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Tensile, impact and dielectric properties of three dimensional orthogonal aramid/glass fiber hybrid composites

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Abstract Aramid/glass hybrid composites with three different stacking sequences and their corresponding single fiber type composites have been fabricated and their tensile, impact and dielectric properties were investigated. The trend of tensile strength and modulus of the composites followed the rule of mixture (ROM) closely and a small but positive hybrid effect for tensile strength of the hybrid composites was observed. The hybrid composites in general had a higher impact resistance than the single fiber type composites and the hybrid composite in which fiber volume fractions for glass and aramid fiber were the most balanced showed the highest impact ductility. The aramid fiber composite showed a lower dielectric constant and a higher dielectric loss than the glass fiber composites. However, the dielectric constant of the hybrid composites decreased first and then increased as the volume fraction of aramid fiber increased, which did not follow the mixing rule for dielectric constants of compounds. The dielectric loss of the composites increased monotonically as the volume fraction of aramid fiber increased which agreed well with the mixing rule.

Introduction

The emergence of 3D woven composites is aimed to improve the weaknesses of traditional laminated structures, namely delamination. Among the different technologies to produce 3D fiber architecture, 3D orthogonal woven preforms have gained industrial acceptance [1–5].

Hybrid composites were used to provide a wider range of properties and reasonable cost for many applications [6, 7]. Much attention has been paid to the mechanical properties of hybrid composites [8–10]. Qiu and Schwartz [11, 12] analyzed the tensile and stress rupture behavior of aramid/glass microcomposites and proposed a stochastic process model for the prediction of lifetime for hybrid composite under constant load. Although many researchers reported positive hybrid effect in tensile strength of hybrid composites [13, 14], if only considering tensile properties of hybrid composite, there is no obvious advantage for adopting hybrid structure since the tensile strength for a hybrid composite is likely to be lower than their single fiber type counterparts. This is because in a hybrid composite, the fiber with higher tensile modulus may fail first while the fibers with lower tensile modulus are only partially loaded when the composite fails, resulting in a much lower tensile strength for hybrid composites than their single fiber type counterparts. The advantage of hybrid composite is usually to reduce the cost of the composites by applying high performance but expensive fiber such as carbon fiber in a critical location to meet particular requirement of an application. More recently, more and more vegetable fibers such as sisal fibers, palm fibers, bamboo fibers and jute fibers have been used to make environmentally friendly composites. Most of these fibers, however, have low tensile strengths and moduli. Therefore high performance fibers such as glass, aramid, and carbon fibers have been used

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together with these low performance fibers to make the resultant composites better in mechanical properties [15–20].

Unlike tensile properties, impact properties and fatigue resistance of composites are largely dependent on the toughness of the component materials. Therefore hybrid composites have a great advantage compared to single fiber type composites. Belingardi et al. [8] studied the bending fatigue behavior of a hybrid glass-carbon fiber reinforced laminated composite composed of intraply biaxial glass-carbon laminae as well as biaxial glass laminae and biaxial carbon laminae. It was found that the hybrid structure reduced the cost of the composite without sacrificing the bending fatigue performance of the composites.

Adding one ‘‘softer’’ fiber may make the composite much ductile in impact than the single fiber type composite. Naik et al. [21] reported that that laminated carbon/glass hybrid composites are less notch sensitive compared with pure carbon or pure glass composites. Gustin et al. [22] replaced the impact-side of a carbon fiber reinforced composite with aramid or aramid/carbon face sheet to improve the impact properties of the composite structure. Sohn et al. [10] placed short aramid fibers in between the layers of carbon fiber/epoxy composite and found that the impact damage performance of the composite was greatly improved. Park and Jang [23–26] have done a series of research work in investigating the mechanical properties especially on the impact behaviors of aramid/glass hybrid composites. It was found that the impact energy and delamination area of untreated hybrid composites depended on the position of aramid layer. In surface-treated composites, however, the position of aramid layer had a minor effect on the impact energy of hybrid composites [25]. In examining the effect of stacking sequence of aramid fiber/glass fiber hybrid composites, the addition of glass layer to aramid layer reduced the impact resistance of hybrid composite due to the restriction in the deformation of aramid layer. When the aramid layer was at the impacted surface, the composite exhibited higher impact energy [26].

Little has been reported in literatures about mechanical properties of 3D hybrid composites. Wan et al. [27] and Kostar et al. [28] studied flexural, impact and shear properties of 3D braided aramid/carbon hybrid composites and found that hybridization lead to a high flexural strength and modulus. Cho et al. [29] studied electrical and mechanical properties of hybrid composites with several types of carbon fibers. They found that the electrical resistance of the composites were changed in a stepwise manner and associated to the fracture process of the fibers in the composites.

For composite structures used in the electrical and aerospace applications, dielectric properties of the materials could be important because this directly affects the velocity and energy loss during the process of signal transmission [30]. Dielectric properties of composites have been studied extensively for laminated composites [31–34]. However, little has been reported for the dielectric properties of 3D woven composites.

In this study, tensile, impact, and dielectric properties of five types of 3D orthogonal woven aramid-glass fiber/epoxy hybrid composites were investigated to show how the structural variation of the hybrid composites affected these properties.

Experimentals

Materials

The yarns for 3D woven preforms are aramid (Twaron 1000) produced by Akzo and E-glass EDR14 300-778 manufactured by Jushi Group Company (Zhejiang, China). The physical properties of yarns are listed in Table 1. The resin system was epoxy resin 618 and cure agent Iminazole 5510 produced by Shanghai Resin Company (China).

Composite manufacturing

Five types of 3D reinforcement geometries with 8 warp and 9 weft layers were adopted in making the composites, namely 17G, 3A11G3A, 5A7G5A, 7A3G7A and 17A. A and G designate aramid fiber and glass fiber, respectively. The configurations of the three types of hybrid composites are shown in Fig. 1. Glass yarns were used as the z yarns for the pure glass fiber preform while aramid yarns were used as the z yarn for the rest. These preforms were consolidated using vacuum assistant resin transfer molding (VARTM). The physical properties and fiber volume fractions of the five types of composites are shown in Tables 2 and 3.

Tensile test

The tensile tests were performed on an Instron universal testing machine model 3382 with a load cell capacity of 100 KN. The dog-bone shaped composite specimens

Table 1 Physical and mechanical properties of the fibers

Properties	E-glass	Aramid
Linear density (Tex)	300	110
Tensile strength (MPa)	1850	3430
Modulus (GPa)	65	138
Elongation at Break (%)	3.2	2.4

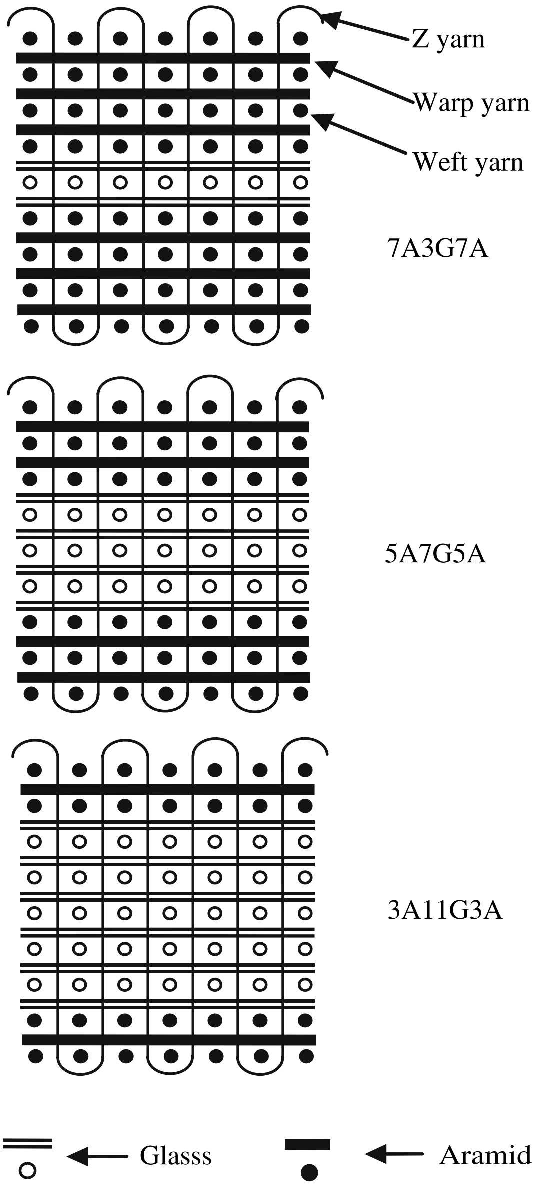

Fig. 1 Structure of the three types of hybrid composites

Table 2 Physical properties of the five types of composites

Composites	Yarns/cm			Thickness (mm)	Area density (g/cm^2)	Density (g/cm^3)
	Warp	Weft	Z			
17G	5.2	13.60	5.2	3.40	0.41	1.98
3A11G3A		14.26		3.16	0.33	1.60
5A7G5A		15.30		3.13	0.30	1.48
7A3G7A		15.22		3.09	0.26	1.40
17A		15.28		3.00	0.22	1.26

(Fig. 2) were tested at a cross-head speed of 2 mm/min. An Instron extensometer was used to measure the extension over 50 mm gauge length. At least five specimens were tested to failure in both the warp and weft directions for each type of the composites. Tensile strength was calculated using peak load and cross-sectional area of the specimen. Tensile modulus was calculated from the stress–strain curves.

Impact test

The impact tests were conducted using dropping-mass tower (Instron model 9250) on rectangular specimens of 100 × 10 mm, with the span length fixed at 50 mm. The drop weight was 4.8 kg and the impact velocity was fixed at 3.2 m/s. Load-displacement curves were recorded and the initiation energy, the propagation energy, and the total energy were calculated. The total impact energy was defined as the sum of the energy absorbed until the maximum load (initiation energy) and the energy absorbed after the maximum load (propagation energy).

Dielectric property test

The dielectric property tests were performed on Agilent 4291B 1.8 GHz Impedance/Material Analyzer. All the specimens were dried before measuring. The dielectric constant and dielectric loss of the composites were obtained in the frequency range from 1 MHz to 1000 MHz.

Results and discussion

Tensile properties

Tensile strength and modulus in the warp and weft directions were presented in Tables 4–7. The ROM prediction were calculated using the fiber strengths, fiber volume fractions, and the bundle efficiencies derived from the two single fiber type composites, namely 17G and 17A. Compared with ROM prediction, most of the hybrid composites showed a small but positive hybrid effect. The observed hybrid effect can be explained as follows. The aramid fiber had higher tensile modulus than the glass fiber. Therefore, when the composite was loaded the aramid fibers would have to carry higher stress than the glass fibers and would break first. When the volume fraction of aramid fiber was low, once the aramid fibers failed, the remaining glass fibers were able to share the applied load and thus the composite could withstand even higher load level. However, when the volume fraction of the aramid fibers reached a certain amount, once the aramid fibers failed the remaining glass fibers were not able to withstand the overload and thus would also fail simultaneously with the aramid fibers, resulting in the lowest tensile strength. When

Table 3 Fiber volume fractions of the five types of composites

Composites	Warp		Weft		Z		Overall fibers (%)	Matrix (%)
	Glass fibers (%)	Aramid Fibers (%)	Glass fibers (%)	Aramid Fibers (%)	Glass fibers (%)	Aramid Fibers (%)		
17G	14.1	0	41.5	0	5.8	0	61.5	38.5
3A11G3A	11.4	2.5	26.0	13.7	0	3.9	57.7	42.3
5A7G5A	7.7	5.0	16.9	22.2	0	3.9	56.1	43.9
7A3G7A	3.9	7.7	5.7	29.9	0	4.0	51.4	48.6
17A	0.0	10.5	0.0	34.8	0	4.0	49.6	50.4

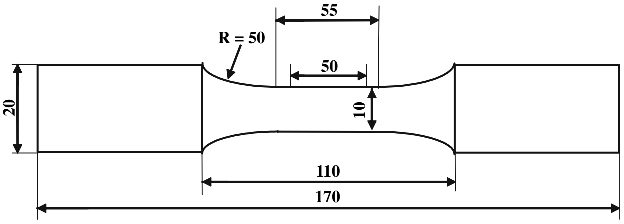

Fig. 2 Configuration of the tensile test specimen (mm)

Table 4 Tensile strengths of the five types of composites in warp direction

Composites	Tensile strength (MPa)		ROM prediction (MPa)
	Mean	STDV	
17G	134.8	8.8	134.8
3A11G3A	163.8	6.7	158.0
5A7G5A	130.7	15.3	112.2
7A3G7A	150.7	41.0	209.9
17A	236.1	23.0	236.1

Table 5 Tensile moduli of the five types of composites in warp direction

Composites	Tensile modulus (GPa)		ROM prediction (GPa)
	Mean	STDV	
17G	13.2	2.4	11.0
3A11G3A	14.4	0.8	11.2
5A7G5A	10.3	1.1	10.7
7A3G7A	10.5	0.5	10.3
17A	10.4	0.3	9.9

Table 6 Tensile strengths of the five types of composites in weft direction

Composites	Tensile strength (MPa)		ROM prediction (MPa)
	Mean	STDV	
17G	504.2	15.9	504.2
3A11G3A	540.4	55.5	548.9
5A7G5A	472.8	33.5	431.8
7A3G7A	673.3	20.6	650.7
17A	676.5	19.9	676.5

Table 7 Tensile moduli of the five types of composites in weft direction

Composites	Tensile modulus (GPa)		ROM prediction (GPa)
	Mean	STDV	
17G	28.1	3.6	30.2
3A11G3A	30.4	4.2	30.4
5A7G5A	27.5	1.6	30.9
7A3G7A	30.8	1.1	29.4
17A	28.7	0.8	29.3

the aramid fiber volume fraction further increased the composite strength increased simply because more aramid fibers were available to share the load. This hybrid effect was analyzed by Marom et al. [13] and later confirmed by others [11, 12]. Recently, Chiang et al [35] performed a Monte Carlo simulation on the tensile properties of glass/carbon/epoxy unidirectional composites and reported that their results showed no hybrid effect in all volume fraction ranges. However, they only compared their results with the prediction from an analytical model and no experimental vilification of the simulation results was given. One exception is that 7A3G7A had a negative hybrid effect in warp direction. This could be due to the large variation of composite strength (coefficient of variation = 27%), which made the difference statistically insignificant.

Unlike for tensile strength, in principle, there should not be hybrid effect for tensile modulus of a hybrid composite. Therefore, tensile modulus of hybrid composites should follow the prediction of ROM. The experimental and the ROM predicted tensile moduli matched reasonably well for the composites in both warp and weft directions as shown in Tables 5 and 7.

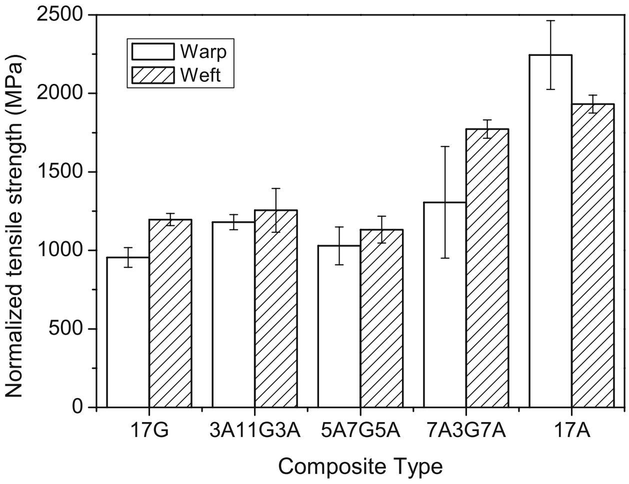

Fig. 3 The normalized tensile strength of the composites in the warp and weft directions

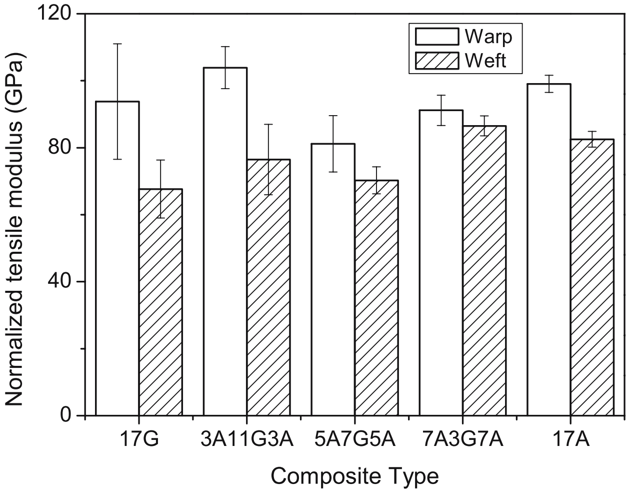

Fig. 4 The normalized tensile modulus of the five types of composites in the warp and weft directions

The normalized tensile strength and modulus were shown in Figs. 3 and 4. The pure aramid composite, 17A, showed the highest normalized tensile strength in both warp and weft directions due to the higher tensile strength of the aramid fiber. Among all the composites, 5A7G5A had the lowest normalized tensile strength in both directions. The significant difference of the normalized tensile modulus in the warp and weft directions shown in Fig. 4 was mainly due to the following reasons. The warp yarns passed through a series of tensioning devices during the weaving process, which leads to a higher and constant tension of warp yarns than that of the weft yarns. Therefore, the warp yarns were straighter than the weft yarns which had small tension when inserted into the fabric during weaving. In addition, the weft yarns were crossed by the z yarns which applied transverse pressure to the top and bottom layers of the weft yarns, creating crimps in the weft yarns. Another factor was that the z yarns were running along the warp direction and thus would also add certain amount of stiffness to the composite in warp direction.

In contrast to the tensile modulus, warp direction had a slightly lower tensile strength than that of the weft direction as shown in Fig. 3. It could be mainly due to the damage of the fibers during weaving process in which the reed moved back and forth and rubbed against the warp yarns. The weft yarns were inserted into the fabric at once without too much damage due to rubbing against the machine parts. However, the crimp in weft yarns could also reduce the tensile strength of the composite. The balance of these two factors determined which direction had a higher tensile strength.

Impact properties

The results of the impact test for the hybrid composites are shown in Tables 8 and 9. The normalized peak load by fiber volume fraction of 17G was the highest due to the largest thickness and thus a much higher bending stiffness, while that for 17A was the lowest due to the smallest thickness and early initiation of failure. Table 9 summarized the total energy, initiation energy and propagation energy of the composites. The ratio of the propagation energy and initiation energy is defined as the ductility index (DI). Obviously, 5A7G5A had the highest DI while 17A had the lowest DI. It was reported that the DI is partially determined by the surface layer fiber type. Park and Jang [26] found that aramid fibers on surface of a hybrid laminated composite effectively increased the impact energy of the composite. In this study, all the hybrid composites had aramid fibers as the surface fiber and therefore the influence of the surface fiber type on the impact energy absorption and DI could not be determined. The DI of all hybrid composites were higher or equal to that of the pure fiber type composites, implying more interfacial debonding and fiber fracture occurred in impact failure process for the hybrid composites. DI was

Table 8 Peak load for impact test of the five types of composites

Composites	Peak load (N)		Normalized Peak load by fiber volume fraction (N)
	Mean	STDV	Mean
17G	454.1	32.9	738.4
3A11G3A	364.8	32.7	632.2
5A7G5A	325.2	26.0	579.7
7A3G7A	332.5	24.3	646.9
17A	279.9	32.0	564.3

Table 9 Impact energy of the five types of composites

Composites	Total energy (J)	Initiation energy (J)	Propagation energy (J)	Normalized initiation energy (J)	Normalized propagation energy (J)	DI
17G	1.76	1.12	0.65	1.82	1.06	0.58
3A11G3A	1.67	1.03	0.64	1.79	1.11	0.61
5A7G5A	1.63	0.82	0.81	1.46	1.44	0.98
7A3G7A	1.19	0.75	0.44	1.46	0.86	0.58
17A	1.35	0.96	0.39	1.94	0.79	0.41

also related to the fiber volume fraction. For the two single fiber type composites, the glass fiber composite had a much higher DI than the aramid fiber composite largely because it had a substantially higher volume fraction (61.5% vs. 49.6%) and thus more interface area than the aramid composite in addition to a larger failure strain for glass fibers.

Dielectric properties

The curves of dielectric constant and dielectric loss versus frequency were shown in Figs. 5 and 6. For the single fiber type composites, when the frequency was larger than 100 MHz, the dielectric constant of 17G showed a higher value than 17A due to a lower dielectric constant for the aramid fiber than that for the glass fiber. For the three hybrid composites, nevertheless, 5A7G5A had the lowest dielectric constant, which is even lower than the pure aramid composite 17A as shown in Fig. 5. This does not agree with the well-known mixing rule for dielectric constant of a multi-component material [36]. On the other hand, dielectric loss did show a trend following the mixing rule, namely the dielectric loss decreased as the volume fraction of the glass fiber increased as shown in Fig. 6.

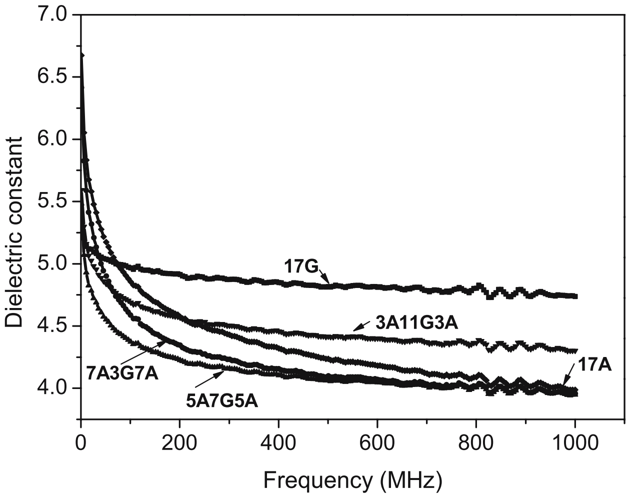

Fig. 5 The dielectric constant versus frequency of the five types of composites

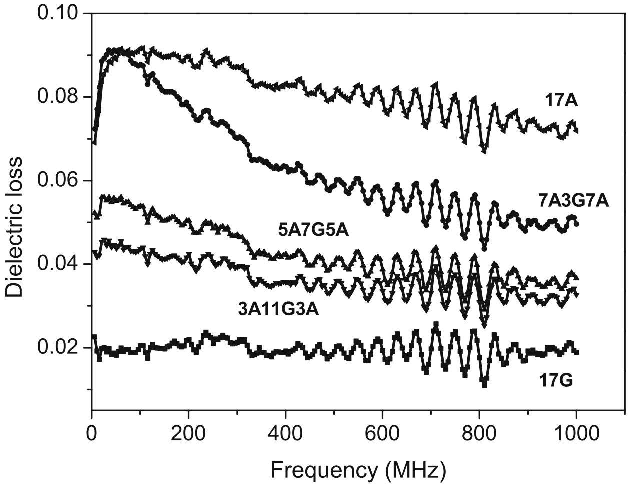

Fig. 6 The dielectric loss versus frequency of the five types of composites

The trend of the variation of dielectric constant with the composition of the composites also depended on the measurement frequency as shown in Fig. 7. In general, the dielectric constant decreased when the aramid fiber content increased till it reached 5A7G5A. The dielectric constant increased at frequencies lower than 100 MHz but remained the same at 1000 MHz as aramid fiber volume fraction increased. In addition, the dielectric constant and dielectric loss showed more stable values as the content of glass fiber increased for the five types of composites shown in Figs. 7 and 8. It also can be seen that the change of dielectric loss with the composition of the composites had the same trend at the four frequencies, namely it increased as the volume fraction of aramid fiber increased in Fig. 8.

Conclusions

The mechanical and dielectric properties of five different types of hybrid composites have been investigated in this paper. The trend of tensile strength of the composites followed the ROM closely. In general, a small but positive hybrid effect for tensile strength of the hybrid composites

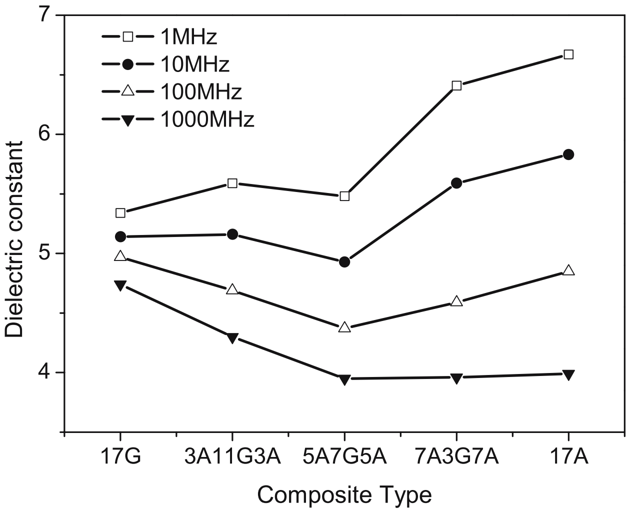

Fig. 7 The dielectric constant of the five types of composites in four different frequency points

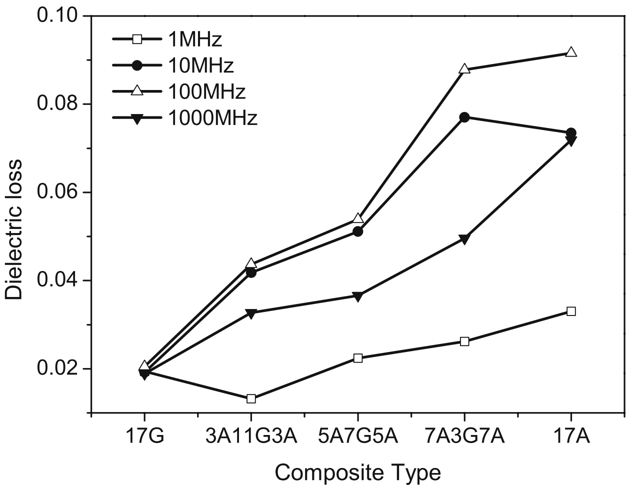

Fig. 8 The dielectric loss of the five types of composites in four different frequency points

was observed. For impact test, the composite that showed the highest impact ductility was 5A7G5A in which fiber volume fractions for glass and aramid fiber were the most balanced. The hybrid composites in general had a higher impact resistance than the single fiber type composites. The dielectric constant of the composites decreased as aramid fiber content increased when aramid fiber volume fraction was below that of 5A7G5A, while the opposite was true when the aramid fiber volume fraction further increased. Therefore dielectric constant of hybrid composites did not follow the mixing rule. The dielectric loss of the composites increased as the volume fraction of aramid fiber increased which agreed well with the mixing rule.

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