It was also seen that the higher loss factor associated with the SW composite was due to the high interaction between two different types of woven fabrics available in the SW composite, which enhanced the energy dissipation properties of the composite. However, the combinational effects

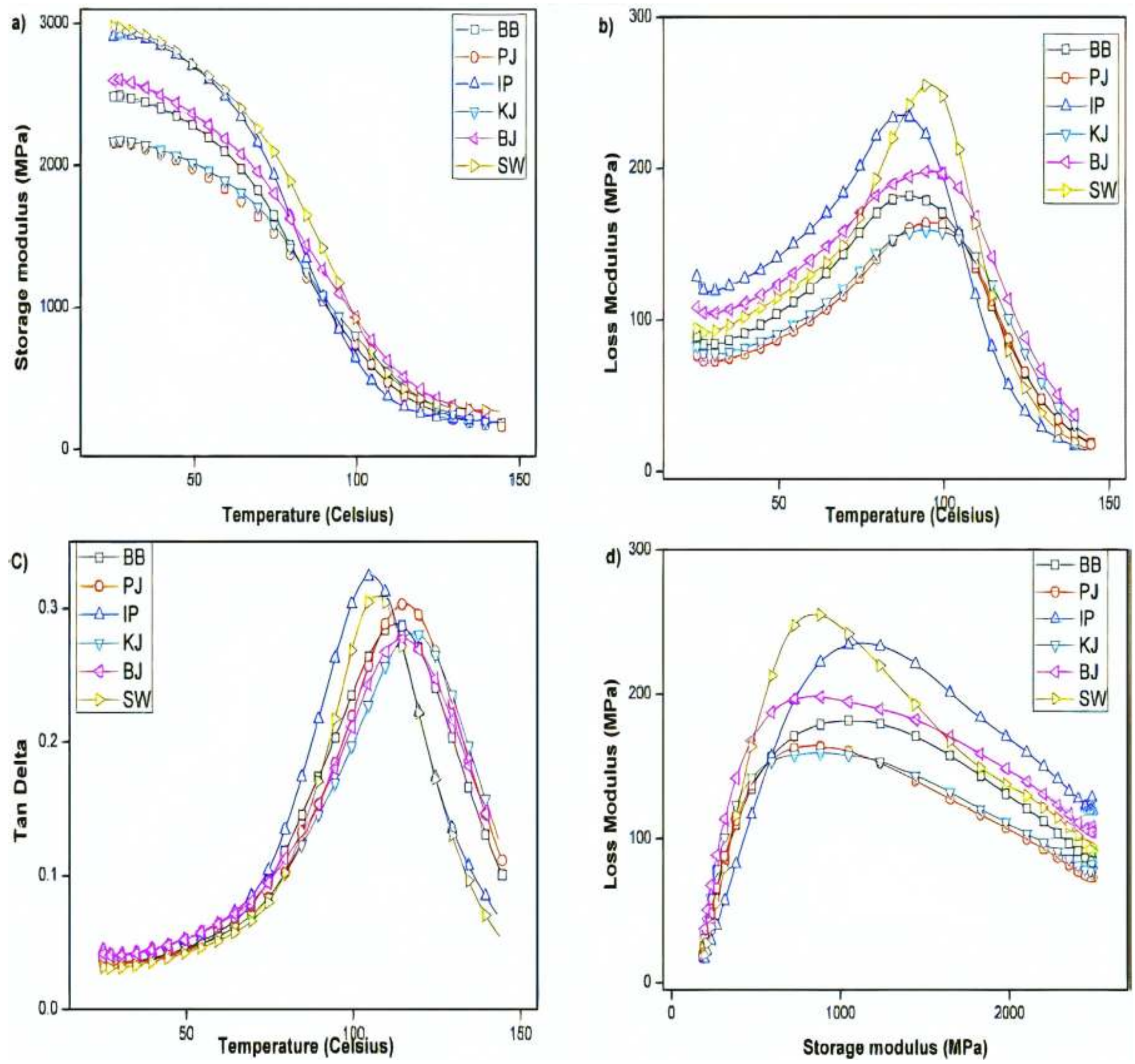

Fig. 6 – Influence of 45 days water immersion on a) Storage modulus, b) Loss modulus, c) Damping factor, d) Cole–Cole plot.

of the basket and plain-woven fabrics in the SW composite enhanced both the strength and damping factor values in the glassy region, which was not observed in the other composites. The T_g value of the SW composite (106.69 °C) fell in the lower temperature region, as compared to BJ, KJ, IP & BB composites. This was due to the combined effect of the basket and plain-woven fabrics in the SW composite, which allowed them to provide much higher resistance against the free molecular movement of the polymer chain in the glassy region. By contrast, it failed in the rubbery region due to the higher interaction between both the fabrics.

In the case of the BJ composite, the higher modulus associated with the four-layer basket woven jute fabrics delivered a higher resistance against the free molecular movement with temperature increase (Tg up to 115.11 °C). This suggested that the reinforcement with stiff fiber and woven fabric enhanced the load carrying capacity of the composite, and made them rigid under thermal environments. This can also be noticed from the higher values associated with the storage and loss modulus of the BJ composite. Compared to the BB composite, the IP composite had a low loss modulus. This was due to the presence of relatively strong jute and weak banana fiber in the woven fabric, which balanced both strength and energy dissipation of the composite.

In the case of the BB composite, the loss factor of the composite was enhanced as well. Although the basket weave provided much better strength and stiffness for the weak banana fiber fabric, the presence of a lower amount of cellulose did not contribute to the load-carrying capacity of the composite within the thermal environment, and the dynamic loading conditions. Hence, it can be concluded that the reinforcement of the strong fiber and suitable weaving patterns influenced the enhancement of the strength, stiffness, and energy dissipation properties of the composites. For PJ composites, the availability of the high crimp in the fiber yarn along warp and weft direction decreased the modulus of the fabrics, which contributed to a higher loss factor.

Figs. 3c, 4c, & 5c revealed that the composite samples immersed in water for 15, 30, and 45 days displayed an increased loss factor value, irrespective of the fiber's strength

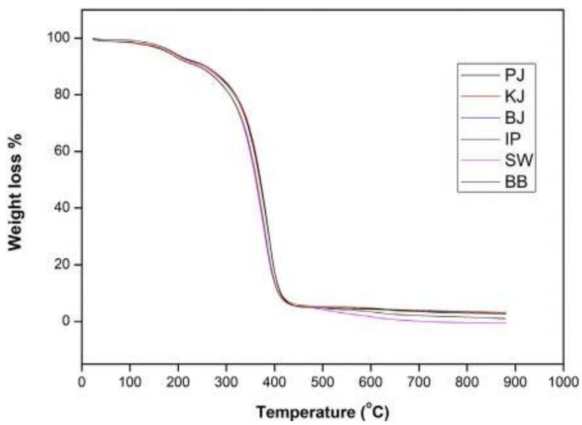

Fig. 7 – Thermogravimetric curves of different composites used in the study.

and weaving patterns. This was because of the interaction of the natural fiber with the water molecules, which affected the fiber-matrix adhesion, which contributed to the advantages of the weaving patterns of the natural fiber reinforcement.

3.5. *Cole–Cole plot*

The Cole–Cole plot is usually used to understand the structural changes that occur due to fiber reinforcement in the matrix, and also helps to investigate the homogeneous nature of materials. Figs. 3d to 6d depict the Cole–Cole plots of the different composites analyzed in this study. From the Figs. 3d to 6d, it can be inferred that the addition of different types of woven fibers and water treatment of the fibers made the materials heterogeneous in nature. From Figs. 3d to 6d, it was observed that the higher value of the Cole–Cole plot denoted a good bonding strength between the reinforcement and the matrix, whereas a lower one denoted a poorer interfacial bonding strength.

3.6. *Thermogravimetry analysis (TGA)*

The influence of the type of natural fiber, its reinforcement, intra-ply hybridization, and sandwich effects on thermal stability, are shown in Fig. 7. From the graph shown the observation can be divided into two stages. The first stage starts from 30 °C to 200 °C. It can be observed that the weight loss associated with the composites in this stage were small, which was due to the thermal degradation of the materials, which occurred during the drying process of the natural fiber. Drying of the natural process helped to reduce the moisture content in the composite. However, the thermal stability of the composites used in this study almost followed the same variation. It revealed that the weaving pattern and the intra-ply hybridization did not influence the thermal stability of the composite, but the fiber type had an influence over the thermal stability. From Fig. 7, it can be noticed that there was a minor change in the thermal degradation curve for both the BB and SW composites, as compared to the KJ, BJ, IP, and PJ, indicating that compared to banana fiber, the jute fiber had slightly higher thermal properties. The difference in the thermal properties were due to the the volume of the cellulose and hemicellulose available in the individual fibers, which influenced the water interaction. The substantial weight losses for the composites started in the temperature range of 200 °C–400 °C. In this region, the constitutes of the natural fibers, such as cellulose, hemicellulose, and lignin start to degrade. Finally, the non-cellulosic contents presented in the natural fibers began to deteriorate after 400 °C. It was observed that, compared to the banana fiber, the jute fiber had more volume of cellulose and hemicellulose.

From Table 3, for a weight loss of about 10%, the composite deteriorated in the temperature range of 150–200 °C. A similar trend was noticed for 20–80% weight loss of the residual mass of the different composites used in this study. It confirmed the presence of cellulose, hemicellulose, and lignin in the fiber cell wall influenced the thermal properties of the composites, other than the weaving pattern, and sandwich effects.

4. Conclusion

Influence of nature of weaving pattern (plain, basket and herringbone) and intra-ply hybridization on dynamic mechanical properties has been analyzed. Results revealed that basket and intra-ply hybrid composite has higher storage and loss modulus compared to herringbone and plain-woven composites. It is also revealed that glass transition temperature as higher for basket and intra-ply hybrid composite. Similarly, sandwich composite enhanced the dynamic properties and glass transition temperature of the composites in this study. It is due to presence of stiff basket woven fabric in the outer layer enhanced the modulus value of the composites. In continuation, effect of water interaction of natural fiber on dynamic properties of composites has been studied. Results revealed that, other than reinforcement effect 45 days water immersion decreased the modulus value of the composites and increased

Table 3 – Effect of reinforcement on thermal properties of natural fiber composites.

Sample	Decomposition temperature (°C) of the different weight loss (%)						
	10%	20%	30%	40%	60%	80%	Residual mass at 400 °C (%)
KJ	163	292	362	411	421	428	1.833
BJ	154	278	337	371	381	417	0.805
IP	162	278	334	368	381	409	0.799
PJ	214	288	333	374	384	417	0.8366
BB	154	271	332	367	374	396	0.787
SW	197	280	321	351	387	402	0.772

the loss factor value. Thus, it reveals that dynamic properties are highly sensitive to the nature of reinforcement, interfacial bonding between fiber and matrix. TGA results reveled that compared to weaving pattern, presence of cellulose and hemicellulose in the fiber cell wall influenced on enhancement of the thermal properties of the composites. The enhanced storage and loss modulus associated with basket woven fabric and plain-woven fabric core sandwich composite increases poor strength for low and medium load structural applications.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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