Characterization of mechanical properties of jute/PLA composites containing nano SiO₂ modified by coupling agents

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Abstract Although jute fiber-reinforced PLA composites show strong application prospects, their low mechanical properties limit their applications to some extent. In this paper, nano-SiO₂ particles as well as nano SiO₂ modified by coupling agents which can efficiently improve the strength and toughness of composite materials are introduced into the PLA matrix. The bending, stretching and thermal properties of designed jute/PLA nonwoven composites were studied. The study shows that the nano-SiO₂ particles are beneficial to the interface performance between the PLA matrix and jute leading to improvement in the mechanical properties and thermal stability. Moreover, thermomechanical properties indicate that the addition of SiO₂ can improve the jute/PLA interfacial adhesion and increase the glass transition temperature of the material. Finally, toughening mechanism of nano-SiO₂ particles in the jute/PLA composite was analyzed.

Keywords Laminating composite materials · Jute non-woven · PLA · Biodegradable · Nano-SiO₂

Introduction

In recent years, thermoplastic composites are increasingly applied to the high-performance engineering field due to their low density, good recyclability, and high production efficiency (Faruk et al. 2012). However, environmental compatibility of these materials is still a huge challenge. In this case, fully biodegradable green composite materials provide a feasible solution. To prepare a completely biodegradable composite material, natural fiber is a desirable reinforcing material and biodegradable polymer can be selected as matrix material, such as jute/polylactic acid (PLA) composite materials. PLA, a polymer material, is produced from renewable agricultural raw materials. It has advantages such as high strength, high hardness, transparency and industrial production, and is one of the most promising biodegradable polymers (Qu et al. 2015). Among all biodegradable reinforced fibers, jute fiber has low cost, biodegradability and excellent mechanical properties, making it one of the most used plant fibers in green composites (Dong et al. 2014). There are wide possible applications for jute/PLA composite, and a lot of research has been proposed to investigate its mechanical properties (Bax and Mussig 2008; Mohammed et al. 2019; Nishino et al. 2003; Pan et al. 2007). However, PLA resin matrix lacks chemical bonds and functional groups that can react with jute. Therefore, the interface compatibility between jute fiber and PLA is poor, leading to weak mechanical properties of final composite. (Balla et al. 2014).
2019; Costa et al. 2012; He et al. 2019; Hossen et al. 2020; Pereira et al. 2019). At present, some physical and chemical methods have been proposed, including fiber treatment technologies such as acylation, alkali treatment, etherification and isocyanate treatment, as well as the use of coupling agents to improve the interfacial bonding property of jute/PLA composites (Dong et al. 2020; Fang et al. 2020a, b; Huda et al. 2007; Kumar et al. 2010; Kakroodi et al. 2012). Nano particle is also a feasible option to toughen the polymer matrix and improve the mechanical properties of fiber-reinforced composites.

In recent years, nano particles have been extensively applied to prepared composites, which has significantly improved the mechanical properties of composites materials (Gauvin et al. 2015; Jumahat et al. 2010, 2012a, b). Among the nanoparticles used as reinforcing materials, many researchers doped nano-silica (nano-SiO$_2$) to improve the mechanical properties of fiber-reinforced composite materials (Jumahat et al. 2010, 2012a, b, 2015; Luo et al. 2018) adopted technology-resin film infusion (RFI) technology to prepare nano-SiO$_2$ modified carbon fiber reinforced composite materials. When the content of nano-SiO$_2$ is 4 wt%, the toughening and strengthening effect is the best. The tensile strength and flexural strength increased to 595.69 MPa and 703.76 MPa, respectively, which were 86.30 % and 126.98 % higher than that of intact sample without SiO$_2$. Hashim et al. (2019) studied the effect of SiO$_2$ nanoparticles as a reinforcing filler on the tensile response of basalt fiber reinforced polymer (BFRP) composites. It was found that the addition of SiO$_2$ nanoparticles showed significant improvement in tensile modulus with 6 %, 14 % and 19 % for 5 wt%, 15 wt% and 25 wt% nano-SiO$_2$ content, respectively. Reddy et al. (2010) used traditional melt blending technology to prepare low nanoparticle loaded polymer composites with improved mechanical properties. The results of tensile tests indicated that the addition of SiO$_2$ nanoparticles showed significant improvement in elastic modulus and toughness (from 0.36 to 0.54 GPa, and 19.06 to 21.05 MJ/m$^3$, respectively). Filling nano-SiO$_2$ into thermoplastic matrix can combine the rigidity of nano-SiO$_2$ with the toughness of thermoplastic matrix, which makes ultimate composites have comprehensive mechanical performance Hashim et al. 2019; Luo et al. 2018; Park et al. 2020).

In this study, nano-SiO$_2$ particles were adopted and dispersed into the PLA matrix aiming to improve the mechanical properties of jute/PLA composite. Moreover, considering the dispersibility, the nano-SiO$_2$ was first modified with different silane coupling agents, then combined into PLA-based composite films and finally incorporated in final laminated composites. This use of sandwich-like lamination structure layer can mix PLA and jute as evenly as possible. Therefore, the effect of silane coupling agents on the mechanical properties of as-prepared composites via hot-pressing technology was comprehensively analyzed.

### Materials and methods

#### Materials

PLA (4032D; 1.24 g/cm$^3$) was supplied by Nature Works, USA; Jute fibers (1.45 g/cm$^3$) were purchased from Shandong Jiangke Linyi Co., Ltd; Nano silica (SiO$_2$, 99.5 %, 50±5 nm) was provided by Suzhou Great Medical Technology Co., Ltd; Silane coupling agent (KH550, KH560, KH570) chemicals were provided by Jiangsu Argon Krypton Xenon Material Technology Co., Ltd. KH550 (NH$_2$CH$_2$CH$_2$CH$_2$-Si(OC$_2$H$_5$)$_3$) belongs to aminosilane, KH560 (CH$_2$-OCHCH$_2$O(CH$_2$)$_3$Si(OCH$_3$)$_3$) belongs to epoxy silane, KH570 (CH$_3$CCH$_2$COO(CH$_2$)$_3$Si(OCH$_3$)$_3$) belongs to methacryloxylpropyltrimethoxysilane.

#### Preparation of modified SiO$_2$

The absolute ethyl alcohol and deionized water were first mixed with a mass ratio of 9:1, and 5 g of SiO$_2$ was added into 100 mL of mixture. The SiO$_2$ solution was then sonicated in an ultrasonic cleaner for 1 h. The coupling agent, e.g. KH550, with a volume fraction of 5 %, was added to the above SiO$_2$ solution and adjusted to the pH of 4 with oxalic acid. The above mixed solution was magnetically stirred for 3 h at 60 °C for reaction. Finally, it was centrifuged and then washed with absolute ethanol solution for 3 times. The obtained precipitate was dried in an oven at 60 °C for 4 h to obtain modified SiO$_2$ powders, named as KH550-SiO$_2$, KH560-SiO$_2$ and KH570-SiO$_2$ respectively. The scheme of preparation process of modified SiO$_2$ is illustrated in Fig. 1.
Preparation of composite SiO$_2$-PLA films

3 g of PLA raw material was dissolved in dichloromethane, stirred magnetically for 1.5 h at room temperature; different mass fractions of modified SiO$_2$ (0.5, 1, 2, 4 and 8 wt%) were mixed into dichloromethane and ultrasonicated for 40 min. These two solutions were mixed and magnetically stirred for 2 h, followed by ultrasonication for 1 h at 35 °C. Then, the solution was poured into a glass plate and placed in a fume hood at room temperature to make the methylene chloride solvent completely volatilize. Finally, the modified SiO$_2$-PLA film was peeled from the mold and placed in a vacuum oven at a temperature of 45 °C for 3 h, as shown in Fig. 2.

Preparation of jute non-woven

The preparation process of jute non-woven is shown in Fig. 3. The aspect ratio of jute fiber is about 314:1. First, the fluffy jute fibers was combed, opened and mixed through a SSL-II coarse-gauge carding machine (Qingdao Kailida Textie Machinery Make Co., Ltd; China) to make the fibers looser and more uniform. Then the loose jute fibers were sent to the blender for further fine opening. The fine opening and carding process make the jute fibers finally become a fluffy and uniform fiber web. Then the fiber web was feed into the cross-laying machine for cross lapping. The fiber web obtained by cross-lapping has higher quality and better uniformity. In order to obtain a certain strength of non-woven fabrics, the four-layer jute fiber net were finally reinforced with a needle punch. The final thickness of the jute nonwoven is 0.51±0.04 mm, and the surface density is 200±2 g/m$^2$.

Preparation of composite material

To remove all moisture, SiO$_2$-PLA films and jute nonwoven were first dried in a vacuum oven at 80 °C for 6 h before hot pressing. The laminated composite material was processed through a compression mold.
using the film stacking method, in which two jute pads were arranged between three PLA films in parallel, as demonstrated in Fig. 4. The entire assembly was then placed in a steel mold controlled under different time and temperature. The laminated material is compacted for 0.5 h under the conditions of a temperature of 180 °C and a pressure of 1 MPa, and then is naturally cooled in the HG-3621 vulcanization machine (Jiangsu Hengguang Precision Instrument Co., Ltd; China) for 8 h. After 8 h, the sample was taken out of the laminating mold with both the width and length of 150 mm and the thickness of 2 mm in which the mass ratio of PLA to jute was 10:3. The samples are numbered according to the type of coupling agent and concentration. For example, 550-0.5, in which 550 represents the silane coupling agent of KH550, the sample untreated with the coupling agent is directly represented by SiO₂, and 0.5 represents 0.5 wt% of the modified SiO₂ mass fraction in SiO₂-PLA film.

Fourier-transform infrared spectroscopy test (FTIR)

FTIR was carried out by Fourier Transform Infrared Spectrometer (5700, Thermo Nicolet Corporation, USA). After drying, the specimen and the dried potassium bromide powder was put into a quartz dish to be fully ground, so that the sample was mixed evenly. After about 10 s of pressing, the sample was tested at the scanning wave number of 400 ~ 4000 cm⁻¹, resolution of 4 cm⁻¹ and scanning number of 32 times.

Fig. 3 The preparation process of jute non-woven fabric

Fig. 4 The preparation process of composite material
Laser particle size analyzer test (DLS)

The SiO$_2$ particles before and after the modification were prepared into a solution and then sonicated, and the supernatant is collected by standing for a few minutes. The particle size was detected by laser particle size analyzer (LS-909, A Malvern Panalytical Brand, China). Each sample was tested for 20 times, and the Z-average, peak size, peak intensity and polydispersity index (PDI) value were obtained. The Z-average value represents the average value of the particle size in the sample. When the number of particles at this size in the sample is the largest, this size is the peak. The peak intensity is the ratio of the number of particles in this size to the total number of particles. PDI refers to the polydispersity index, which is the ratio of the standard deviation of the particle size distribution to the average value. It is generally believed that the smaller the PDI value, the more concentrated the particle size distribution and the higher the credibility.

Fracture SEM analysis of composites

The particle morphology of the specimen was observed by a field emission scanning electron microscope (S-4800, Hitachi, Japan). The samples were scanned and observed by firing gun under the acceleration voltage of 3.0 kV after 90 s gold sprayed by ion sputtering.

Flexural test

The flexural test was carried out on an electronic universal material tester (Instron 336, USA) with a three-point bending fixture. According to the GBT1449-2005 standard, the sample was cut into a size of 50 mm×25 mm with a cutting machine and measured at a speed of 2 mm/min.

Tensile properties

The tensile test was carried out using the universal tensile testing machine (Instron 3365, USA) in accordance with the ASTM D3039 standard. The composite samples were cut into 125 mm×12.5 mm at a tensile speed of 2 mm/min.

Dynamic mechanical thermal analysis (DMTA)

Dynamic thermomechanical analyses were performed using a thermomechanical analyzer (SDTQ800, TA Instruments, USA) in dual cantilever mode. The sample was cut into rectangular splines of 51 mm × 10 mm and tested in air atmosphere under heating from room temperature to 180 °C at a heating rate of 3 °C/min.

Results and discussions

The composition and physical property of modified SiO$_2$.

The FTIR is adopted to verify the graft polymerization of silane coupling agents on SiO$_2$ surface. Figure 5 shows the infrared spectra of KH550, KH560 and KH570 as well as corresponding silane coupling agent grafted SiO$_2$. It can be seen from Fig. 5b that the infrared spectrum of the SiO$_2$ before and after modification has a large absorption peak near 1100 cm$^{-1}$, which is the antisymmetric absorption peak of Si-O-Si bond, and near 800 cm$^{-1}$ is the symmetrical contraction vibration of the Si-O-Si bond. In Fig. 5, the infrared spectrum of KH550-SiO$_2$ showed two bending vibration peaks of primary amine at 1650–1560 cm$^{-1}$, indicating that -NH$_2$ in KH550 has successfully grafted nano-SiO$_2$. KH550 shows characteristic peaks of –CH$_2$– at 2940 and 1640 cm$^{-1}$, while KH550-SiO$_2$ also has a shoulder peak at 2940 and 1460 cm$^{-1}$, which further indicates that KH550 has successfully modified nano-SiO$_2$ particles. Compared with FTIR spectrum of SiO$_2$, in the spectrum modified by KH560-SiO$_2$, the stretching vibration absorption peak of methyl appears near 2878 cm$^{-1}$ which is related to characteristic methyl peak of KH560, indicating that KH560 silane coupling agent has been successfully grafted to the
second Si–O surface (He et al. 2019). In the infrared spectrum of KH570 and KH570-SiO₂, there is a C=O stretching vibration absorption peak on the carbonyl group at 1718 cm⁻¹, which indicates that KH570 has been successfully grafted onto nano-SiO₂.

The particle size of original and modified SiO₂ is shown in Table 1. The surface morphology of original and modified SiO₂ is shown in Fig. 6. Due to the large specific surface area, the nano-SiO₂ particles are easy to agglomerate together, so that the total surface area is reduced, resulting in a lower surface energy. It can be clearly seen that the unmodified particles are larger than modified particles, and KH560 has the best modification effect on SiO₂ particles. The unmodified nano-SiO₂ has a higher PDI value, relating to a larger, un-uniform particle size and serious aggregation. The particle size and PDI of the modified nano-SiO₂ powder are reduced, indicating that the nano-SiO₂ modified by the silane coupling agent can effectively prevent its agglomeration and achieve the modification purpose. On the one hand, the hydroxyl groups on the particle surfaces are replaced by organic functional groups, reducing the number of active silanol groups, thereby reducing the tendency of nanoparticles to agglomerate. On the other hand, the grafted long carbon chain increases the distance between particles and the steric hindrance of the hydroxysilyl polycondensation reaction on the particle surface, which increases the difficulty of effective collisions and more conducive to the dispersion of nanoparticles.

**Bending property**

The experiment was repeated at least 5 times for each sample. Figure 7a and b shows the bending strength and modulus of pure jute/PLA fibers composites involving SiO₂ and modified SiO₂ nanoparticles with different mass fractions. It can be seen that the bending modulus of jute/PLA fibers composites is relatively low. With incorporation of SiO₂, the bending strength and modulus of the composites is more or less improved. Compared with pure jute/PLA composite

**Table 1** The specification of prepared nano SiO₂

| Sample        | Z-Average (nm) | Peak Size (nm) | Peak Intensity (%) | PDI   |
|---------------|----------------|----------------|--------------------|-------|
| SiO₂          | 300            | 220.8          | 65.2               | 0.343 |
| KH550-SiO₂    | 107.7          | 143.3          | 69.3               | 0.287 |
| KH560-SiO₂    | 67.6           | 92.7           | 100                | 0.210 |
| KH570-SiO₂    | 91             | 136.6          | 100                | 0.229 |

Fig. 5 (a) FTIR spectra of KH550, KH560 and KH570; (b) FTIR spectra of SiO₂, KH550-SiO₂, KH560-SiO₂ and KH570-SiO₂ nanoparticle
material, there is no significant improvement in the bending performance of the sample SiO$_2$-4. However, after adding the nano-SiO$_2$ particles modified by the coupling agents, the bending strength and modulus of 550-4 increased to 29.95 MPa and 1.25 GPa respectively, which were 149.5 and 76.8 % higher than those of the jute/PLA composite, and increased by 137.4 and 72.0 % compared with the unmodified SiO$_2$ jute/PLA composite. The bending strength and modulus of 560-4 were increased to 36 MPa and 2.17 GPa respectively, and the bending strength and modulus of 570-4 were 34 MPa and 2.01 GPa. Compared with the jute/PLA fibers composites, the bending strength of 560-0.5, 560-1, 560-2, 560-4 and 560-8 composites increased by 2.8, 96.6, 74.7, 74.2 and 68.3 % respectively. It is also found from Fig. 7a and b that as the mass fraction of different types of added SiO$_2$ increases, the change trend of material bending strength and modulus is basically same.

The similar phenomena can be also observed in the bending strain and bending break work of jute/PLA composites. The bending break work was calculated by integrating the tensile stress-strain curves. As shown in Fig. 7b, the increase of SiO$_2$ improves the bending strain and bending break work of jute/PLA composites.

In short, the bending performance of the sample increases with the increase of the SiO$_2$ mass fraction, peaks at about 1 wt%, and then decreases. The SiO$_2$ sample modified with KH560 has the best bending strength and modulus. It is mainly due to the fact that the modification realizes the interface combination through the coupling agent, and then strengthens the effect of stress transmission (Yang et al. 2009; Sanivada et al. 2020; Fang et al. 2020a, b; Li et al. 2013). Sample 560-1 has best bending performance resulting from the excellent dispersibility and uniform particle size as illustrated in Table 1.

The fracture morphology

In order to illustrate the toughening mechanism, the fracture morphology of the reinforced PLA-based composite after the tensile test is shown in Fig. 8. The tensile fracture surface of the jute/PLA composite, illustrated in Fig. 8a, shows large amounts of fiber extraction leading to a lower mechanical resistance to some extent. This is consistent with comparatively large elongation ratio of the composite material which also indicates poor interfacial cohesiveness. Figure 8b shows the SiO$_2$ particles modified by KH560 are evenly distributed in PLA matrix. At this time, delamination occurs in the tensile section, and the
bending strength is weakened. With the increase of SiO\(_2\), there are more holes appeared which are prone to cause fracture. Nano-SiO\(_2\) particles induce local plastic deformation of the PLA matrix, showing a rougher fracture surface. At the stress concentration point, SiO\(_2\) particles produce a large number of small cracks, and has a small amount of fibers extraction, as shown in the Fig. 8d. There are a large number of cracks and fiber extraction at the break of sample 560-4, generating large amount of energy consumption when it breaks. Due to the poor dispersibility of SiO\(_2\), the modified SiO\(_2\) re-aggregated at 8 % by mass fraction. As the mass fraction of SiO\(_2\) increases, there are more contact points between SiO\(_2\) and jute, which reduces the adhesion between jute and PLA, as shown in Fig. 8f.

Stretching property

The tensile property of the jute/PLA composite and the nano-SiO\(_2\) jute/PLA composites is shown in Fig. 9. The tensile strength of 560-0.5 increased from 1.47 MPa in the jute/PLA composites to 11.03 MPa. The elastic modulus of 560-0.5 is as high as 2.01 GPa, which is 614.2 % higher than the 0.28 GPa of the jute/PLA composites. The tensile strength of 560-1 is 8 MPa and the elastic modulus of 560-1 is 0.81 GPa. The tensile strength of 560-2 is 7.59 MPa and the elastic modulus is 2.32 GPa. The tensile strength of 560-4 is 11.92 MPa and the elastic modulus is 2.57 GPa. The tensile strength of 560-8 is 5.02 MPa and the
The elastic modulus is 1.20 GPa. The tensile break work of SiO$_2$-4, 550-4, 560-4, and 570-4 is increased by 138.0, 389.7, 609.5, 417.0 % compared with the jute/PLA fibers composites.

It is concluded from Fig. 9 that the cooperation of nano-SiO$_2$ can effectively improve the tensile tolerance of composite materials. With the increase of nano-SiO$_2$ content, the change trend of the tensile properties of the composite material before and after modification is basically the same. And when the SiO$_2$ mass fraction is same, the sample modified by KH560 has the best tensile strength. This can be attributed to the small particle size and uniform shape of SiO$_2$ modified by KH560, which is consistent with the DLS data.

When preparing jute/PLA laminates, SiO$_2$ can be more evenly dispersed in the matrix, thereby enhancing the effective load transfer between jute and PLA, improving the tensile properties of the composite material. The silane coupling agent can serve as a bridge to improve the compatibility of the interface between SiO$_2$ and jute/PLA, and then strengthening the stress transmission. Figure 10 shows the interaction between the SiO$_2$ particles and the interface of the jute/PLA composite before and after the modification.

The silane coupling agent can react with the silicon hydroxyl group on the surface of SiO$_2$ after being hydrolyzed. The degree of aggregation of modified-SiO$_2$ is reduced, exposing more binding sites that can interact with PLA. At the same time, the long-chain structure of the coupling agent will generate entanglement on the interface between jute fiber and PLA, which efficiently enhances the interface bonding performance, expedites interfacial stress transfer, and ultimately improves the mechanical properties of the composite material.

**Dynamic mechanical thermal analysis (DMTA)**

Figure 11 shows the dynamic storage modulus ($E'$), loss modulus ($E''$) and loss coefficient tanδ($E''/E'$)of jute/PLA composites with different contents of SiO$_2$. The Fig. 11a and b respectively shows the stored modulus values and corresponding temperatures of different samples at the beginning of chain segment movement. In the temperature range studied, the storage modulus of the jute/PLA composite modified by SiO$_2$ is higher than that of the untreated jute/PLA composite. In addition, different variables showed the
same change pattern. With the increase of SiO₂ content, the storage modulus of the modified jute/PLA composite material increases first and then decreases. The increase in storage modulus and corresponding temperature of chain segment starting to move indicates that the interface adhesion between jute and PLA has been improved, resulting in greater stress transfer between them (Porras and Maranon 2012). That is, the increase of the SiO₂ content can improve the interfacial adhesion until the concentration reaches 4 wt%. Because of the poor dispersibility, the effect of the coupling agent on SiO₂ modification is not obvious when the SiO₂ content is too high, and the jute/PLA interface adhesion begins to decrease.

The loss modulus represents the energy dissipated by the jute/PLA composite under stress (Laly et al. 2003; Doan et al. 2007). It is observed from Fig. 11c and d that the loss modulus value of the SiO₂-modified jute/PLA composite is much higher than that of the untreated jute/PLA composite. It is known that the maximum value of loss modulus corresponds to the glass transition temperature (Tg) of the composite material. The Tg of the untreated jute/PLA composite is around 57.3 °C. In contrast, the Tg of the SiO₂-modified jute/PLA composite material moved to the high temperature zone, reaching a maximum of about 74.2 °C.

Finally, the loss factor tanδ, which refers to the ratio of the loss modulus to the storage modulus, represents the damping energy of the material. The decrease of
the tanδ value indicates the fact that SiO2 improves the bonding strength between PLA and jute, and reduces the fluidity of PLA macromolecules in the composite material. Due to the improvement of the hydrophobicity, the interfacial adhesion is enhanced, and the fluidity of the polymer chains at the jute/PLA composite interface is reduced. From Fig. 11e, the composite without SiO2 shows a significantly high tanδ value among all prepared samples, indicating higher damping energy and poor interfacial interaction. The addition of SiO2 can effectively reduce the tanδ value and the KH560 modified composites has the lowest tanδ value, indicating the dispersibility of SiO2 modified by KH560 is best. Among all samples modified by KH560, jute/PLA composite with a SiO2 content of 4 % has the best interfacial bonding, as shown in Fig. 11e and f.

Comprehensively, the sample 560-4 has the best thermomechanical property. Figure 11g shows the comparison of DMTA between jute/PLA composite and sample 560-4. The glass transition temperature of sample 560-4 is 29.5 % higher than that of the jute/PLA composite, indicating that the experimental optimization has improved the bonding strength of the interface between PLA and jute. The storage modulus values of different samples decrease with increasing temperature. The tanδ value of the jute/PLA composite material increases with the increase of temperature when the mass fraction of SiO2 treated by KH560 was 4 wt%. Once beyond the maximum temperature at 69.2 °C, it shows an opposite trend in the rubber area.

Conclusions

The present research shows that the addition of modified-SiO2 improves the interface performance between PLA and jute and elevates the mechanical properties of the composite material. Meanwhile, the smaller and more uniform the particle size of SiO2, the better the mechanical properties of the composite material. Compared with jute/PLA composite, the flexural strength and flexural modulus of sample 560-4 increase by 150.3 % and 77.4 %, respectively, while the tensile strength and tensile modulus increase by 816.9 and 700.1 %, respectively. The excellent mechanical properties derive from the mechanical enhancement of the SiO2 itself as well as the improvement of the jute/PLA interface by the silane coupling agent. In addition, the fracture morphology of the composite material shows that the plastic deformation of the matrix caused by SiO2 are the main toughening mechanisms. The analysis of thermomechanical properties shows that the addition of SiO2 can improve the thermomechanical properties and glass transition temperature of composite materials.
Fig. 11 The DMTA of jute/PLA composite. (a) Storage modulus; (b) The temperature corresponding to storage modulus; (c) The maximum loss modulus; (d) The temperature corresponding to the maximum loss modulus; (e) The maximum tan δ; (f) The temperature corresponding to the maximum tan δ; (g) The comparison of DMTA between jute/PLA composite and sample 560–4.

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Declarations

Conflict of interest The authors declare that there 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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