

ESTIMATION OF THE DYNAMIC PROPERTIES OF EPOXY GLASS FABRIC COMPOSITES WITH NATURAL RUBBER PARTICLE INCLUSIONS

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ABSTRACT

Conventional materials are being replaced in the field of engineering by composite materials, due to their tailorable properties and high specific properties. These materials are extensively used in structural applications. Damping is one of the important properties of the materials used in structures, and needs to be enhanced in order to reduce structural vibrations. In the present work, the improvement of the material damping of glass fabric epoxy composites with particle rubber inclusions is studied. The effect of particle size on the damping and stiffness parameters at different frequencies and temperatures is studied experimentally. Considerable enhancement in damping without significant reduction in stiffness is observed at lower particle sizes. The damping property in both bending and shear modes is more with 0.254 mm rubber particle inclusions among the selected sizes. A lower reduction in stiffness is observed with the inclusion of lower particle sizes (0.254 mm and 0.09 mm) when compared with higher particle sizes. An ANN-based prediction model is developed to predict these properties for a given frequency/temperature and particle size. The predicted values are very close to the experimental values with an maximum error of 5%.

Keywords: Composites; damping enhancement; artificial neural networks.

INTRODUCTION

In the contemporary world, several conventional materials are being replaced by composites due to their several properties. Composites are finding application in many fields, from household articles to aircraft components (Ibrahim et al., 2012; Bachtiar et al., 2010; Adebisi et al., 2011; Saadatmanesh et al., 1994). In aircraft and other such applications, energy dissipation by mechanical damping is of considerable importance for reducing vibrations (Crandall, 1970). Damping in the structures is attained by either active methods or passive methods (Trindade et al., 2002). The use of sensors and actuators in active damping increases the system complexity and reduces the reliability. Passive damping is an inherent property of the system with less complexity and higher reliability (Trindade et al., 2002). The improvement in passive damping of structures has been achieved by various researchers through surface attachments (Hardinnawirda and Aisha, I. 2012; Mantena et al., 1991), co-cured viscoelastic layers (Rotz and Barrett, 1991) and fibre-coating techniques (Finegan and Gibson, 1997). Viscoelastic tapes were sandwiched between the base structure and a constrained layer for damping enhancement (Mantena et al., 1991). Though an improvement in damping is observed, the weight of the structure is increased due to the constrained layer. Rotz and Barrett

(1991) designed composites with required damping using co-cured viscoelastic layers. Delamination at the interface is a major drawback with co-cured layers (Finegan and Gibson, 1997). Though the toughness and damping are two distinct properties, both involve the energy release phenomenon. Rubber particles were included in polymers (Collyer, 1994) to improve fracture toughness, but studies on damping with particle rubber inclusions are limited. A composite sound absorber is fabricated using recycled rubber particles with good attenuation properties to dampen the sound (Hong et al., 2004). Enhancement of structural damping with natural rubber particle inclusions and the effect of their size on modal damping ratios were studied using vibration tests (Ravi Sankar et al., 2010; Jeffrey et al., 2011). Composites with polypropylene and silicon rubber with Wollastonite as the fibrous filler in different proportions was fabricated to study its effect on mechanical properties following to the addition of silicon rubber (Bhaskar and Sharief, 2012; Umar et al., 2012; Upinder et al., 2009). Also short glass fibre (SGF) reinforced poly propylene composite was toughened with styrene-ethylene butylene styrene (SEBS) elastomers (Tjong et al., 2002).

Though damping is enhanced through CLD, co-cured layers and fibre coating methods a considerable increase in weight, delaminations at interleaved co-cured layers, and significant reduction in stiffness are the drawbacks of each of the cases respectively. Work reporting an improvement in the toughness of polymers using particle elastomers and resin modifications is limited to studies on toughness alone, but very few on damping even though both involve the process of energy dissipation. Damping enhancement through the addition of rubber particles though effective, the studies are confined to structural damping, depends on the shape and size of the structures and boundary conditions (Ravi Sankar et al., 2010). It requires a huge quantum of experimentation to decide upon the optimal choice of particle size. Hence there is a need to characterise the material damping (loss factor, $\tan \delta$) and dynamic stiffness (storage modulus, E') which is an inherent property of the material. DMA is a tool to characterise these properties. $\tan \delta$ and E' are complimentary to each other, and an optimal decision to strike a break-even is crucial. In this context, the aid of Artificial Neural Networks (ANN) may be sought.

The application of ANN for the mapping of the system and obtaining various outputs in the field of composites has gained momentum (Bose and Liang, 1998; Sapuan and Mujtaba, 2010; Zhang and Friedrich, 2003). The use of ANN in predicting different parameters in composites is well demonstrated by various researchers. Pidaparti and Palakal (1993) were among the first to use ANN as a constitutive model for composites. ANN was used to predict the fatigue strength of composites (Aymerich and Serra, 1998; Lee et al., 1998). A Back Propagation Neural Network (BPNN) was used to predict the fatigue failure of a glass fibre/epoxy laminate with a range of fibre orientation angles under various loading conditions (Al-Assaf and EI Kadi, 2001; Mathur et al., 2007). The results obtained were comparable with other prediction methods. The error between the experimental and predicted results was found to be less than 5% in most cases. However, in some cases the error was up to 28%. ANN was applied to predict the mechanical and wear properties of short-fibre reinforced polyamide (PA) composites (Jiang et al., 2008). The predictions reported remarkable accuracy with the experimental results. Though BPNN is widely used, it suffers from major set-backs like local minima, poor convergence, etc. As an alternative, a Radial Basis Function (RBF) is used. A study of free vibration in symmetric composite plates based on a collocation by radial basis functions and pseudo spectral methods was presented and produced highly accurate results (Ferreira and Fasshauer, 2007). Both

BPNN and RBF techniques were used to study the impact from components and process conditions on the properties of Pb-Al composite materials (Zhu et al., 2010). The predicted values were compared with experimental data and the RBF results were claimed to be the best. From the above literature, it can be concluded that ANN can be effectively used in composite materials research. Though BPNN is widely used, it suffers from major limitations and RBF is proven to be a better choice.

In the present work, the damping related parameters $\tan \delta$ and E' of particle rubber included in an epoxy glass fabric composite are evaluated in flexure and shear modes at different frequencies and in flexure at different temperatures using DMA. The RBF network is used for the prediction of the dynamic characteristics ($\tan \delta$ and E') of the composites. The estimated dynamic properties are used for building two RBF models to predict $\tan \delta$ and E' under two different scenarios, viz. in three-point bending and in shear, at various frequencies and in three-point bending with a temperature sweep.

EXPERIMENTATION

Sample Fabrication

Glass fabric epoxy composites with and without rubber particle inclusions are fabricated as per the required standards for DMA testing. Glass fabric epoxy composites of size 300 mm × 180 mm × 4 mm (die dimensions) are fabricated with and without natural particle rubber inclusions using a hand layup technique, from which the samples for DMA testing are cut. Natural rubber particles are segregated into four different particle sizes: 0.9 mm, 0.45 mm, 0.254 mm and 0.09 mm. The segregated rubber particles of specific size are mechanically mixed in Lapox®12 epoxy resin followed by sonication for an hour in a sonicator for dispersing the particles uniformly in the resin. The weight of the particle rubber inclusions is 10% of the total weight of the composite (inclusions + resin + fibre). Before applying the rubber particle filled epoxy resin to the glass fibres, a hardener (Lapox® K6) is mixed in the proportion 1:0.1 by weight. The mixture is added to glass fabric mats. A PVA mould releasing agent is applied to the mould before the laying up process for the easy removal of the fabricated composite plates. Serrated rollers are used to compact the material against the mould and to remove entrapped air, if any. The plates in the die are processed in press at room temperature under a pressure of 200 Kpa for 24 hr and then removed. The edges of the produced composite plates are finished with emery paper. In all the specimens the nominal content of glass fibre in the composite is set at 40% by weight, and the remaining 60% is resin, which is evaluated by burn out tests as per the ASTM standard (ASTM D2584-08, 2008). From the fabricated plates, rectangular samples of size 60 mm × 10 mm × 4 mm for three-point bending and 10 mm × 10 mm × 4 mm for shear are cut for testing in DMA Q800.



Figure 1. DMA samples for three-point bending

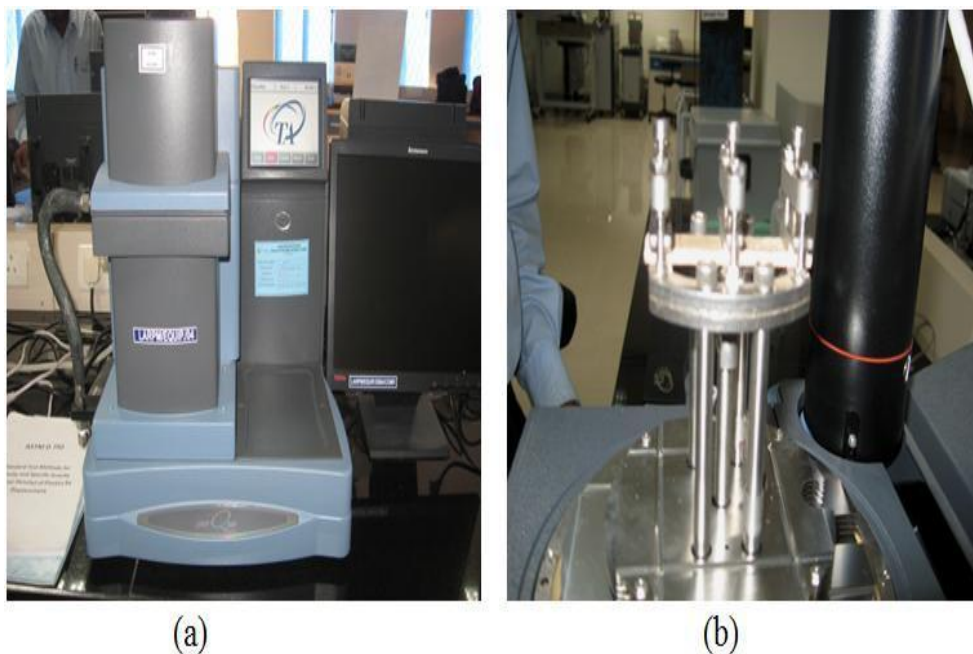


Figure 2. (a) DMA (b) specimen in DMA

Scanning Electron Microscopy

The properties of natural rubber particles included in composites strongly depend on the dispersion of the rubber particles in the matrix. To observe the dispersibility of natural

rubber particles in epoxy resin, cross-sections were examined by a Zeisis EVO MA15 scanning electron microscope (SEM) with an acceleration voltage of 10 KV. Samples are sputter coated with gold to make them conductive prior to SEM observations.

DMA Studies

The dynamic properties E' and $\text{Tan } \delta$ in three-point bending and in shear are evaluated with frequency sweep at room temperature and in three-point bending at 10 Hz with a temperature sweep. For temperature dependent properties, the samples are heated to 180°C in the case of the neat composite and up to 120°C in the case of rubber-containing composite at a heating rate of $1^{\circ}\text{C}/\text{min}$.

RESULTS AND DISCUSSION

SEM Studies

The morphology of the cross-section of natural rubber-filled epoxy glass fibre composites is examined using SEM in order to examine the distribution of rubber particles in the composite. Figure 3 shows SEM images of the cross-section of glass epoxy composite specimen with rubber particle inclusions. It is observed that the rubber particles are well distributed in the matrix. The uniform dispersion of the rubber particles lead to ascertaining the dynamic properties $\text{Tan } \delta$ and E' .

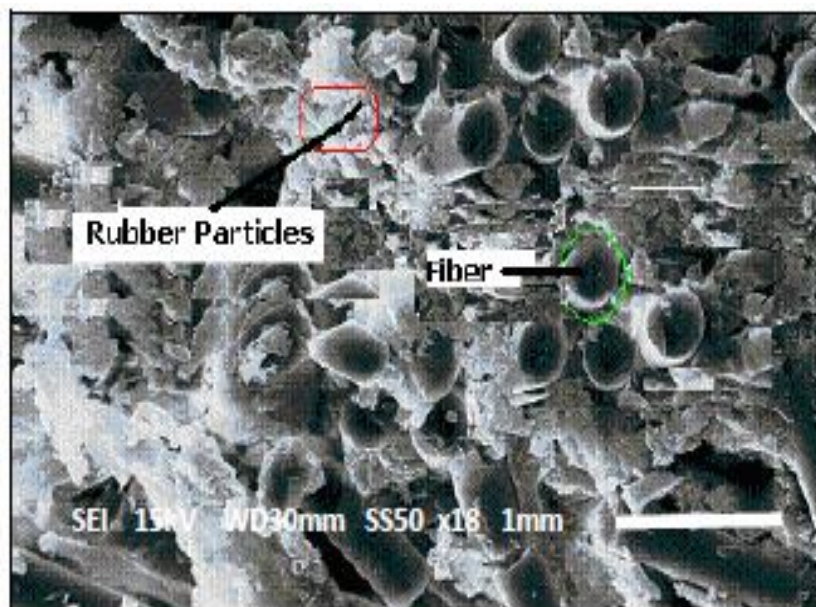


Figure 3. SEM micrograph of rubber-containing glass fabric epoxy composite.

DMA Studies

i) Frequency Sweep

Flexural loss factors (measure of damping) in the three-point bending of the glass epoxy composite with a frequency sweep in the range of 0–200 Hz at room temperature are

reported in Figure 4. $\tan \delta$ in bending is increased with a frequency up to 110 Hz and then decreased for all the particle sizes considered. A similar trend is observed in the case of the loss factor in shear. DMA results reported in Figure 5 represent the variations in $\tan \delta$ in shear with frequency for all particle sizes. $\tan \delta$ increases with frequency up to 100 Hz and then decreases for all particle sizes considered. At lower frequencies, the energy dissipation is less and hence a lower $\tan \delta$ is reported. The damping is directly proportional to the square of the amplitude, and at higher frequencies the amplitudes are lower (Rao, 2004). Hence $\tan \delta$ in both bending and shear modes increase up to a certain frequency and then decrease. An increment in $\tan \delta$ is observed in both bending and shear with the addition of natural rubber particles in the epoxy glass fabric composite. The viscoelastic natural rubber particles present at the interphase (a third phase at the interface of the fibre and matrix due to chemical reactions), producing a micro slip and generate damping leading to an increase in $\tan \delta$. Experimental results revealed that the loss factor decreased with the size of the natural rubber particle inclusions in bending and shear except for the sizes 0.254 mm and 0.0975 mm. A specific observation is that in both modes $\tan \delta$ is maximum for a particle size 0.254 mm among the selected particle sizes. For a fibre composite system, the total damping present in the system depends on the damping capacity of the fibres, matrix and interphase formed between matrix and fibre. The probability of the existence of smaller particles such as 0.0975 mm in the fibre matrix interphase is very low, and hence a lower damping is reported with 0.0975 mm compared with 0.254 mm. Similarly at higher rubber particle sizes the energy dissipation due to micro-shear yield mode of deformation is suppressed and decreases the damping (Charles, 1996). Hence, 0.254 mm rubber particle inclusions improved the damping of the composite among the selected particle sizes.

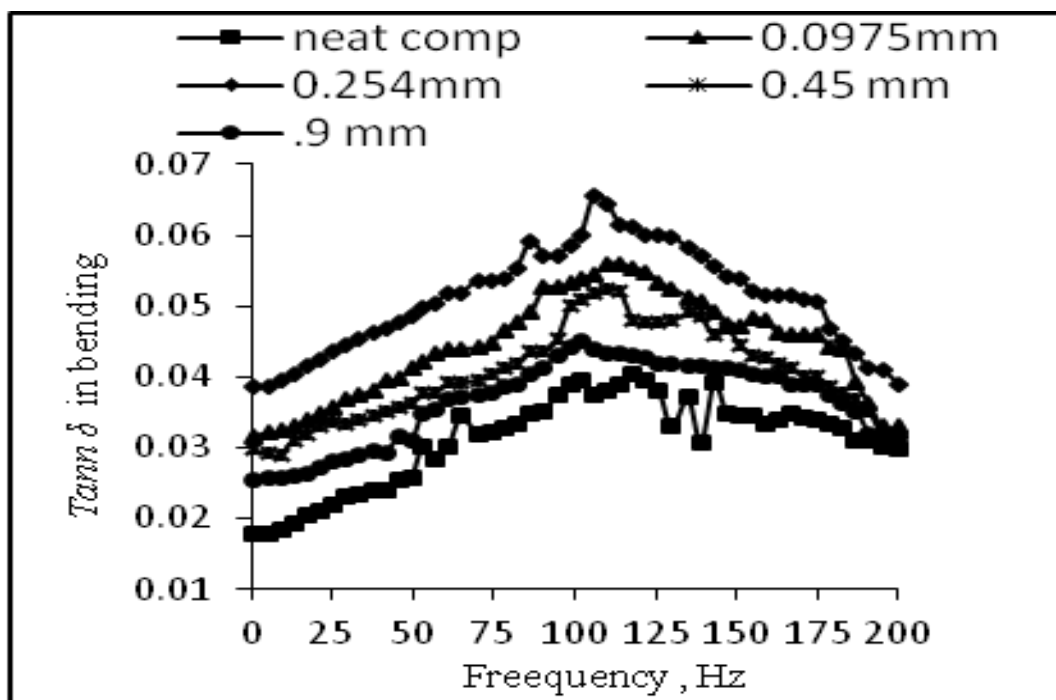


Figure 4. Variation in flexural loss factor in 3-point bending.

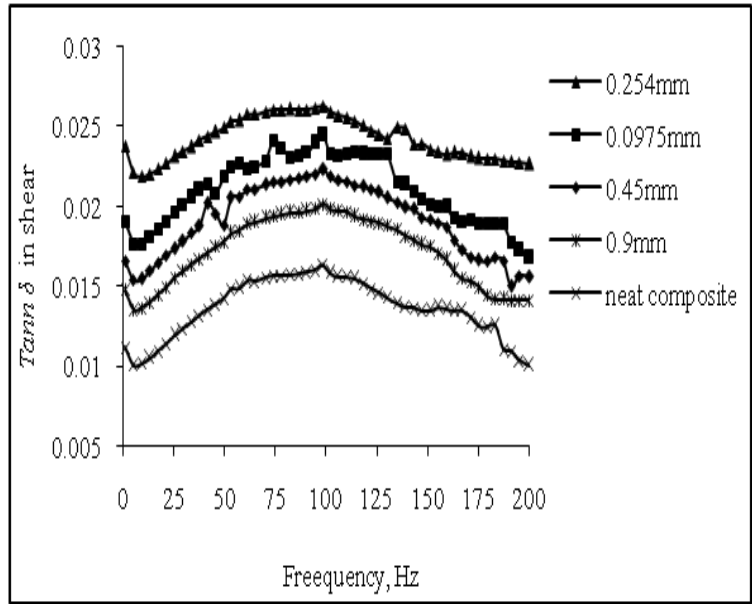


Figure 5. Variation in shear loss factor with frequency

Figure 6 shows the variation in E' in the flexural mode with frequency for all composite specimens. It is observed that the flexural storage modulus at all particle sizes is almost constant with frequency up to a range of 100 Hz to 110 Hz, and then increases slightly. The rubber particle inclusions in the glass epoxy composite reduce the flexural E' . The micro-slip between the rubber particles at the interphase layers is attributed to be the reason for this reduction in stiffness (Cho et al., 2006; Ravi Sankar et al., 2010). The reduction in flexural E' increased with the size of the rubber particle inclusions. For smaller particle inclusions, i.e. 0.0975 mm and 0.254 mm, the reduction is at about 10% to 15%, whereas at particle sizes of 0.45 mm and 0.9 mm it is about 30% to 40%. This is due to stress concentrations in larger particles due to abrupt changes in the material properties.

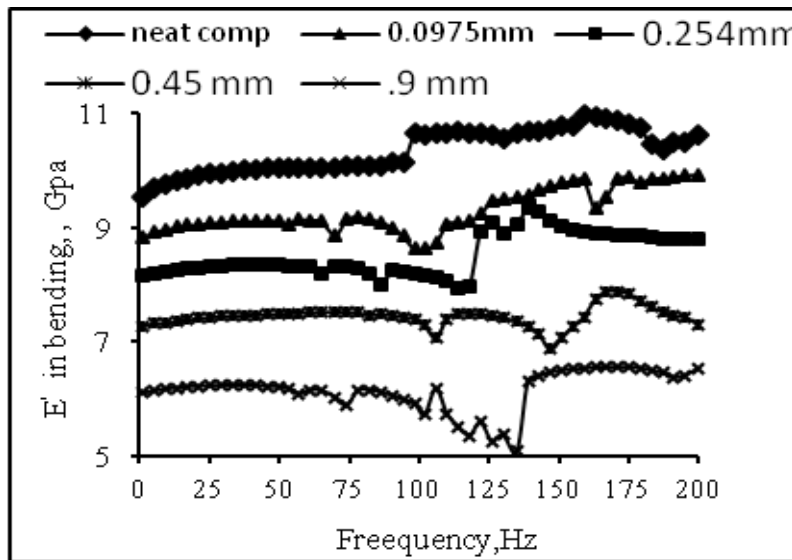


Figure 6. Variation in E' (bending) with frequency.

The experimental values presented in Figure 7 explain the effect of particle size on E' in shear with frequency. The E' in shear mode is almost constant with the frequency considered. As in the case of three-point bending, the rubber particle inclusions reduce the shear E' at all frequencies. The shear E' is reduced by 10% to 20% to that of the pure composite, for all the sizes of rubber particle inclusions. Among the selected particle sizes, E' in shear is reduced with an increase in the size of the inclusions. This may be due to the stress-raising tendency of larger particle sizes (Cho et al., 2006; Ravi Sankar et al., 2010).

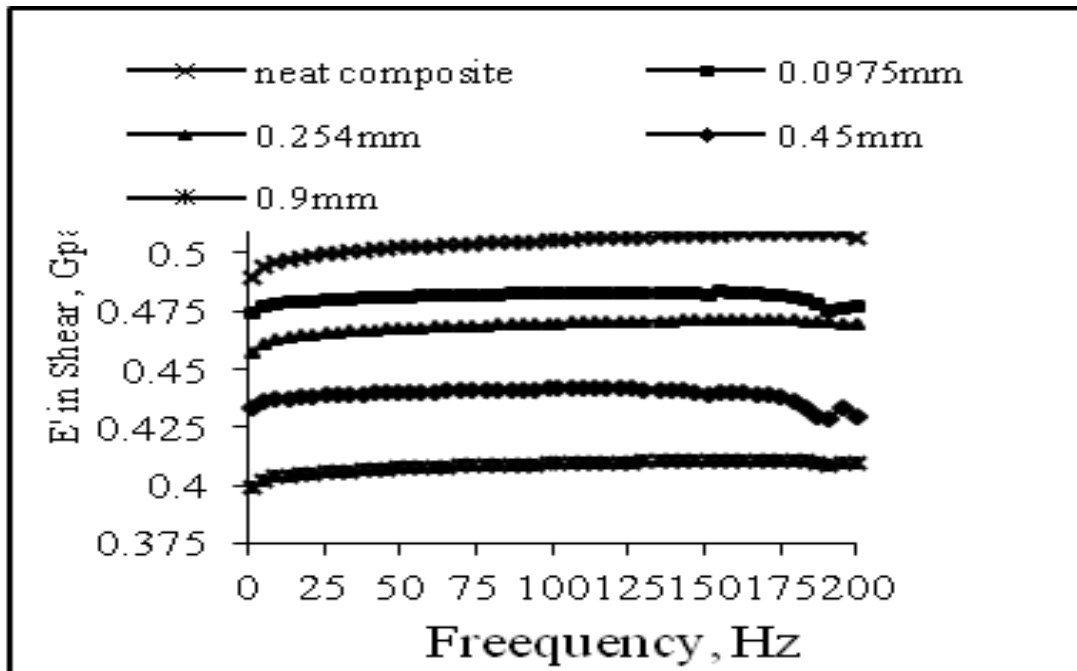


Figure 7. Variation in shear storage modulus with frequency

ii) Temperature Sweep

The effect of rubber particle size inclusions in the glass epoxy composite on loss factors in three-point bending with temperature at 10 Hz is reported in Figure 8. It is observed that the glass transition temperature T_g is shifted to the lower side due to the addition of rubber inclusions because of the increased mobility of the rubber molecules at higher temperatures. T_g for the neat composite is around 140°C , whereas for the rubber-filled composites it is around 85° to 90°C . The size of particle inclusions on T_g is insignificant. The peak magnitude of the loss factor is highest with a particle size of 0.254 mm, as in the case of the frequency sweep. The magnitude of the peak is decreased with increase in particle size. At temperatures over 90°C , the micro-slip at the interphase of the fibre, matrix and particle inclusions increased significantly and the mobility of polymer chains also increases at higher temperatures, thereby considerably increasing damping. The DMA results revealed (Figure 9) that E' in three-point bending at a constant frequency of 10 Hz. E' slightly decreased with temperature for all composite specimens. The reduction in E' in three-point bending is drastic on passing through the T_g . On passing through T_g the molecular relaxations of viscoelastic rubber particles and polymer chains take place and causes a reduction in the storage modulus.

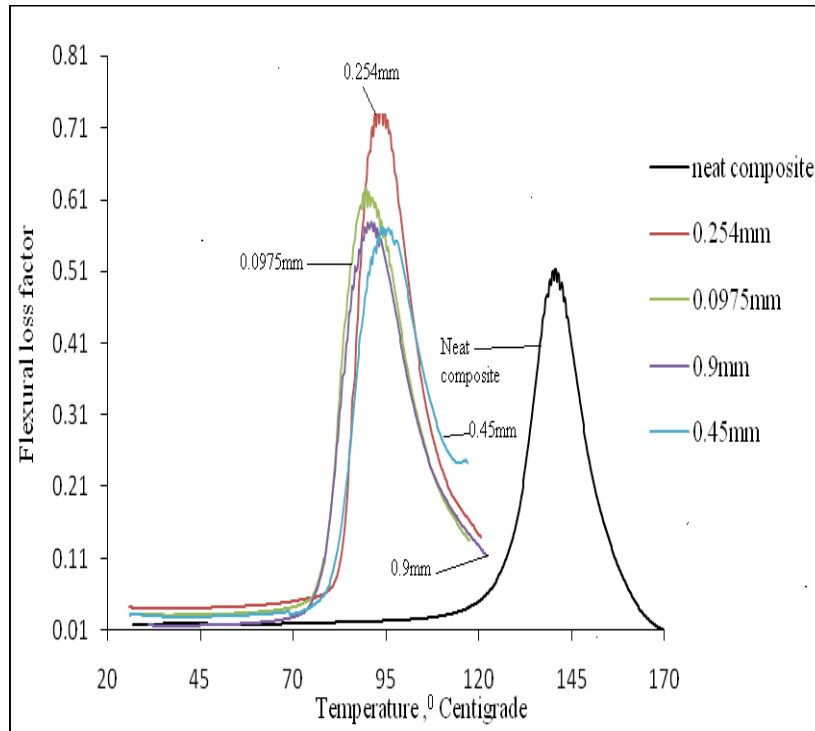


Figure 8. Variation in $\tan \delta$ (bending) with temperature

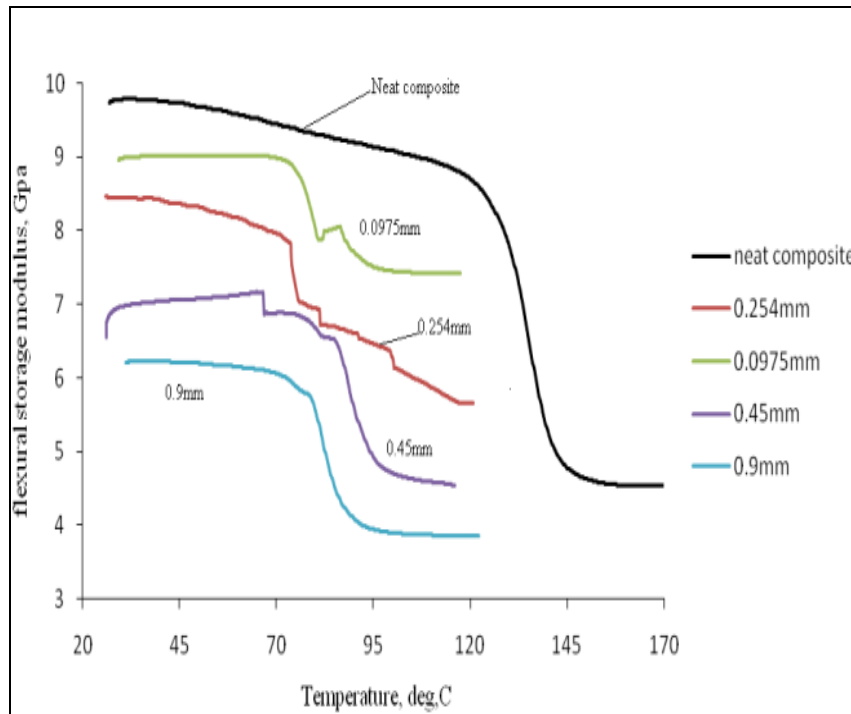


Figure 9. Variation in E' in bending with temperature.

IMPLEMENTATION OF ANN

The dynamic properties estimated are used for building two RBF models to predict the storage modulus and loss factor in two different scenarios: viz. in three-point bending

and shear the in case of a frequency sweep, and in three-point bending at 10 Hz in the case of a temperature sweep. RBF networks have a static Gaussian function as the nonlinearity for the hidden layer processing elements (Bose and Liang, 1998).

Table 1. Input and output parameters of ANN model.

Input			
Model I		Model II	
Frequencies (Hz)	1–200	Temperature (°C)	Up to 200
Particle sizes (mm)	0.09, 0.254, 0.45, 0.9	Particle sizes (mm)	0.09, 0.254, 0.45, 0.9
Output (Model I and II)			
Storage modulus		In bending	
Loss factor		In bending	

Table. 2 Predicted and experimental values of dynamic properties at various frequencies

Freq Hz	Size mm	Experimental				Predicted				Percentage Error			
		Bending		Shear		Bending		Shear		Bending		Shear	
		E MPa	tan δ	E MPa	tan δ	E MPa	tan δ	E MPa	tan δ	E	tan δ	E	tan δ
13.2	0.098	9009	0.0331	478.6	0.0181	8893	0.03425	476.32	0.019	1.2909	-3.415	0.4764	-3.34
17.2	0.098	9038	0.034	479.1	0.0186	8921	0.03515	476.83	0.019	1.2956	-3.431	0.4738	-3.13
21.2	0.098	9060	0.0349	479.5	0.0191	8942	0.0361	477.27	0.02	1.2991	-3.394	0.4651	-2.93
25.4	0.098	9078	0.0358	479.9	0.0196	8960	0.03697	477.68	0.02	1.302	-3.418	0.4626	-2.76
45.6	0.098	9128	0.0397	481.1	0.0209	9008	0.04095	478.96	0.021	1.3179	-3.115	0.4448	-2.83
29.4	0.254	8329	0.0446	466	0.0235	8392	0.04284	466.58	0.023	-0.75	3.9632	-0.1245	3.399
33.5	0.254	8340	0.0455	466.4	0.0238	8402	0.04369	466.94	0.023	-0.741	3.9692	-0.1158	3.221
37.6	0.254	8346	0.0463	466.7	0.0242	8409	0.04445	467.23	0.023	-0.756	3.9957	-0.1136	3.125
41.6	0.254	8349	0.0469	467	0.0244	8410	0.04515	467.51	0.024	-0.732	3.635	-0.1092	2.734
21.2	0.45	7410	0.0331	438.4	0.017	7468	0.03371	440.15	0.017	-0.788	-1.868	-0.3992	-2.21
25.4	0.45	7428	0.0338	438.8	0.0174	7486	0.0344	440.55	0.018	-0.784	-1.914	-0.3988	-2.16
29.4	0.45	7444	0.0335	439.1	0.0179	7502	0.03419	440.86	0.018	-0.779	-2.173	-0.4008	-2.05
33.5	0.45	7447	0.0339	439.3	0.0184	7506	0.03467	441.07	0.019	-0.786	-2.229	-0.4029	-1.92
102	0.45	7290	0.051	441.5	0.0219	7348	0.05155	443.37	0.022	-0.789	-1.174	-0.4236	-1.19
98.5	0.9	5908	0.0441	409.3	0.0243	5908	0.04407	409.3	0.024	0	0	0	0

An exact fit model of RBF is chosen with a spread constant of 0.5. Among the available experimental data of around 400 data points in the case of the frequency model and 2000 data points in the case of temperature model (more data points are taken for the temperature model as the observations are highly non-linear), 50 data points are kept aside for testing purposes, while the rest of the data points are used for training the network. The network was implemented using MATLAB 7®. For the present study, frequencies and particle sizes are selected as input variables and E', Tan δ in bending and shear are chosen as the output parameters. The same network is also used separately to predict the loss factors and storage modulus in bending at a given temperature and particle size within the range considered at 10Hz. The input and output

parameters are presented in Table 1. ANN simulation (testing) results for different frequencies and different temperatures are shown in Tables 2 and 3 respectively. It can be seen that the predicted values are very close to the experimental values, in fact in some cases they are the same. Percentage errors obtained are less than 5% in all cases, thus validating the models.

Table. 3. Predicted and experimental values of dynamic properties in bending at various temperatures.

Temp. (°C)	Size (mm)	Experimental		Predicted		Percentage Error	
		Modulus (MPa)	tan δ	Modulus (MPa)	tan δ	Modulus (MPa)	tan δ
29.65	0.0975	8969	0.0321	8917	0.03295	0.5798	-2.783
59.1	0.0975	9018	0.0353	8896.7	0.03664	1.3451	-3.875
37.97	0.254	8436	0.0408	8467.9	0.0389	-0.378	4.76
114.4	0.254	6537	0.1854	6444.3	0.18256	1.4181	1.5318
39.7	0.45	7398	0.0292	7458.6	0.02989	-0.819	-2.314
76.33	0.45	7497	0.0435	7480.3	0.04511	0.2228	-3.68
96.73	0.45	5475.3	0.5667	5508.7	0.5727	-0.61	-1.061
40.42	0.9	6226	0.0167	6226	0.01676	0	-0.119
96.01	0.9	3932	0.4984	3929.1	0.4914	0.0738	1.4045
122	0.9	3857.62	0.115	3857.5	0.11362	0.0031	1.2

CONCLUSIONS

The dynamic properties of particle rubber-containing composites are estimated using DMA. ANN-based prediction models to predict the dynamic properties of these composites are developed using RBF. Based on the results obtained the following conclusions may be drawn.

- i) Inclusion of rubber particles is found to increase the loss factors in both bending and shear, whereas the storage modulus decreases. The loss factors in bending and shear decreased with the size of the natural rubber particle inclusions except for sizes of 0.254 mm and 0.0975 mm. A specific observation is that both loss factors are maximum with a particle size of 0.254 mm among the selected particle sizes.
- ii) At smaller particle inclusions, i.e. 0.0975 mm and 0.254 mm, there is a reduction in E' of about 10% to 15%, whereas at particle sizes of 0.45 mm and 0.9 mm it is about 30% to 40%. At smaller particle sizes a considerable improvement in Tan δ with lower reduction in stiffness is observed in both bending and shear modes at all frequencies considered.
- iii) A shift in T_g is observed with the inclusion of rubber particles. The size of the particles has no significant effect on the glass transition temperature.
- iv) ANN models are found to be accurate and able to predict Tan δ and E' for both frequencies and temperatures.

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