

Improving the Mechanical Properties of Ramie-Polylactic Acid Green Composites by Surface Modification using Single Bath Alkaline and Silane Treatment

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Research Article

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Abstract

This research work emphasises on improving the interfacial adhesion of ramie/ polylactic acid (PLA) composites. For this purpose, ramie fabric was modified using vinyl trimethoxy silane with two different hydrolysing agents, i.e. sodium hydroxide and ammonia. The surface modified ramie fabric was characterised by static water contact angle, elemental dispersive X-ray (EDX) and Fourier transform infrared spectroscopy (FTIR). FTIR and EDX analysis confirmed the presence of silica. The tensile strength of fabric showed a decrease after the silane treatment. The composites were prepared by compression moulding using untreated and treated ramie fabrics with PLA. The treatment improved tensile and impact performance of ramie/PLA composites due to enhanced interfacial adhesion between fibre and matrix. Dynamic mechanical analysis (DMA) results revealed that treated ramie/PLA composites have higher storage modulus and lower tangent delta than untreated composites.

1. Introduction

Use of composites as engineering material has opened up a new horizon of materials science. The widespread use of composites in structural and semi-structural applications has played an instrumental part in shaping the modern developments. However, due to these tremendous advantages, composite consumption has skyrocketed in recent years. According to a survey, municipal solid waste (MSW) generation per capita was of 500 g/day in 2011, which was relatively high in urban India. Enormous waste generation leading to a rise in the greenhouse gas emissions has also been reported, which results in threats like global warming, climate change and poor air quality index [1]. These environmental concerns, although necessary, are limiting the composite utilisation and raising concerns related to sustainable development. The recycling of many composite materials is still hindered by techno-economic reasons [2]. Thus, renewable and sustainable eco-friendly composites have become the need of the hour. The use of biocomposites in various applications like automotive, packaging and medical field has become a subject of great interest to the scientific society [3–5]. The use of bio-based polymers with natural fibres as reinforcement represents a sustainable solution to recycling and solid waste generation. However, there is a limited number of bio-based polymers used as the matrix in composite materials. Polylactic acid (PLA) is one of the bio-based polymers that fulfils the mechanical, engineering and economic requirements for large scale implementation.

Polylactic acid (PLA), a biodegradable bio-based thermoplastic high-strength, and high-modulus aliphatic polyester is produced from natural renewable sources like corn sugar, sugar cane, potato, etc. [6]. Among the biopolymers, PLA has been reported to be the most successful in developing alternatives and replacing the materials based on non-biodegradable fossil polymers [7]. However, applications of PLA are still limited due to its low flexibility. To improve the toughness of PLA, many fillers and plasticisers have been used [8, 9]. Natural fibres are one of the potential candidates in improving the toughness of PLA. Besides improving the toughness, natural fibres offer advantages like environmental friendliness, biodegradable nature and a lower density than the synthetic fibres, like glass, carbon etc., commonly used in the composites. Siakeng et al. [10] found that incorporating coir/pineapple fibre at 30 wt.% in PLA

improved its toughness by 30%. Similarly, Ovlaque et al. [11] reinforced PLA with milkweed floss fibres and found that the impact strength of PLA was improved by 12%. Jayamani et al. [5] reported that the impact strength of PLA improved after incorporation of sisal fibre to about 6 kJ.m^{-2} from 4 kJ.m^{-2} . Aydemira and Gardner [12] used cellulose nanofibrils (CNFs) to reinforce PLA and polyhydroxybutyrate blend to improve the ductility of PLA. They reported that CNFs improve the mechanical and thermal properties of PLA at 1 wt.% loading.

In general, it has been claimed that natural fibres can pave the way for sustainable composites by offering advantages such as weight reduction, low cost, improved mechanical properties and low carbon footprint compared to synthetic fibres. However, tensile properties of natural fibres are inferior to those of their synthetic counterparts, though the former's specific tensile strength and stiffness are comparable with glass. For example, ramie fibre has higher stiffness than glass, and the former is well accepted as a reinforcement for polymeric composites. Nevertheless, the hydrophilic nature of natural fibres results in an inferior interface and thereby causes poor mechanical properties of composites to reinforce hydrophobic matrices [13–16]. Thus, to improve the interfacial adhesion, chemical or physical modifications of natural fibres are required. Among chemical treatments, alkaline treatment is extensively used for the modification of cellulosic fibres [17, 18]. This treatment exposes cellulose microfibrils and promotes the hydroxyl group's ionisation present on the fibre surface to the alkoxide groups [19]. True et al. [18] studied the effect of alkaline and/or silane treatment of the sisal fibres on the mechanical properties of sisal/PLA composites and found that the strength of sisal/PLA composite improved significantly as compared to that of untreated sisal/PLA composite. Yang et al. [20] used cyclic loading after alkaline treatment to improve ramie/PLA composites' mechanical properties. This study confirmed that the alkaline treatment and cyclic loading act synergistically to enhance ramie/PLA composites' overall mechanical properties. Another well-established way to enhance the interface of natural fibres in polymeric matrices is the use of coupling agents. Silane-based coupling agents promote covalent bonding between natural fibres and polymeric matrices [21–26]. The mechanism of surface modification using coupling agents involves the reaction of alkoxy silane group with hydroxy groups present on the fibre surface and another active group with a polymer matrix [27]. Song et al. [28] treated hemp fibres with silane before manufacturing its composites with PLA. They found that silane treatment helped uniform distribution and better adhesion of the hemp fibre into PLA, which resulted in improved mechanical and thermal properties of hemp/PLA composites.

Similarly, Jandas et al. [29] and Li et al. [30] used various silane coupling agents for the surface treatment of natural fibres. They found that these composites' mechanical properties improved significantly compared to that of untreated natural fibre composites. Aphichartsuphaphajorn et al. [24] used alkaline and silane simultaneously on flax fibre followed by composite fabrication with biobased resin furan. The study revealed that the combination of alkali and silane yielded better mechanical properties than that obtained with individual alkali or individual silane treatment.

Ramie is a very strong natural fibre and available in Korea, China, Japan, and India's north-eastern parts. With its good mechanical performance, low specific mass, lustre, absorbance and resistance to bacteria,

ramie fibre is a promising reinforcement among cellulosic fibres [31, 32]. The search of extant literature shows that development of green composites using ramie fabric has not been explored much [33–36].

The present study explores the effect of one bath alkaline/silane treatment on the properties of ramie/PLA composites. In the first step, ramie fabric was treated with silane and alkali (i.e. sodium hydroxide and ammonium hydroxide), followed by investigating the effect of treatment on the mechanical, morphological properties of ramie fabric. In the second part, PLA composites with untreated and treated ramie fabrics were prepared using compression moulding technique followed by evaluation of mechanical performance and thermomechanical analysis.

2. Materials And Methods

Polylactic acid pellets (4043D) with 6% D-lactide and 94% L-lactide, were purchased from NatureWorks Co. Ltd. Coimbatore, India. Sodium hydroxide and ammonia solutions (25 wt. % NH_3) were procured Merck Chemicals, India. Vinyl trimethoxy silane, used as a coupling agent, was purchased from TCI Chemicals, India. The plain-woven ramie fabric used in this study, having fabric sett of 16 cm^{-1} in both warp and weft directions, was woven on a CCI sample weaving loom. The ramie yarn's linear density was 80 tex (g km^{-1}), and the areal density of the woven fabric was 285 g m^{-2} . Figure 1 shows SEM images of ramie yarn and fabric.

2.1 Ramie fabric treatment

For the hydrophobic treatment of ramie fabric, two different types of alkali, i.e. sodium hydroxide (NaOH) and ammonia were used as hydrolysing agents for silane. Before modification, ramie fabric was washed with ethanol for 30 min and dried at $60 \text{ }^\circ\text{C}$ for 30 min. The silane concentration used for the treatment of ramie fabric was 10% on weight of fabric with material to liquor ratio of 1:30. A solution containing vinyl trimethoxy silane in ethanol/water solvent mixture (80/20 v/v) was stirred at $40 \text{ }^\circ\text{C}$ for 30 min, followed by sodium hydroxide ammonia with stirring for next 30 min. In case of treatment with sodium hydroxide, 1M solution was prepared in deionised water, and 1 ml of this solution was added in the 100 ml of solution containing silane.

On the other hand, for hydrolysis with ammonia, 10 ml of as received ammonia was used in 100 ml silane solution in ethanol/water. The fabric samples were dipped into this solution for 12 h, followed by drying at $80 \text{ }^\circ\text{C}$ for 1.5 h. The schematic of silane treatment is shown in Fig. 2. In this study, neat ramie fabric, ramie fabric treated with silane hydrolysed with ammonia and sodium hydroxide are coded as NR, HRSA and HRSS, respectively.

2.2 Preparation of ramie/PLA composites

For manufacturing of ramie/PLA composites, the ramie fabric was placed between two neat PLA films followed by compression moulding. For film preparation, PLA pellets were dried at $60 \text{ }^\circ\text{C}$ for 12 h in a

vacuum oven. A pre-weighted amount of PLA pellets was then placed inside the mould, followed by placement of the mould between two solid stainless-steel plates. The thickness of the stainless-steel mould was 0.2 mm. After that, the stainless-steel plates were placed inside compression moulding machine (LabTech LP-S-30) for preheating at 180°C for 2 minutes followed by pressing at 80 bar pressure for 3 minutes and drying in an ambient atmosphere. The thickness of all the films was 200 ± 20 μm . Figure 3 shows the schematic of the manufacturing process of PLA films.

For manufacturing of ramie/PLA composites, the ramie fabric was placed between two neat PLA films. The samples were then preheated for 10 s at 170°C, followed by pressing at an optimum pressure of 10 bar for 2 min. Use of higher pressure than this resulted in shearing of warp and weft yarns. The fibre volume fraction was kept at 40 ± 2 % for all ramie/PLA composites. Table 1 shows the description of the sample codes used for composites in this study.

Table 1
Sample codes for composite samples

Sample code	Description
NP	Neat PLA film
NR_Com	Neat ramie/PLA composite
HRSA_Com	Ramie/PLA composite having silane hydrolysed with ammonia
HRSS_Com	Ramie/PLA composite having silane hydrolysed with sodium hydroxide

2.3 Testing and characterisation

2.3.1 Morphology characterisation

Surface morphology of ramie/PLA composites, before and after silane treatment, was examined by Zeiss EVO 50 scanning electron microscopy (SEM) at 10 kV operating voltage. SEM also analysed the cross-sections of fractured composite samples after tensile testing. All the samples were dried in a vacuum oven and coated with 5 nm thick gold coating before SEM characterisation.

2.3.2 Elemental dispersive X-ray (EDX)

Elemental dispersive X-ray (EDX) was used to identify elemental composition of neat and silane treated ramie fabrics. Zeiss EVO 50 scanning electron microscope operating at 10 kV was used for this study.

2.3.3 Contact angle Measurement

To confirm the hydrophobicity of ramie fabric, static contact angle measurement was performed on KRUSS drop shape analyser (DSA100). The static water contact angle was measured by placing a droplet of distilled water (2 μL) onto the fabric surface using a syringe. The angle was measured at five different positions of fabric, and the average value was reported.

2.3.4 Fourier transform infrared spectroscopy (FTIR)

Chemical modification of ramie fabric by silane was confirmed by FTIR analysis. The spectra were collected from 4000 to 400 cm^{-1} wavenumber using a Nicolet 20SXB FTIR spectrometer (Thermo Fisher Scientific Inc., U.S.A.) with 64 scans for each sample in attenuated total reflectance (ATR) mode. To eliminate the effect of moisture, samples were dried at 40 °C before testing.

2.3.5 Tensile testing

The tensile testing of ramie fabric was done as per ASTM 5035 whereas ramie-PLA composites were tested as per ASTM D3039 using a universal tensile tester (Tinius Olsen H5KS). Samples with a gauge length of 100 mm and 25 mm wide were tested at a crosshead speed of 10 mm/min. Five specimens were tested for each sample of the fabric, and four samples were tested for composites, and then the average was calculated.

2.3.6 Izod impact testing

Notch impact strength of the composites was evaluated according to ASTM D256 on Tinius Olsen IT 504 plastic impact tester with 7.6 J impact energy. Rectangular specimen having dimensions 64 mm × 13 mm (length × width) were tested. The thickness of all the samples was 3 ± 0.1 mm. A notch was created by cutting the specimen to a depth of 3 mm through the width towards the sample's centre. The angle of the notch was 45° at the tip of the notch. The specimen was mounted on clamp from one end with a notched side facing the striking edge.

2.3.7 Dynamic Mechanical Analysis

Dynamic mechanical analysis (DMA) of ramie/PLA composites was performed to study the dynamic mechanical properties as a function of temperature. The testing was carried out on DMA Q850, TA instruments, in three-point bending mode at a constant frequency of 1 Hz and 30 to 110 °C temperature range at a rate of 2 °C/min. A rectangular-shaped specimen, having 32 mm × 13 mm × 3 mm (length × width × thickness) dimensions, was used. The clamp with 15 mm span length was used for testing composites.

3. Results And Discussions

3.1 Characterisation of silane modified ramie fabric

After the silane treatment of ramie fabric with sodium hydroxide and ammonia as a catalyst, the samples were tested for hydrophobicity by measuring the contact angle using drop shape analyser. Before and after silane treatment, the surface morphology of ramie fabric was analysed by scanning electron micrographs shown in Fig. 4.

As shown in Fig. 4, neat ramie fibres have a clean and smooth surface. After the silane treatment, a uniform coating of silane, with small silica particles, is visible on the fibre surface. The surface of treated fibres also displays small cracks and increased roughness. Figure 5 shows the static water contact angle

(CA) of the silane treated ramie fabrics. The contact angles of 128° and 118° indicate that the silane treated fabrics have become hydrophobic.

This can be attributed to the configuration of silane molecules at the fibres' surface, which is supposed to bend and orient its non-polar head (-CH₂) towards the surface. Simultaneously, its -OH group form strong hydrogen bonding with the hydroxyl groups of cellulose. The vinyl group (CH = CH) on the surface of ramie fabric is confirmed by FTIR peak present at 1600 cm⁻¹.

The FTIR spectra of neat and silane treated ramie fabrics are shown in Fig. 6. The wavenumber region from 500 to 4000 cm⁻¹ was studied to confirm any chemical linkage between the silane and ramie fibre. For untreated ramie, the spectra at 2900 cm⁻¹ belong to the vibrations of C-H stretching from -CH₂ group of cellulose and hemicellulose [25, 37]. Similarly, the peaks ranging from 3000 cm⁻¹ to 3500 cm⁻¹ show hydroxyl group presence in cellulose. After silane treatment of ramie fibre, a new absorption band appears at 760 cm⁻¹, representing the vibrations of the Si-O-Cellulose and Si-C bonds linked to the hydroxyl groups of the fibre surface [38, 39]. It is also noticeable from the FTIR that the peak intensity decreases between bands from 1200 cm⁻¹ to 900 cm⁻¹ after treatment with silane using sodium hydroxide as a catalyst during the treatment. This suggests that sodium hydroxide had also removed non-cellulosic content present on the surface of the ramie fibres. A similar finding has also been reported by other researchers [40]

To further confirm the presence of silane, elemental analysis of neat and treated ramie fabrics was conducted. Figure 7 illustrates the EDX spectra of neat and treated ramie fabrics. Table 5 shows the concentration of carbon, oxygen, silica and sodium in ramie fabric before and after silane treatment. Presence of silica is established in silane treated samples (HRSA and HRSS). Besides, ramie fabric treated with silane and sodium hydroxide also shows the presence of sodium.

Table 2
Elemental analysis of ramie fabrics before and after silane treatment

Element	NR		HRSA		HRSS	
	Normalised wt. (%)	Atom (%)	Normalised wt. (%)	Atom (%)	Normalised wt. (%)	Atom (%)
Carbon (C)	38	45	39	50	34	43
Oxygen (O)	62	55	41	39	50	48
Silica (Si)	-	-	20	11	13	7
Sodium (Na)	-	-	-	-	3	2

Neat ramie fabric (NR), ramie fabric treated with silane hydrolyse using ammonia (HRSA) and sodium hydroxide (HRSS)

3.2 Tensile properties of ramie fabrics

Tensile strength and elongation at break of ramie fabrics before and after silane treatment is shown in Fig. 8. Neat ramie fabric shows tensile strength of 5.8 cN tex^{-1} and elongation at break of 20.5%. However, silane treated ramie fabrics display decreased tensile strength with a slight increase in elongation at break. This change is more prominent in case of sodium hydroxide, and silane treated ramie fabric. The decrease in tensile strength is probably due to ramie's additional delignification resulting in itching of fibre surface. The presence of OH^- and Na^+ ions in the silane solution causes slight removal of pectin hemicelluloses, waxes and lignin, which has a detrimental effect on ramie fabric [41].

One-way ANOVA was used to determine whether there is a significant difference in the means of tensile strength of ramie fabric before and after silane treatment. Besides, Tukey's test, which is a single-step multiple comparison statistical test, was used to determine whether the tensile strength of ramie fabrics after silane treatment with sodium hydroxide or ammonia differ significantly from each other. Tables 3 and 4 show the analysis of variance (ANOVA) and Tukey's test.

Neat ramie fabric (NR), ramie fabric treated with silane hydrolyse using ammonia (HRSA) and sodium hydroxide (HRSS)

Table 3
ANOVA of tensile strength of ramie fabric by silane treatment

	DF	SS	MS	F value	P value
Between the treatment	2	1.64	0.82	9.9	0.0029
Within the group	12	0.99	0.08		
Total	14	2.64			

DF- Degree of freedom, SS- Sum of squares, MS- Mean square, F value- Empirical *F* ratio (MS between groups/MS within groups), If $P \leq 0.05$ there is a significant difference between the mean values of the samples

Table 4
Tukey's test for the comparison between tensile strength of ramie fabrics

	Mean diff.	q value	Probability	Significance level	Significance
NR HRSA	0.14	1.1	0.726	0.05	Insignificant
NR HRSS	0.76	5.9	0.003	0.05	Significant
HRSA HRSS	0.62	4.8	0.013	0.05	Significant
*q- parameter calculated for each pair of means being compared.					

It is evident from the ANOVA results that the loss in tensile strength is significant after silane treatment as the *P*-value (0.0029) is lower than 0.05. On the other hand, Tukey's test reveals that silane treatment with

ammonia does not significantly affect the tensile properties of ramie fabric. In contrast, it is significant in case of silane treatment with sodium hydroxide.

3.3 Tensile properties of ramie/PLA composites

Table 5 shows the ANOVA results for the tensile strength of the three ramie/PLA composites. From the P -value (6.0571×10^{-5}); it can be inferred that ramie/PLA composites' strength improves significantly after silane treatment of ramie fabric.

Table 5
ANOVA of tensile strength of ramie/PLA composites

	DF	SS	MS	F value	P-value
Between the composites	2	44.14	22.07	34.48	6.0571×10^{-5}
Within the group	9	5.77	0.64		
Total	11	49.91			

3.4 SEM analysis of Tensile fractured samples

SEM images of the broken tensile samples of neat and silane treated ramie/ PLA composites are shown in Fig. 10. Neat ramie/PLA composite shows ramie fibres' debonding from matrix, suggesting a poor interfacial adhesion between fibres and PLA. Also, ramie yarns in weft direction are not sufficiently adhered to PLA matrix, and their debonding from matrix can be identified. Orue et al. [18] also reported for sisal/PLA composites that the fibres are debonding from matrix results from poor interfacial properties.

In silane treated ramie/PLA composites, the ramie fibres seem intact with the PLA matrix in both cases, i.e. with sodium hydroxide and ammonia. The fibre breakage is more prominent than the fibre pull-out, unlike the neat ramie/PLA composites. Oushabi et al.[39] also reported that the alkali and silane treatment of date palm fibre improves the interfacial strength of palm fibres and epoxy composites.

3.5 Impact strength of ramie/PLA composites

Impact strength of neat PLA and ramie/PLA composites is shown in Fig. 11. Neat PLA film shows very low impact strength, i.e., 30.4 J m^{-1} . It is a well-known fact that neat PLA polymer exhibits a brittle nature with very low impact strength [6, 44, 45]. The addition of ramie fabric as reinforcement improved the impact strength of PLA drastically from 30.4 to 194.5 J m^{-1} .

This improvement in the impact strength of neat ramie/PLA composite can be attributed to higher elongation at break of the ramie fabric (20.5%). Also, ramie fibres which act as reinforcement help in better stress transfer during the impact loading and the presence of the ramie fabric hinder the crack propagation after crack initiation thus resulting in improvement in impact performance [32, 42]. Similar improvements in impact strength after reinforcing polymer matrices with high elongation fibres have been reported by other researchers also [46, 47]. After silane treatment with ammonia, the impact strength

of ramie/PLA composites was improved by 13% (from 194.5 J m^{-1} to 220.5 J m^{-1}). However, composite containing ramie fabric having silane treatment with sodium hydroxide shows only 3% improvement in impact strength. This additional improvement in the impact strength, after silane treatment, can be attributed to the improved adhesion between hydrophobic fibre and matrix [30, 47].

3.6 Dynamic mechanical analysis of ramie/PLA composites

The storage modulus and damping factor ($\tan \delta$) of ramie/PLA composites, evaluated in the three-point bending mode, is shown in Fig. 12. It can be seen that the storage moduli of silane treated ramie fabric reinforced composites are higher than that of neat ramie/PLA composite. This implies better elastic behaviour of composites reinforced with silane treated fabrics. Over the range of temperatures under investigation, the silane and sodium hydroxide treated ramie fabric reinforced composite shows the highest storage modulus. The storage modulus decreases with the increase in temperature, and a steep fall is observed around 56°C for all the ramie/PLA composites. This drop can be attributed to the transition of neat PLA polymer from glassy to rubbery stage [48, 49]. At this point of transition, silane and sodium hydroxide treated fabric reinforced composite (HRSS_Com) shows the highest storage modulus of 2.5 GPa followed by silane and ammonia treated fabric reinforced composite (HRSA_Com) with 2.1 GPa and neat fabric composite (NR_Com) with 1.5 GPa. Better adhesion between matrix and hydrophobic ramie fibre, obtained after silane treatment, is the most plausible reason for improving the storage modulus of ramie/PLA composites. At the testing temperatures beyond 90°C , all the composites show an increase in storage modulus, which might be due to cold crystallisation of PLA [48, 50].

Change in the loss factor ($\tan \delta$) of ramie/PLA composites as a function of temperature is shown in Fig. 12b. The composite having neat ramie fabric as reinforcement exhibits a higher $\tan \delta$ value as compared to those of composites reinforced with silane treated fabrics. The higher value of $\tan \delta$ in neat composite can be attributed to efficient energy dissipation due to higher friction values at the poor interface between neat ramie and PLA matrix. Since the $\tan \delta$ peak value is related to fibre matrix adhesion, lower $\tan \delta$ peak values of silane treated composites, correspond to better adhesion and compatibility between silane treated ramie and PLA matrix [16].

4. Conclusions

In this study, the mechanical and thermo-mechanical performance of ramie/PLA biocomposites was explored as a function of fibre surface treatment. Static water contact angle confirmed that the fabric surface had been modified to hydrophobic from being hydrophilic after treatment with silane. FTIR and EDX of the treated fabric further confirmed the surface modification of the fabric. Though the tensile strength of fabric declined after silane treatment, especially with sodium hydroxide, the tensile strength of composites reinforced with silane treated fabrics was 10–12% higher than that of composite reinforced with neat fabric. Also, DMA analysis showed that silane ramie/PLA composites have higher storage modulus at the onset of transition temperature. The results imply that treatment of silane improves the

fibre-matrix interface and thereby the stress transfer from matrix to fibre enhances; as a result, tensile, impact and dynamic mechanical properties improve.

Declarations

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Conflict of Interests

The authors declare that they have no conflict of interest.

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Figures

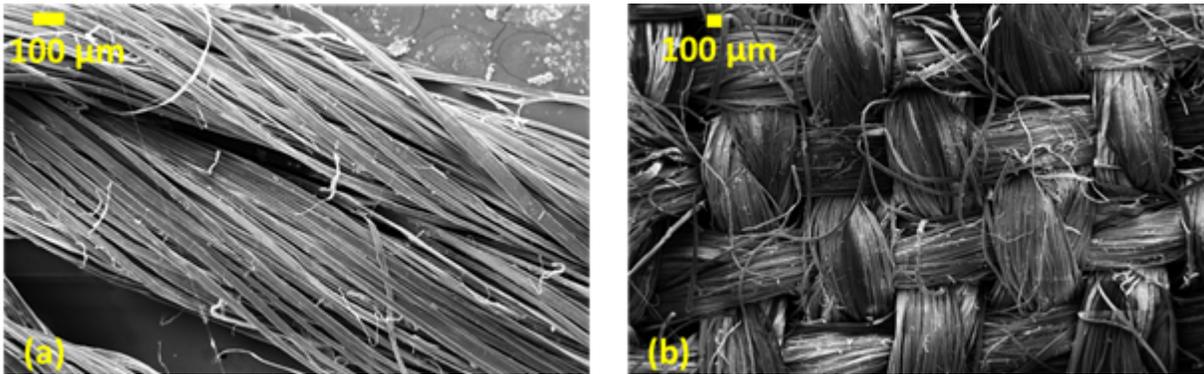


Figure 1

SEM images of ramie (a) yarn and (b) fabric

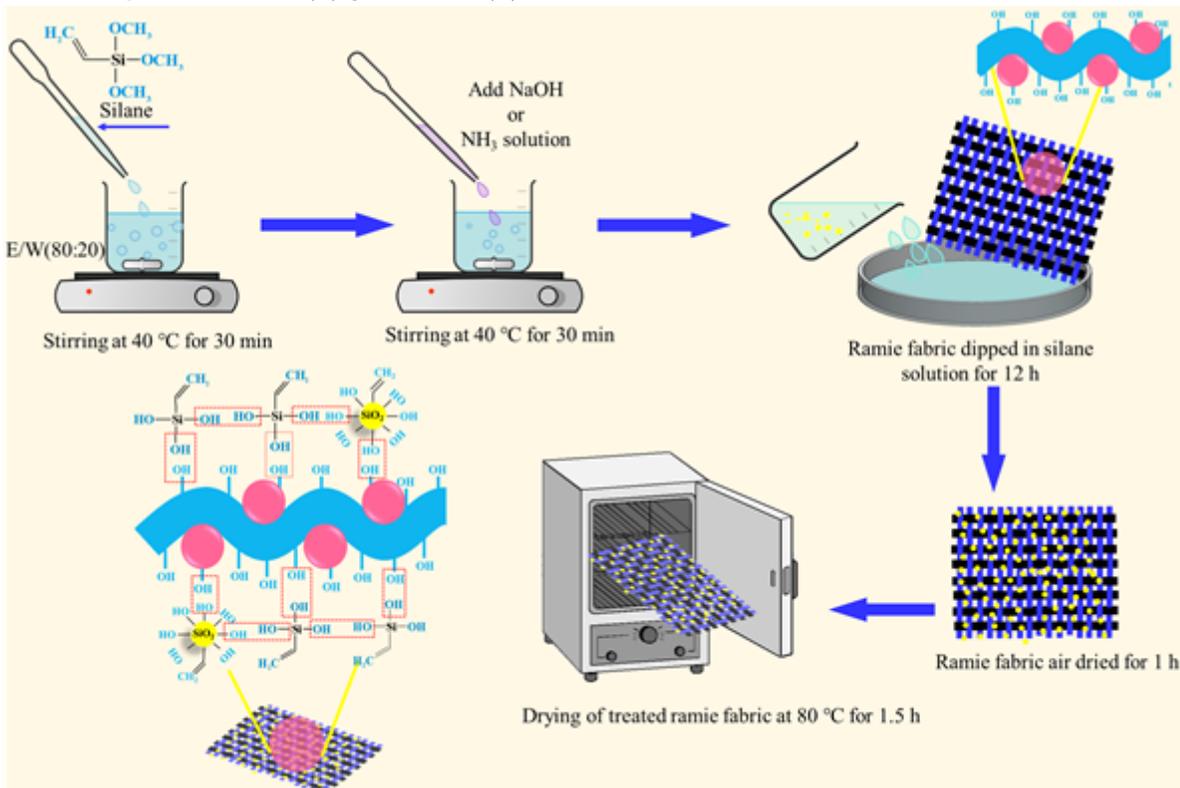


Figure 2

Schematic representation of ramie fabric treatment with silane

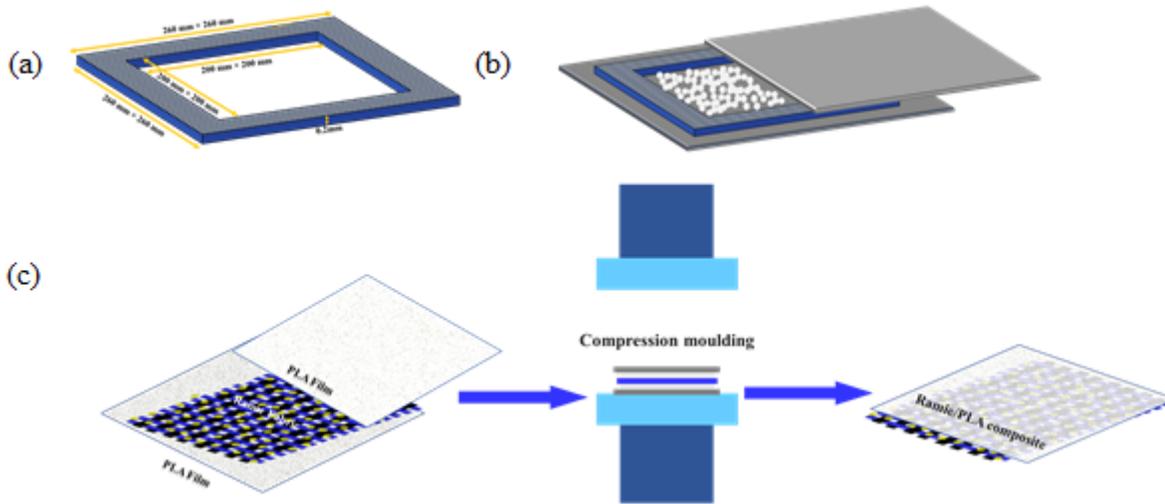


Figure 3

Schematic view of (a) mould used and (b) PLA film preparation (c) ramie/PLA composite preparation by compression moulding

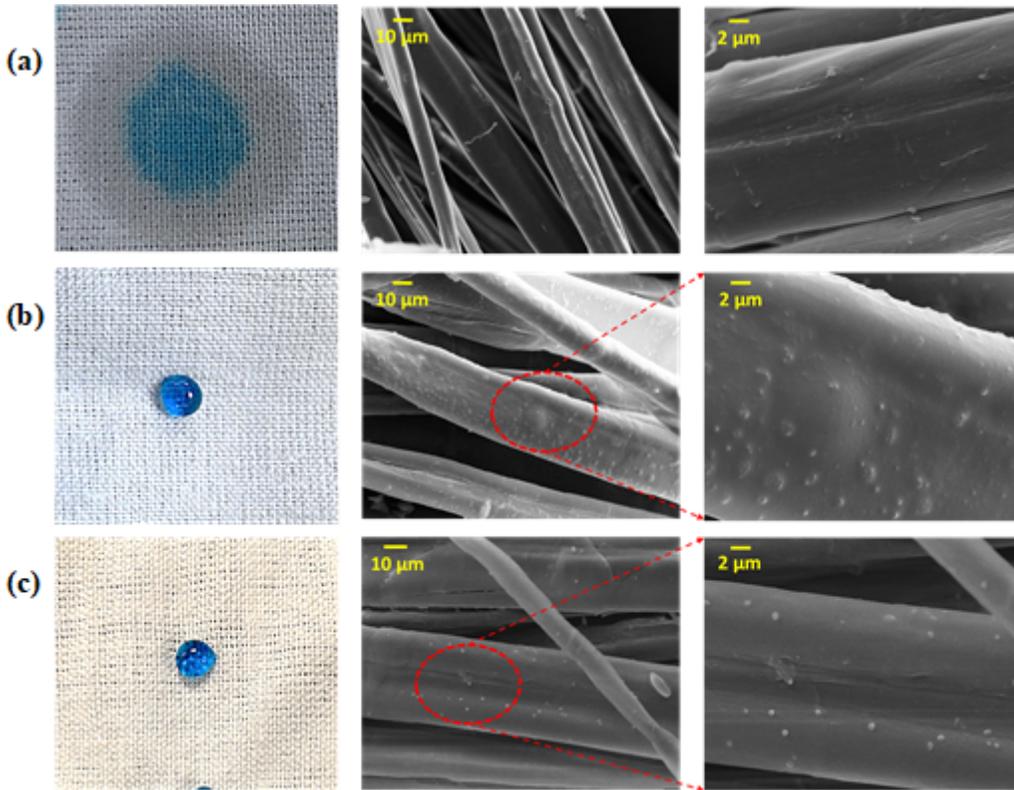


Figure 4

SEM images of ramie fabric (a) before and after treatment with silane using (b) ammonia and (c) sodium hydroxide solution

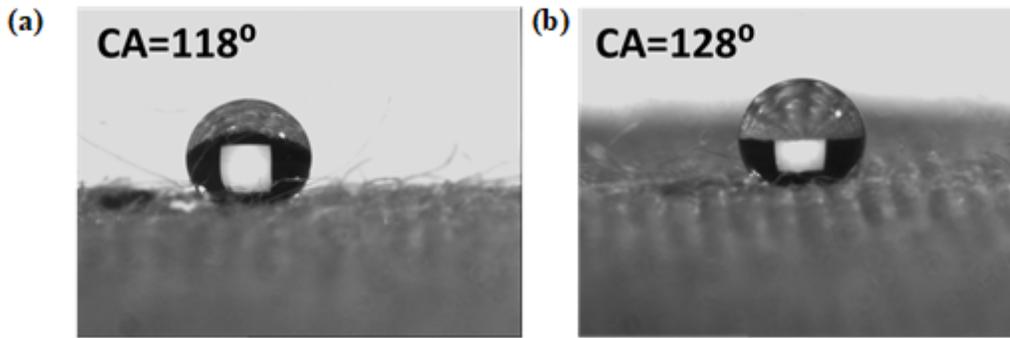


Figure 5

Static water contact angles after silane treatment of ramie fabric with (a) ammonia and (b) sodium hydroxide

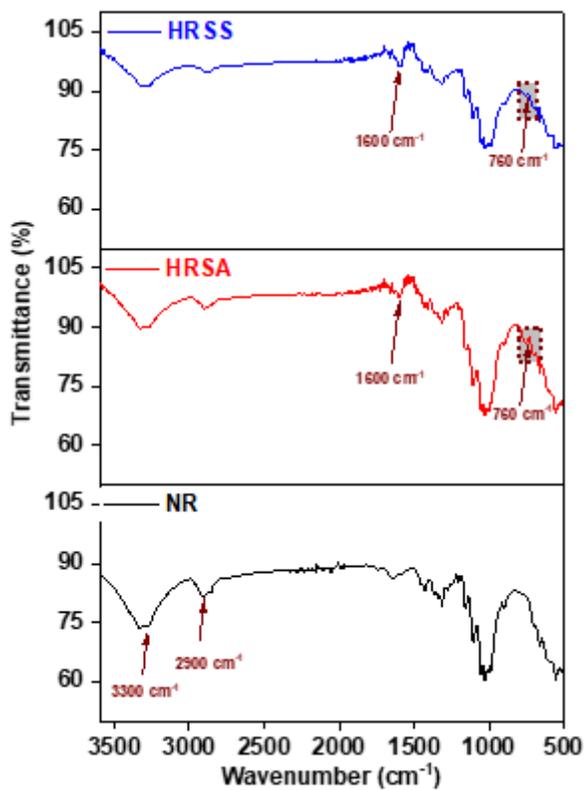


Figure 6

FTIR spectra of ramie fabric (a) before and after treatment with silane using (b) ammonia and (c) sodium hydroxide

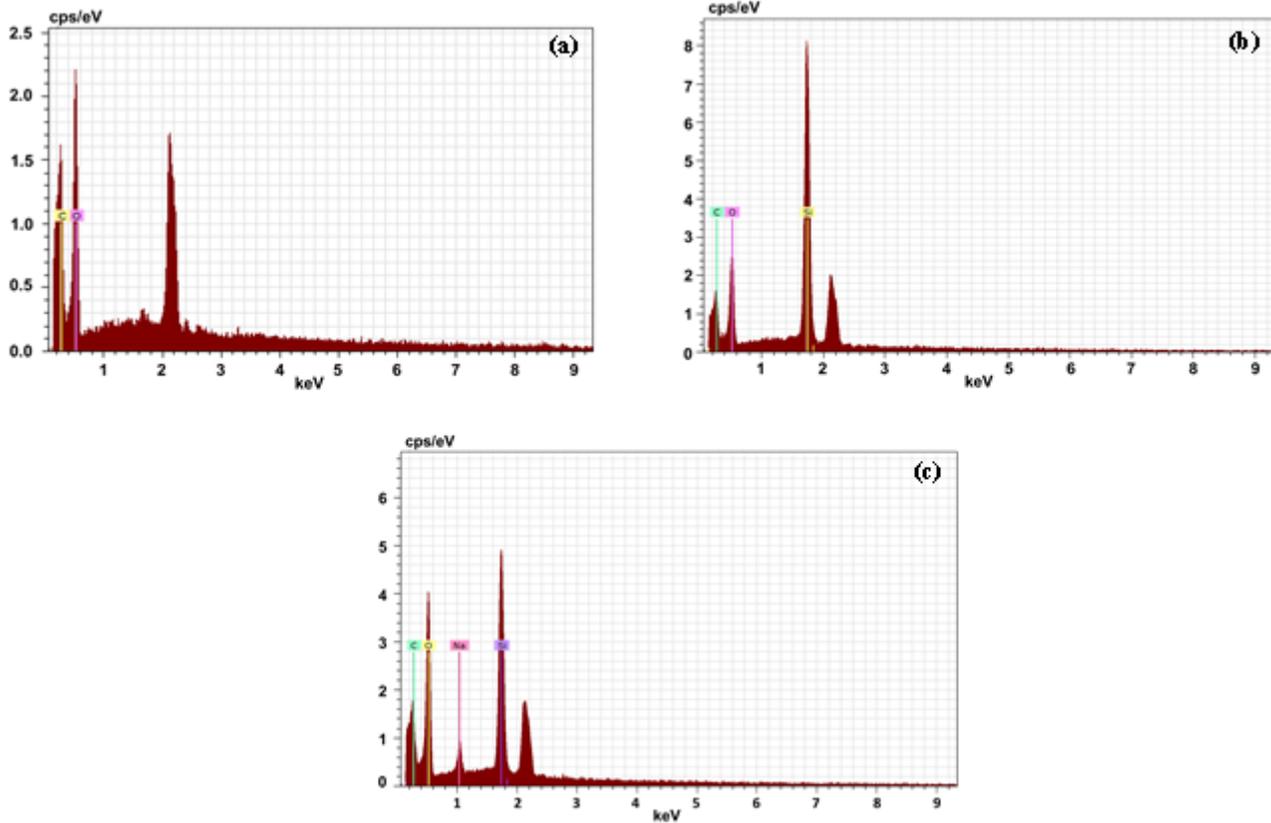


Figure 7

EDX spectra of ramie fabrics (a) untreated and treated with silane hydrolyse using (b) ammonia and (c) sodium hydroxide

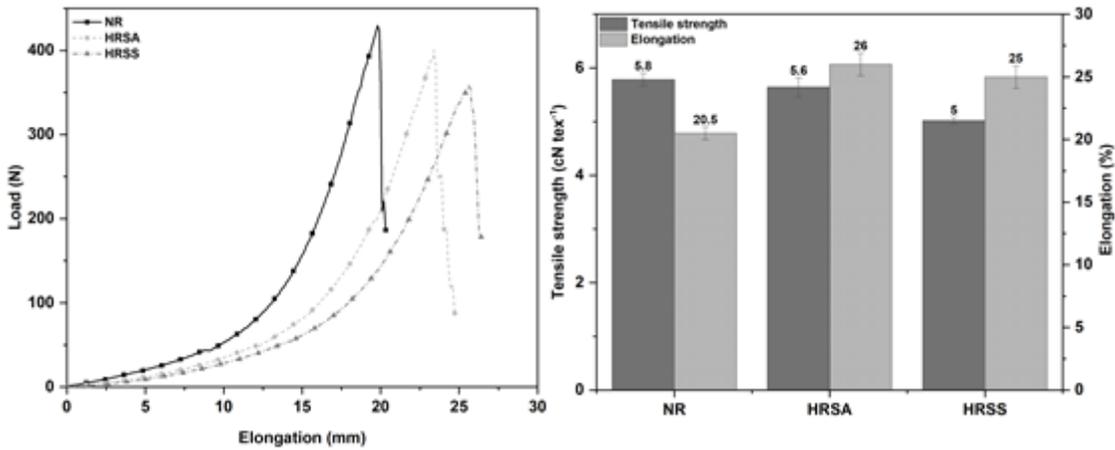


Figure 8

Tensile properties of neat and silane treated ramie fabrics

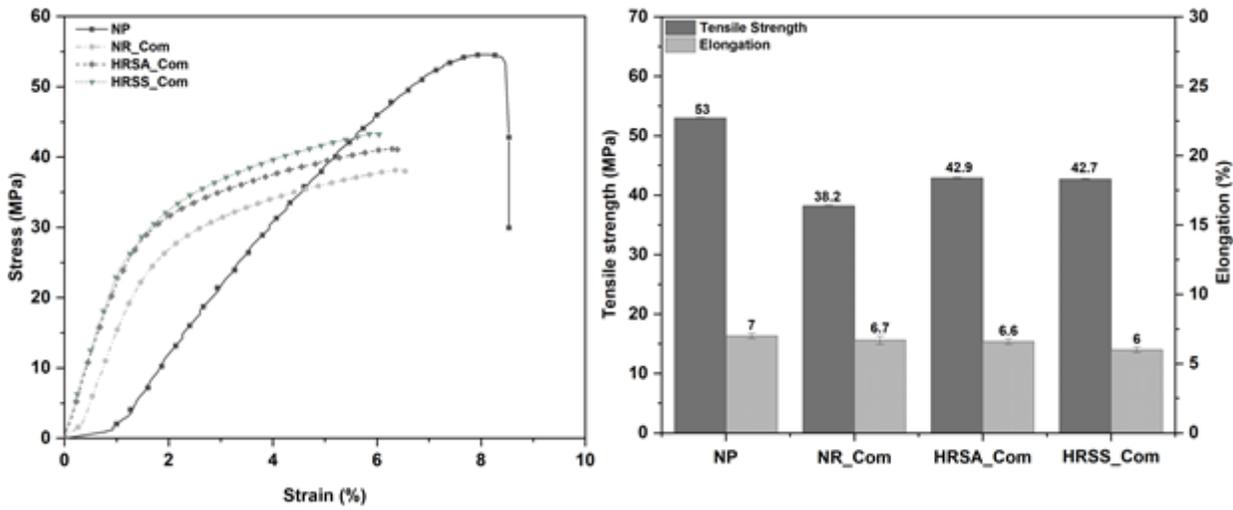


Figure 9

Tensile properties of PLA and ramie/PLA composites PLA (NP), ramie fabric treated with silane hydrolyse using ammonia (HRSA_Com) and sodium hydroxide (HRSS_Com)

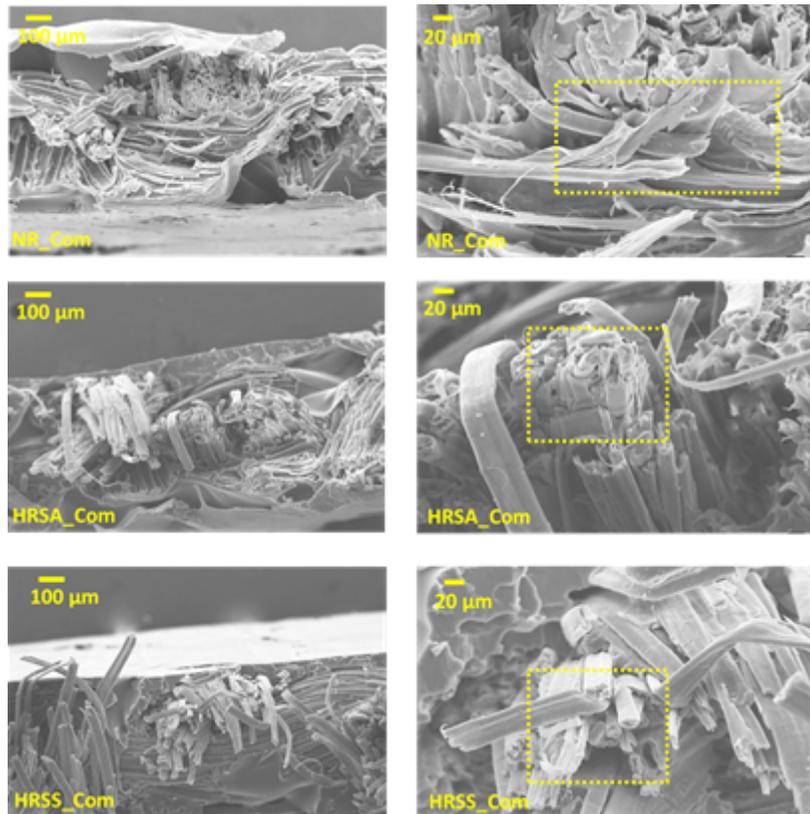


Figure 10

SEM images of tensile broken ramie/PLA composites Neat ramie (NP_Com), ramie fabric treated with silane hydrolyse using ammonia (HRSA_Com) and sodium hydroxide (HRSS_Com)

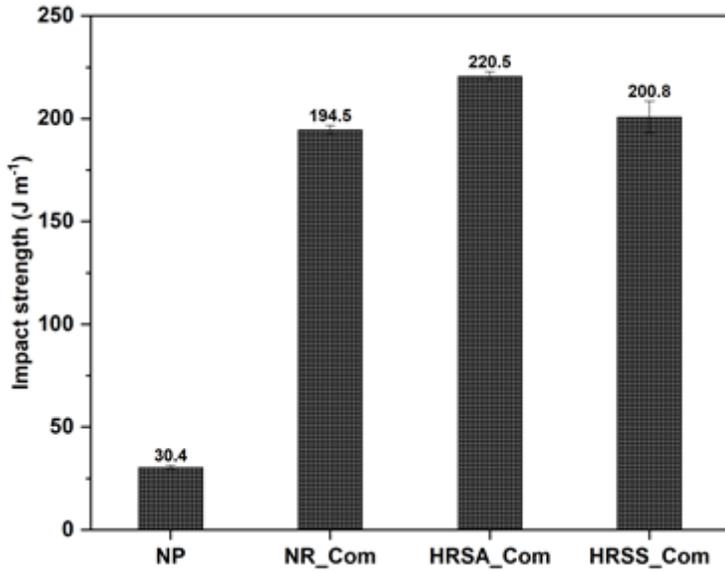


Figure 11

Impact strength of PLA and ramie/PLA composites Neat ramie (NP_Com), ramie fabric treated with silane hydrolyse using ammonia (HRSA_Com) and sodium hydroxide (HRSS_Com)

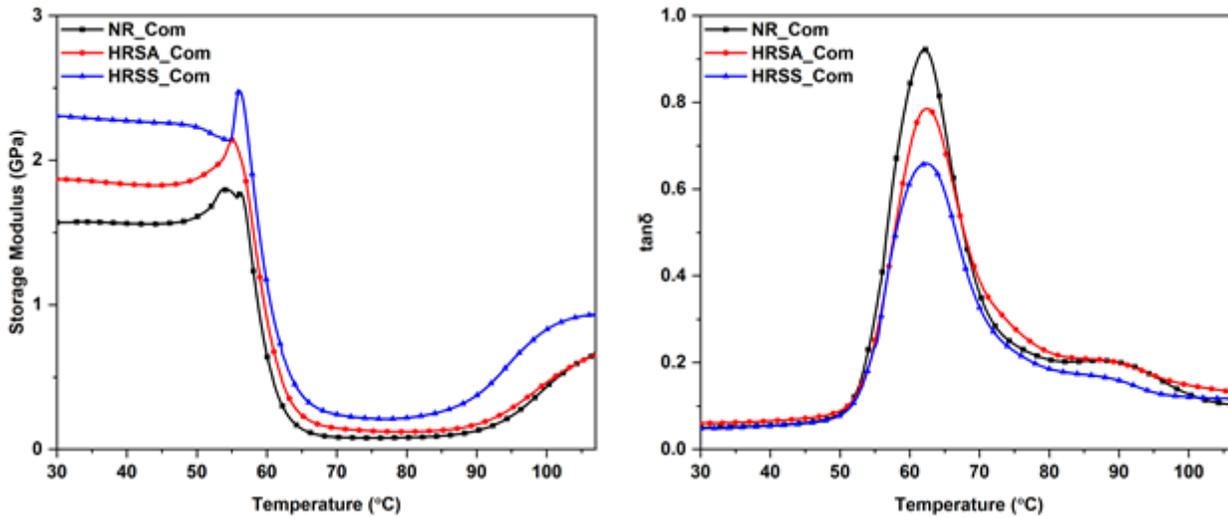


Figure 12

DMA of ramie/PLA composites (a) storage modulus and (b) tanδ Neat ramie (NP_Com), ramie fabric treated with silane hydrolyse using ammonia (HRSA_Com) and sodium hydroxide (HRSS_Com)