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Material properties

## Mechanical characterization of epoxy composites modified with reactive polyol diluent and randomly-oriented amino-functionalized MWCNTs

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### ABSTRACT

Increased fracture toughness of diglycidyl ether of bisphenol A (DGEBA) type epoxy resin was obtained without compromising other desired mechanical properties, such as strength and stiffness, by combining the benefits of adding polyether polyol and amino-functionalized multi-walled carbon nanotubes (NH<sub>2</sub>-MWCNTs) simultaneously. The effect of concentration on the morphology of three-phase nanotube/polyol/epoxy composites was investigated using scanning electron microscopy (SEM). Mechanical properties were evaluated by three point flexure and single edge notch bend (SENB) fracture toughness tests. Addition of a polyether polyol to the epoxy resin increased mode-I fracture toughness and flexural strain energy, while adversely affecting flexural strength and stiffness. A synergistic effect was observed with the addition of amino-functionalized multi-walled carbon nanotubes (NH<sub>2</sub>-MWCNTs) into polyol toughened epoxy, with significant improvements in fracture toughness and strain energy as well as in flexural strength and stiffness. Matrix plastic deformation and lower crosslink density due to polyether polyol in the epoxy system increased toughness while reducing flexural strength and stiffness. However, incorporation of uniformly dispersed 0.3 wt.% loading of NH<sub>2</sub>-MWCNTs into the polyol-toughened epoxy composites improved the mechanical properties as well as fracture toughness, compared with pristine epoxy and polyol-toughened epoxy.

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### 1. Introduction

Epoxy resins are increasingly utilized as matrices for high performance composite materials, protective coatings, adhesives and many other industrial and structural applications due to their high stiffness, strength, low shrinkage during cure, low volatility, excellent chemical resistance, dimensional stability and excellent adhesion with fillers, fibers and other substrates [1]. The epoxide groups present in epoxy molecules are highly reactive with many

substances, forming a crosslinked structure through polymerization reactions that result in good stiffness, strength and thermo-mechanical properties. However, high crosslink density results in brittleness, with poor resistance to fracture and crack growth.

It is well known that incorporation of rubber particles [2–4], rigid particles [5–7] and thermoplastics [8–10] can effectively improve the toughness properties of epoxy resin systems. However, a rubbery phase due to presence of rubber particles or thermoplastic polymer in epoxy systems decreases thermo-mechanical properties significantly. Incorporation of rigid particle fillers, such as silica, alumina and glass beads can improve the toughness of epoxy resins without substantial reduction in glass

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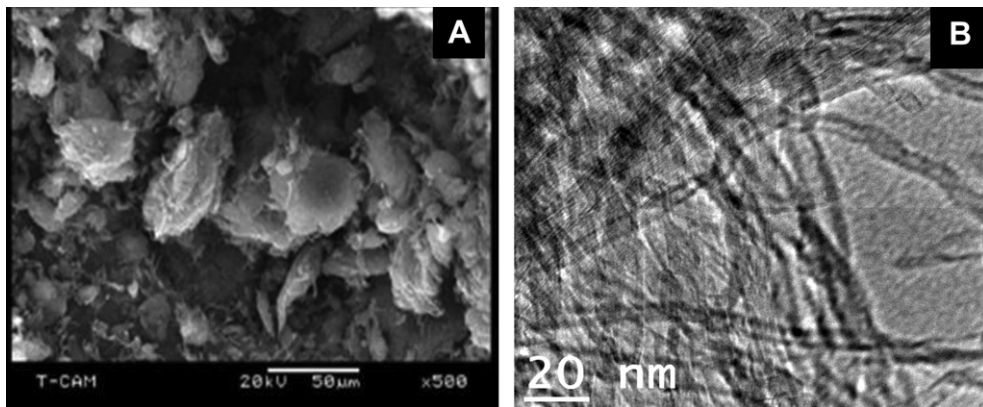


Fig. 1. SEM (a) and TEM (b) micrographs of as-received  $\text{NH}_2$ -MWCNTs [25].

transition temperature [5–7]. In comparison with rubber-modified epoxy, the improvement in toughness is much lower in the rigid particle modified epoxy. Additionally, high application viscosity and processing constraints become significant limitations to the incorporation of rubber, thermoplastic and rigid particles into epoxies.

Because of their excellent elasticity and good impact strength, a number of polyol based reactive diluents have been considered as a good choice to improve the resistance to brittle fracture behavior of epoxy resins [11,12]. In addition to the toughening effect on the epoxy system, lower viscosity and extended pot life increase the resin wetting action and the level of filler loading without substantial decrease in curing rate and thermal stability. These properties make polyols suitable for modification of an epoxy matrix to obtain improved peel and impact strengths, and facilitate processing of fiber-reinforced polymer composites. Isik et al. used a polyether polyol as a toughener for epoxy resins [12]. They found 160% improvement in impact properties by Charpy impact test.

A successful route to counteract the reduction in mechanical and thermo-mechanical properties of toughened epoxy blends can be the incorporation of nanoparticles as reinforcing materials. Simultaneous addition of soft and rigid particles into an epoxy resin enhanced mechanical properties as well as toughness through different toughening mechanisms [12–15]. Balakrishnan et al. [14] studied the influence of clay concentration and acrylic rubber particles on the mechanical properties of epoxy composites. With increasing organoclay content, they found an increase in tensile modulus and strength with a decrease in ductility, while using only rubber had the opposite effect. However, using both additives at a loading of 5.5 wt.% clay content and 16 phr rubber in epoxy resins resulted in a 30% enhanced fracture energy with 12% and 19% improvements of tensile strength and modulus, respectively. Kinloch et al. [15] used 10 wt.% nanosilica and 9 wt.% CTBNs rubber in epoxy composites in order to improve fracture energy without compromising mechanical properties. They got 100% improvement in fracture energy. However, they did not obtain any improvement in flexural modulus.

Among the nanoparticles, carbon nanotubes (CNTs), have emerged as potentially major candidates for modification of

an epoxy matrix because of their exceptional strength and stiffness, high flexibility and elongation at break, and high thermal and electrical conductivity. Recently, the properties of epoxy polymer matrices have been modified successfully by incorporating CNTs as reinforcing materials [16–19]. These studies showed an improvement in fracture toughness as well as in mechanical strength and stiffness even at low nanotube content. However, to employ CNTs as effective reinforcements in polymer composites, proper dispersion and interfacial adhesion between polymer and CNTs are the most important issues and challenges in the field of composite structures. Multi-walled carbon nanotubes (MWCNTs) have a lower specific surface area than single-walled carbon nanotubes (SWCNTs) due to their much larger diameter and, hence, exhibit better dispersibility in polymer suspensions. Previously, it has been shown that amino functionalization in CNTs enhances the dispersibility and interfacial adhesion in the epoxy matrix over some other functionalizations such as carboxyl or silane [17]. In our recent study [20], epoxy systems were modified using  $\text{NH}_2$ -

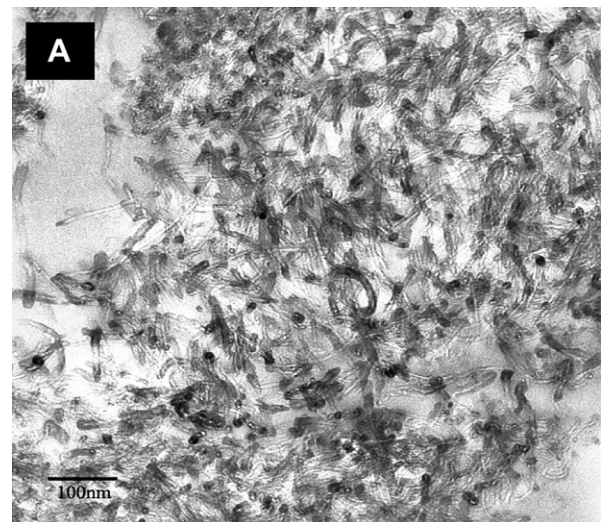


Fig. 2. TEM micrograph showing quality of dispersion of  $\text{NH}_2$ -MWCNTs in epoxy resin [25].

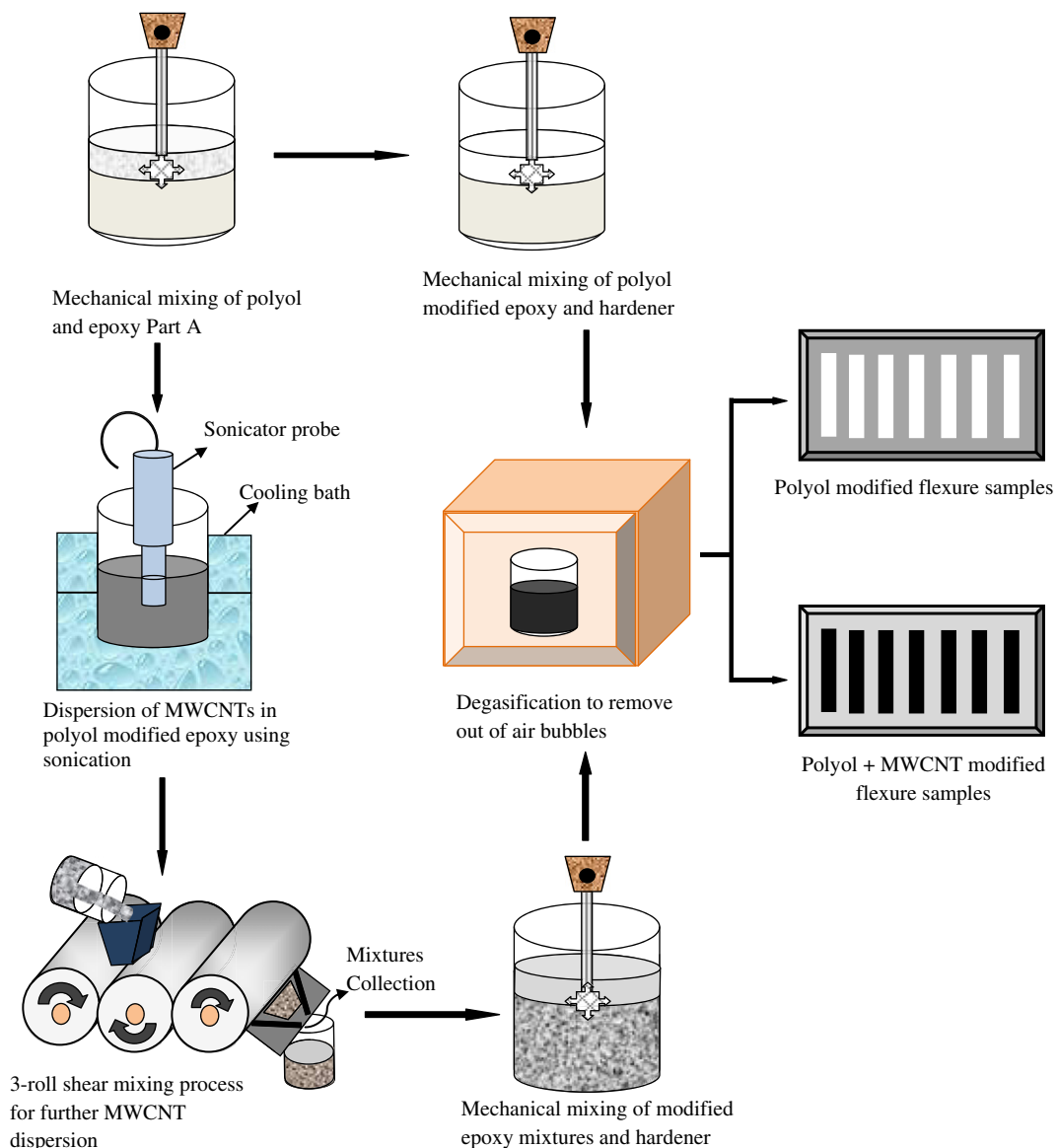
**Table 1**  
Formulation of modified epoxy samples.

Sample code	Resin (phr)	Hardener (phr)	Polyol content (phr)	NH <sub>2</sub> -MWCNT content (wt.%)
EP	100	30	0	0
EPCNT	100	30	0	0.3
EPPOL5	95	30	5	0
EPPOL5CNT	95	30	5	0.3
EPPOL10	90	30	10	0
EPPOL10CNT	90	30	10	0.3
EPPOL15	85	30	15	0
EPPOL15CNT	85	30	15	0.3

MWCNTs through a combination of ultrasonication and a three roll shear mixing dispersion process. Incorporation of 0.3 wt.% loading of NH<sub>2</sub>-MWCNTs has been found to be optimum in terms of mechanical and thermo-mechanical

properties. To the best of our knowledge, no study on the combined effect of polyether polyol and CNTs on epoxy resin system have yet been reported.

This paper introduces the synergistic effects of combining the benefits of adding polyether polyol and NH<sub>2</sub>-MWCNTs into an epoxy resin in order to develop an improved matrix material for fiber-reinforced composite structures. 0.3 wt.% NH<sub>2</sub>-functionalized MWCNTs were incorporated into pristine DGEBA epoxy resins by combining sonication and calendaring dispersion techniques to synthesize nanocomposites. Epoxy-terminated polyether polyol as a toughener at various calculated loadings was mixed into the DGEBA/NH<sub>2</sub>-MWCNTs system using a high speed mechanical stirrer. The resulting three phase epoxy composite system with amine hardener was used to fabricate toughened epoxy nanocomposites at elevated cure temperature. Three point flexure and mode-I fracture toughness tests were performed



**Fig. 3.** Schematic of fabrication process of modified epoxy composites.

to investigate the effect of polyether polyol and functionalized MWCNTs on the mechanical properties of epoxy nanocomposites. MWCNT dispersion in epoxy was investigated using TEM. In addition, the effect of MWCNTs and polyether polyol on the cured epoxy structure was investigated using SEM analysis. All results were compared with control epoxy results containing no MWCNTs or polyether polyol.

## 2. Experimental

### 2.1. Materials

An unmodified diglycidylether of bisphenol A (DGEBA) epoxy resin with epoxide equivalent weight of 175 g/eq. and a relatively low viscosity of 786 cps at room temperature was used in this study. The curing agent (Part-B) was a mixture of 70–90% cycloaliphatic amine and 10–30% polyoxylalkylamine. Epoxy terminated polyether polyol (triglycidyl ether of propoxylated glycerin) with an epoxide equivalent weight of 620–680 g/eq. and viscosity of 200 cps at room temperature was used as a toughener to prepare toughened epoxy samples. DGEBA, curing agent and polyol were supplied by Applied Pleramics Inc. Amino functionalized multi-walled carbon nanotubes (MWCNT-NH<sub>2</sub>), synthesized by catalytic chemical vapor deposition, were supplied by Nanocyl Inc. They have an average diameter of 10 nm, length of 1 micron and carbon purity >95%. Fig. 1 shows the scanning and transmission electron micrographs of as received carbon nanotubes at different magnifications. High specific surface area and cotton-like entanglements caused the formation of agglomerates as reported by Reynaud et al. [21].

### 2.2. Manufacturing process

#### 2.2.1. Dispersion of NH<sub>2</sub>-MWCNTs into epoxy resin

The NH<sub>2</sub>-MWCNTs were mixed with unmodified DGEBA epoxy resin as per the calculated weight ratio. The mixture was then sonicated at room temperature for 1 h at 35% amplitude and a 30 s on/30 s off cycle pulse mode. To further improve the dispersion of the NH<sub>2</sub>-MWCNTs, the sonicated mixture was then passed through a three roll shear mixing device. A varying gap setting between the rolls and multiple passes of 20 μm (1st pass), 10 μm (2nd pass) and 5 μm (3rd pass) was used to induce high shear

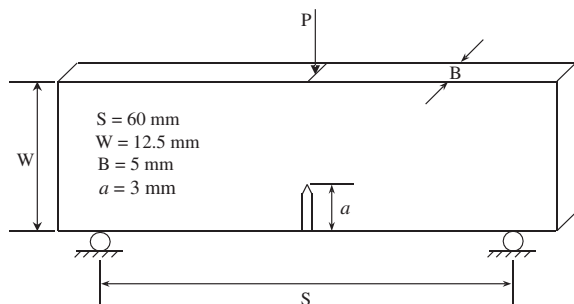


Fig. 4. SENB specimen geometry and loading configuration for quasi-static fracture tests.

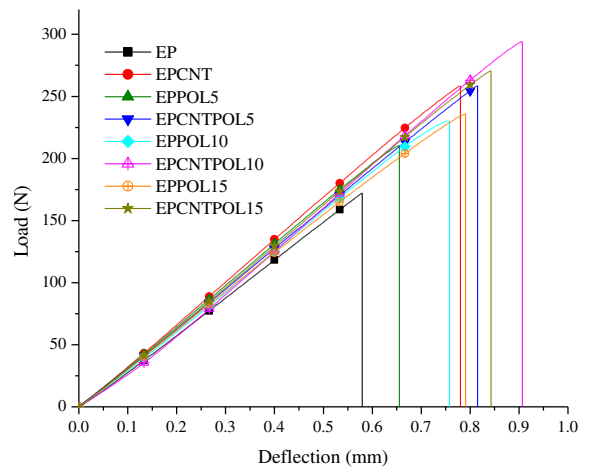


Fig. 5. Typical load-deflection responses obtained from SENB fracture tests.

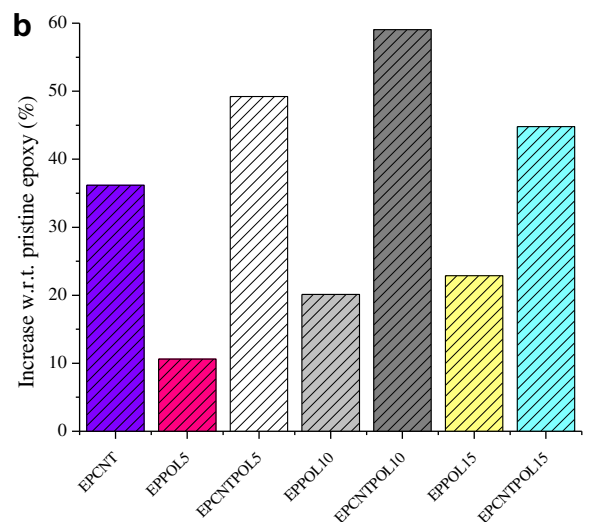
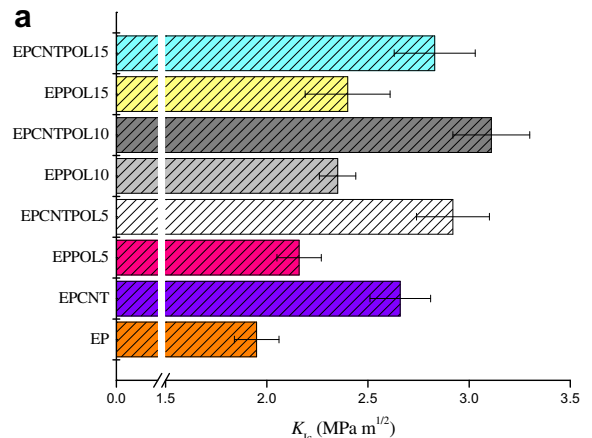


Fig. 6. (a) Mode-I fracture toughness ( $K_{Ic}$ ) of different formulations, (b) Improvements of fracture toughness of epoxy resin using polyol and NH<sub>2</sub>-MWCNTs.

force in the mixture. The roller speed of the three rolls was maintained at a ratio of 1:3:9 with a maximum speed of 200 rpm in all the three passes. Fig. 2 shows the dispersion state of  $\text{NH}_2$ -MWCNTs in epoxy suspensions after sonication and 3-roll shear mixing.

### 2.2.2. Dispersion of polyether polyol into epoxy resin blends

A conventional mechanical mixing technique was used to disperse polyether polyol into the resin. Polyether polyol was mixed with unmodified epoxy resin and modified  $\text{NH}_2$ -MWCNTs/epoxy resin blends as per calculated weight ratio through a high speed mechanical stirrer. The mixture was stirred at room temperature for 10 min at a speed of about 800 rpm. Table 1 presents the epoxy composite formulations used in this study.

### 2.2.3. Preparation of cured epoxy composites

The curing agent was added at a stoichiometric ratio to the pristine and modified systems and blended with a high speed mechanical stirrer for 10 min at a speed of about 800 rpm. The resulting blend was placed in a degasification oven at room temperature to remove entrapped air bubbles that were generated due to the intense mechanical mixing. After completely removing the bubbles, the mixture was poured into a Teflon coated metal mold and cured for 2 h at 60 °C. The cured material was taken out of the mold and placed in an oven for post cure at 100 °C for 5 h. Finally, samples were prepared for mechanical tests by machining.

Schematic representation of the whole fabrication process is shown in Fig. 3.

## 2.3. Material characterization

### 2.3.1. Micrograph analysis

The dispersion state of the MWCNTs in the epoxy resin was investigated by transmission electron microscopy (TEM) using a Zeiss EM10 Transmission Electron Microscope operated at 60 kV. The analysis of fracture surfaces was done using a Zeiss EVO50 scanning electron microscope (SEM) at 20 kV accelerating voltage and optical microscope. Specimen surfaces for SEM observations were coated with thin gold film to protect the fracture surfaces from beam damage and to prevent charge build up.

### 2.3.2. Mechanical characterization

In order to characterize the toughness of formulated epoxy composites in terms of the mode-I fracture toughness or critical-stress-intensity factor,  $K_{Ic}$ , quasi-static fracture tests were performed in accordance with ASTM D5045 [22]. The cured composite sheets were machined into rectangular coupons of nominal dimensions 100 mm × 12.5 mm × 5 mm; (span 60 mm). An edge notch of 3 mm length was cut into the samples and the notch tip was sharpened using a razor blade. The three-point bend specimen geometry and loading configuration are shown in Fig. 4. The single edge notched bend (SENB) specimens

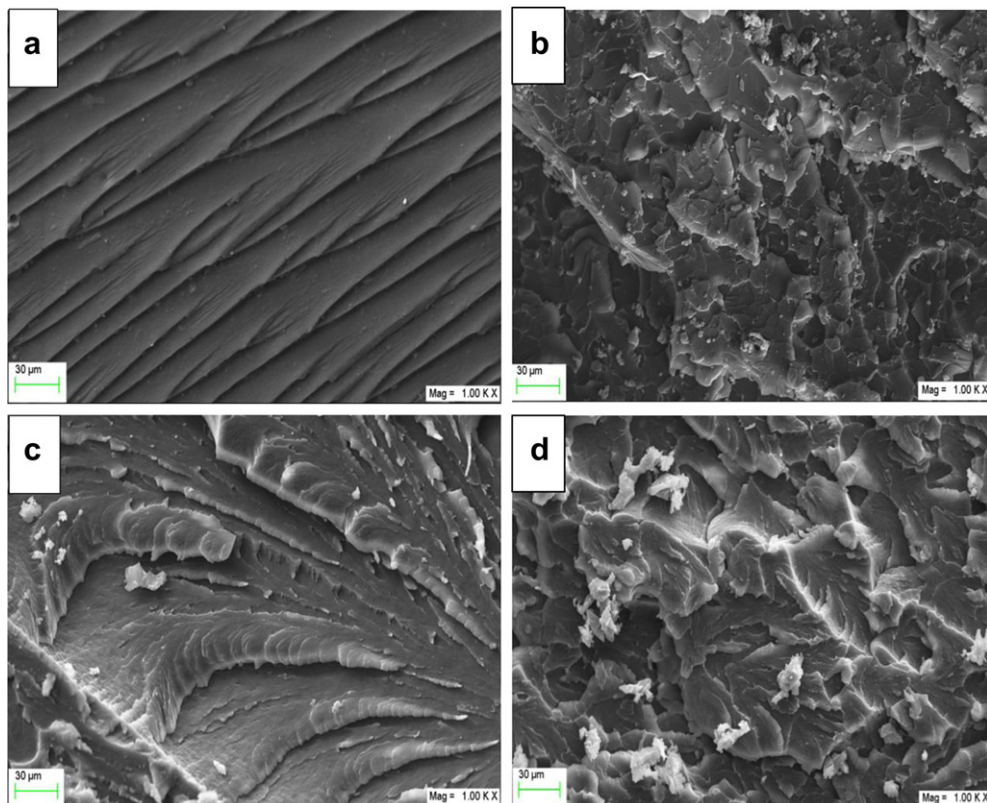


Fig. 7. SEM micrographs of fracture surfaces at magnification of ×1000: (a) control epoxy, (b) CNT/epoxy, (c) 10 phr polyol/epoxy, (d) CNT/10 phr polyol/epoxy.

were loaded in a displacement control mode at a crosshead speed of 0.2 mm/min using an Instron 4465 testing machine. The load vs. deflection data was recorded up to complete fracture of the specimens, and the mode-I fracture toughness,  $K_{Ic}$  was calculated using the load ( $P$ ) at crack initiation. A minimum of five specimens were tested for each category. The mode-I fracture toughness,  $K_{Ic}$  for a SENB specimen loaded in three-point bending was calculated using Eq. (1),

$$K_{Ic} = \frac{Pf\left(\frac{a}{W}\right)}{B\sqrt{W}} \quad (1)$$

where,  $f(a/W)$  is the geometric correction factor:

$$f\left(\frac{a}{W}\right) = \frac{3\frac{S}{W}\sqrt{\frac{a}{W}}}{2\left(1+2\frac{a}{W}\right)\left(1-\frac{a}{W}\right)^{3/2}} \left[ 1.99 - \frac{a}{W}\left(1-\frac{a}{W}\right)\left\{ 2.15 - 3.93\left(\frac{a}{W}\right) + 2.7\left(\frac{a}{W}\right)^2 \right\} \right]$$

and ' $P$ ' is the maximum load, ' $S$ ' is the span, ' $W$ ' is the specimen width, ' $a$ ' is the pre-crack length, ' $B$ ' is the specimen thickness.

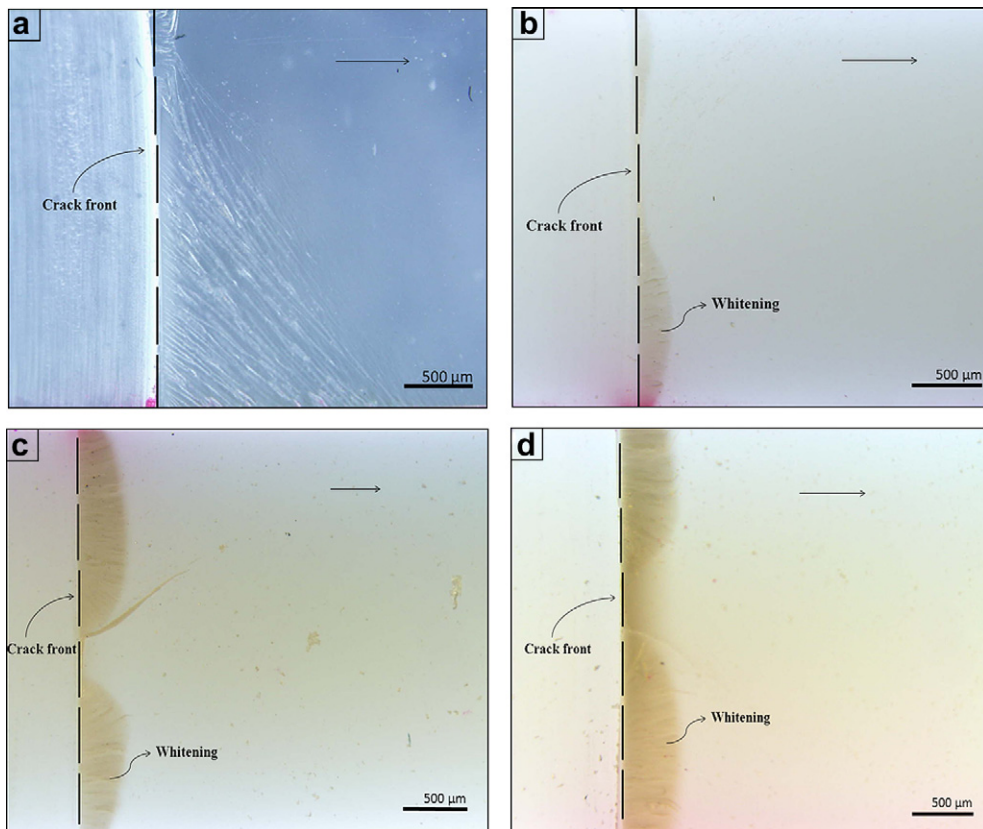
A three point bend flexure test was conducted to evaluate flexural properties of modified and unmodified epoxy

composites according to ASTM D790-02 [23]. Samples were precisely cut to 52 mm × 3.25 mm × 12.25 mm dimensions to maintain a span to thickness ratio of 16:1. Load-deflection data for each sample was collected from the test. The tests were performed using a Zwick-Roell Z 2.5 testing machine in displacement control mode with a crosshead speed of 1.2 mm/min. A minimum of eight specimens were tested for each category.

### 3. Results and discussion

#### 3.1. Mode-I fracture toughness ( $K_{Ic}$ )

Typical load-deflection curves obtained from SENB tests, and the variation in properties as a function of composition type, are shown in Figs. 5 and 6(a), respectively. The load-deflection plots are generally linear with a slight nonlinearity just before abrupt fracture, justifying the usage of Eq. (1). The positive effect of incorporating of polyether polyol and  $\text{NH}_2$ -MWCNTs in epoxy on mode-I fracture toughness is clearly evident, as shown in Fig. 6(b). There is a significant improvement in the toughness with the addition of MWCNTs in the epoxy system. However, a significant synergistic effect of polyether polyol and MWCNTs on the toughness of epoxy has been observed. With the presence of 0.3 wt.% MWCNTs and 10 phr polyol, fracture toughness achieved its highest value



**Fig. 8.** Optical micrographs of fracture surfaces in front of crack tip from SENB test: (a) control epoxy, (b) 5 phr polyol/epoxy, (c) 10 phr polyol/epoxy, (d) 15 phr polyol/epoxy (straight arrow indicates crack growth direction).

with a total enhancement of about 60% compared to pristine epoxy. Mode-I fracture toughness,  $K_{Ic}$  increased from  $1.95 \text{ MPa}\cdot\text{m}^{1/2}$  to  $3.11 \text{ MPa}\cdot\text{m}^{1/2}$  at simultaneous loading of 0.3 wt.% MWCNTs and 10 phr polyol into epoxy system, whereas only 0.3 wt.% MWCNTs loadings showed an average of  $2.66 \text{ MPa}\cdot\text{m}^{1/2}$ , and only 10 phr loading of polyol into epoxy showed  $2.35 \text{ MPa}\cdot\text{m}^{1/2}$ . A similar tendency has been observed in all other categories.

In order to investigate the behavior, the fracture surfaces of pristine epoxy and modified epoxy composite specimens were comparatively examined by SEM. The micrographs of fractured surfaces of unmodified and modified epoxy samples at  $\times 1000$  magnification near the crack tip are shown in Fig. 7(a–d). A nearly featureless fracture surface is seen in unmodified epoxy samples, as shown in Fig. 7(a). The surface is relatively smooth with presence of some fine lines that indicates generally uninterrupted crack propagation after originating from the crack initiation region. From the figures, it can be said that crack propagation occurs in a brittle and unstable manner, which accounts for the low fracture toughness.

Fig. 7(a) and (c) shows the micrographs of fracture surfaces of CNT-modified epoxy and 10 phr polyol-modified epoxy samples. It shows a rough fractured surface that presents ductile fracture of the composites. Rough surfaces with curved lines indicate that a significant amount of plastic deformation occurred in the material prior to fracture. Deviation of fracture planes from its

original crack initiation plane indicates an interrupted crack path deflection that requires more energy for the propagation of the crack.

Fig. 7(d) shows a micrograph of a fracture surface for an epoxy sample with 10 phr polyols and 0.3 wt.%  $\text{NH}_2$ -MWCNTs. The fracture surface appeared to have a greater degree of roughness compared with CNTs-toughened and polyols toughened epoxy surfaces. This rougher surface can again be attributed to continual crack deflection and propagation in different fracture planes due to the presence of carbon nanotubes and immiscible polyol particles. More curved and ridged patterns were observed throughout the fracture surface, which indicates that nanotubes and polyol might contribute simultaneously to increasing toughness of epoxy composite.

In addition, the presence of some whitening in the fractured planes, as shown in Fig. 7(c–d), might be a result from rupture of elastomeric particles such as polyol. Fig. 8(a–d) shows the optical micrographs of the damage zone of SENB specimens. As can be seen from the figure, plastic deformations at the plastic zone of modified resin are accompanied by stress whitening. The size of the stress whitening in the plastic zone increases with the increase of polyol contents in the epoxy. The enhancement of fracture toughness can be attributed to increased deformation of epoxy and reduction of yield strength due to the interaction of elastomeric particles and epoxy. The reduction of macroscopic yield strength promotes crack tip blunting and

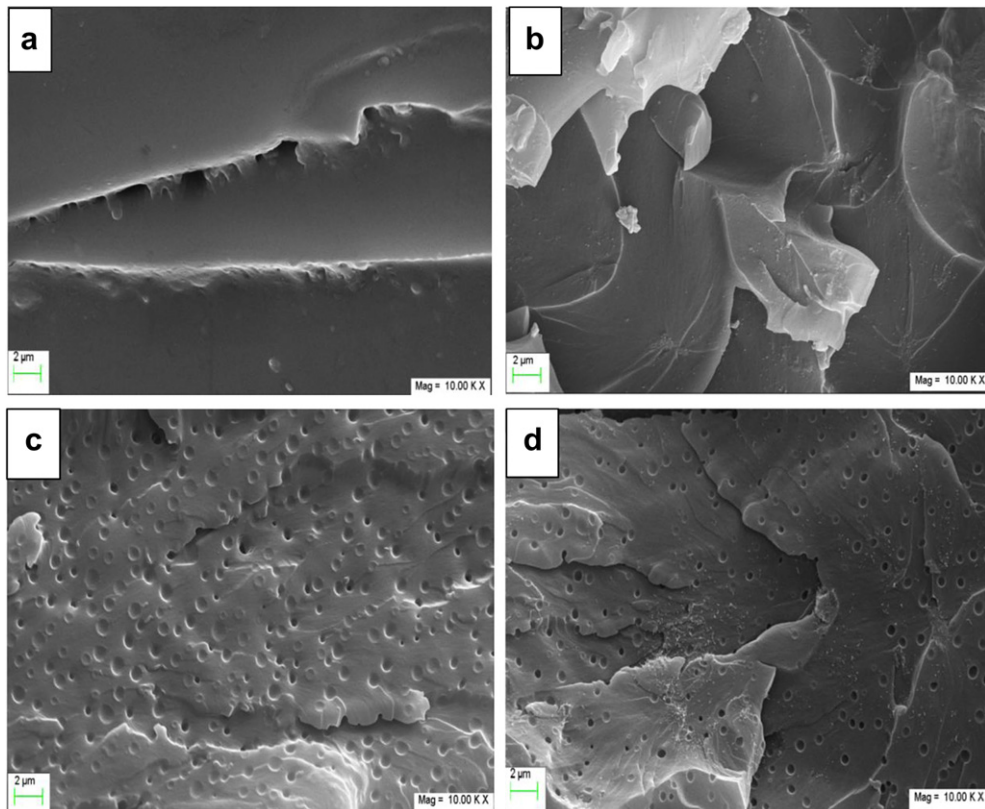


Fig. 9. SEM micrographs of fracture surfaces at magnification of  $\times 10,000$ : (a) Control epoxy, (b) CNT/epoxy, (c) 10 phr polyol/epoxy, (d) CNT/10 phr polyol/epoxy.

produces a larger plastic zone around the crack tip that contributes to the improvement of fracture toughness. Thus, plastic deformation in the plastic zone of modified resin has caused stress whitening, which may be a reason for toughness improvement.

As shown in Fig. 9(c), polyol-toughened fracture surface that has been magnified 10,000 times shows a large number of uniformly dispersed spherical holes. The cavitations in rubber particles make it easy to differentiate the two distinct phase morphology. From the SEM observation it can be said that polyols mixed with epoxy groups and formed an immiscible rubbery phase with epoxy systems during the polymerization reaction. Uniform distribution of spherical polyol domains throughout the epoxy matrix allows uniform plastic deformation and considerable shear yielding, as expected for ductile systems. Cavitation is the most important factor for rubber toughened systems, as reported by Bagheri et al. [24]. They showed that generation of voids due to cavitations of rubbery domains acts as crack interrupters that are essential for shear deformation of the matrix. This is potentially the main source of increased energy absorption capability, toughness properties and failure strain of polyol-toughened and polyol-CNT toughened epoxies.

### 3.2. Flexural properties

Typical stress–strain behavior obtained from the 3-point flexure tests is shown in Fig. 10. Fig. 11(a–c) compares the flexural properties as a function of composition type. The positive effect of incorporation of polyether polyols and NH<sub>2</sub>-MWCNTs on flexural properties is clearly evident. With the presence of both MWCNTs and polyols, flexural strain energy achieves its highest value. Average flexural strain energy was calculated from the area of load-deflection curves. In comparison to pristine epoxy samples, flexural strain energy was also found to be 99% higher at 10 phr polyol and 0.3 wt.% NH<sub>2</sub>-MWCNTs loading. It is even higher than that of only polyol-toughened or only CNT-toughened epoxy composites.

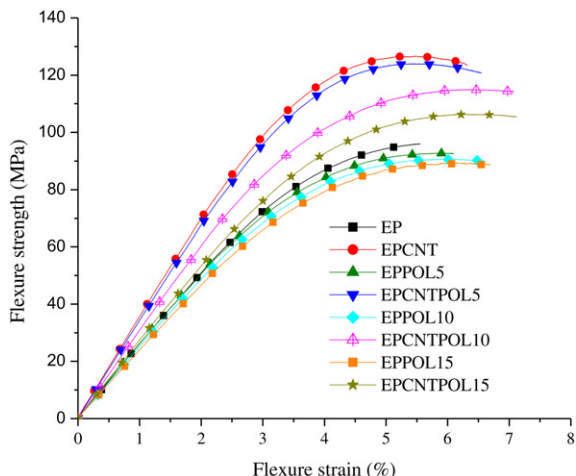


Fig. 10. Typical flexural stress-strain responses of different formulations.

As expected, the addition of polyols in pristine epoxy resins increased the flexural strain energy due to high extensibility or elongation property of the rubbery polyol domains. It could be also explained via rubber toughening mechanism as reported by Bagheri et al. [24]. On the other hand, carbon nanotubes have a high aspect ratio and show highly flexible elastic behavior during loading. Because of

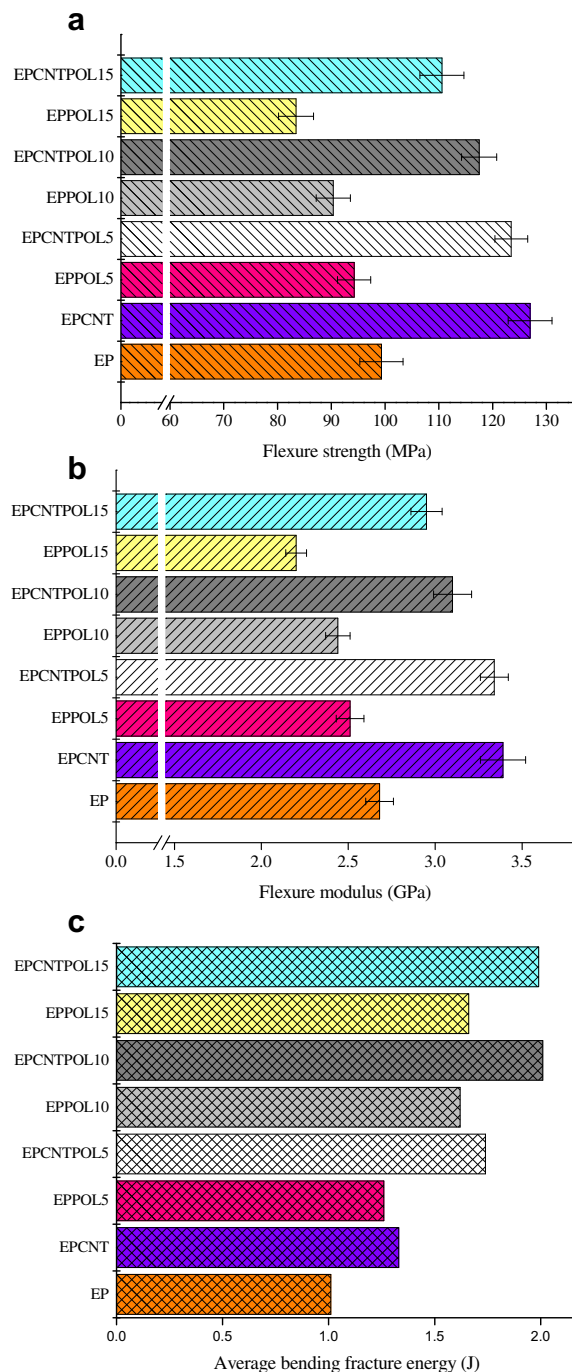


Fig. 11. Effect of NH<sub>2</sub>-MWCNTs and polyol contents on (a) flexure strength, (b) flexure modulus and (c) flexure strain energy of epoxy composites.



the strong interfacial bonding with this reinforcement, the nanophased resin systems exhibited higher absorption of energy. It was reported that polymer matrix added with amino-functionalized MWCNTs can increase the fracture energy as crack propagation can be resisted by bringing up the crack faces of nanotubes [19]. Bridging between epoxy matrix and MWCNTs, and thus better adhesion between them, has been observed due to crosslink interaction, as found by SEM investigation of cured epoxy/MWCNT composites (Fig. 12). When crack propagates in nanocomposites through a nanotube, crack tips cannot break the strong MWCNTs due to bridging by crosslinking. The energy of the tips is significantly reduced by the large quantity of nanotubes pulled out, as seen in Fig. 12. As a result, crack tips are then forced to arrest or change their crack propagation direction. A great deal of short and highly curved patterns of crack propagation into the matrix systems is clearly observed from Fig. 7(d) due to this phenomenon. As a result, crack initiation and propagation become difficult within the matrix as compared to samples with no CNTs, resulting in higher energy absorption capability. Toughness and energy absorption mechanism could be explained by energy dissipation of MWCNTs during nanotubes pull-out in the nanocomposite.

Flexural strength and modulus were observed to decrease with increasing amount of polyols in comparison

to pristine samples, as shown in Fig. 11(a–b). Flexural strength exhibit a declining trend with higher polyol contents as the rubbery effect of polyol domain may become dominant at higher content. As the polyol domain becomes larger at higher content, as shown in Fig. 13, the stress concentration effect of these domains could be higher, resulting in lower flexural strength. The flexural modulus gradually decreases for a similar reason. Rubbery phases may induce reduction in stiffness of the samples. The average diameter of the holes at 5 phr loading has been found to be in a range of 600–700 nm and at 15 phr it becomes 800–1000 nm. The larger diameter domains may act as defects and crack initiators instead of crack arrester, leading to reduced flexural properties. Additionally, the crosslink density of cured epoxy systems can be correlated with the mechanical strength and stiffness. It is reported that the crosslink density of the cured epoxy resin systems is reduced with polyol loading [25]. Hence, it can be rationalized that phase separated polyol domains occupy the space between the reaction sites as epoxy resin cures, thereby hindering the cross-linking reaction at those particular sites. However, the addition of MWCNTs into polyol toughened epoxy enhances both flexural strength and modulus.

Amino-functionalized MWCNTs can be rationalized to serve as a curing agent due to the presence of  $-NH_2$  groups.

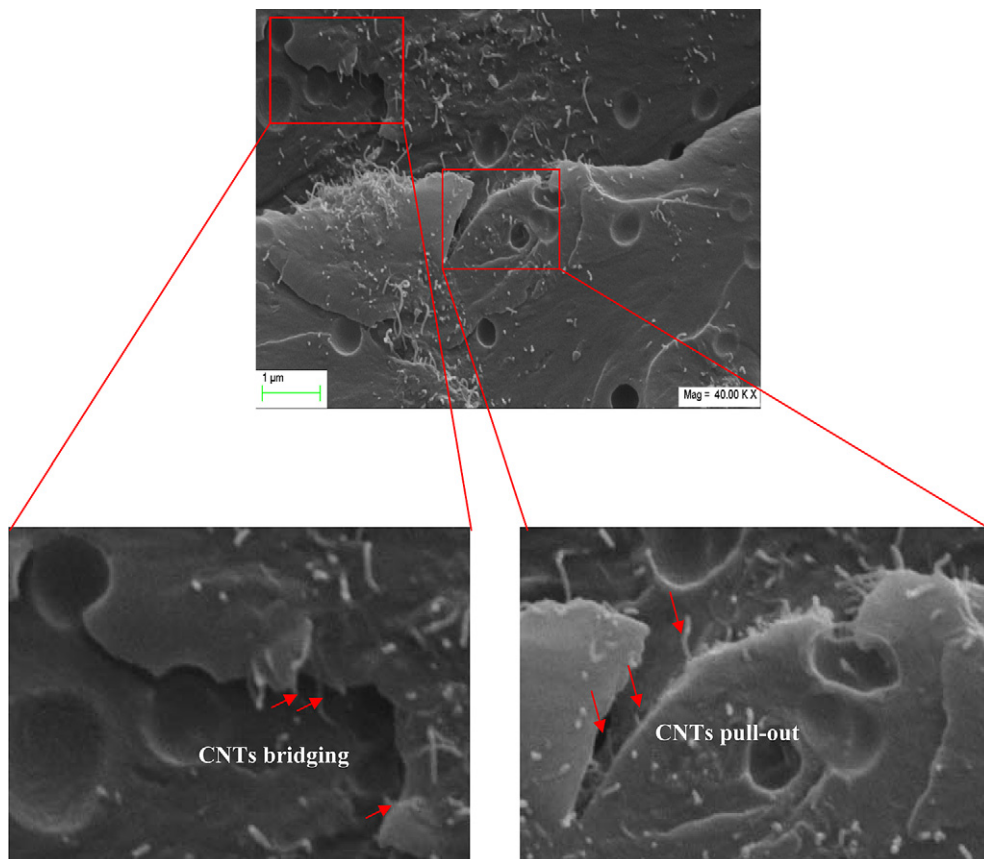


Fig. 12. SEM micrographs of nanotube bridging and pull-out in nanophased toughened epoxy specimen at magnification of  $\times 40,000$ .

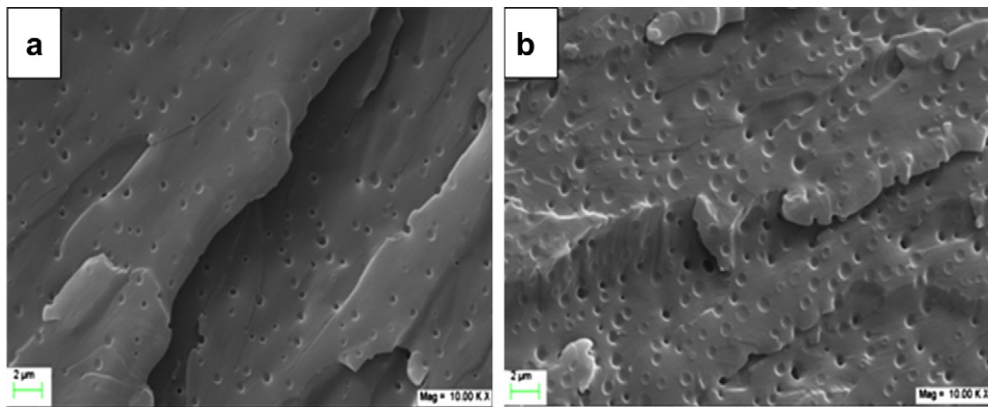


Fig. 13. SEM micrographs of fracture surfaces of polyols toughened epoxy specimen at 5 phr loading (a) and 15 phr loading (b) at magnification of  $\times 10,000$ .

Since  $\text{NH}_2$ -MWCNTs were mixed with epoxy and polyol before adding the curing agent, there may be better interfacial interactions among them. The interfacial reaction takes place between amine functional groups of CNTs and epoxide groups of DGEBA and epoxy terminated polyol, resulting in a ring opening reaction followed by a cross-linking reaction [25]. Thus, amino-functionalized CNTs promoted the crosslink density of epoxy composites and induced restricted mobility in the system, due to the formation of covalent bonds between the  $\text{NH}_2$ -MWCNTs and epoxide groups in epoxy resin and epoxy-terminated polyol. Mobility restrictions due to the presence of MWCNTs might also be due to physical and secondary chemical interaction, as reported by Abdalla et al. [26]. In addition, amino-MWCNTs may act as compatibilizers that improve the miscibility between the epoxy and the polyol. The average diameter of the voids for epoxy/polyol systems has been found to be 700–800 nm for 10 phr polyol loading samples, while they become 500–600 nm for MWCNT loadings, as measured by software associated with SEM [Fig. 9(c–d)]. The noticeable increase in flexural strength and modulus at 0.3 wt.% MWCNTs can be attributed to better dispersion of MWCNTs and better interfacial interaction between the  $\text{NH}_2$ -MWCNTs and epoxy/polyol systems. This improved interfacial interaction may have facilitated better stress transfer during loading, and thus an increase in flexural properties.

#### 4. Conclusions

In this study, toughener ‘polyether polyol’ and amino functionalized MWCNTs were incorporated into epoxy composites at different concentrations to enhance mechanical properties. Based on the experimental and micrographic results, the following conclusions are reached:

- Incorporation of polyether polyol in an epoxy system increased fracture toughness up to 20% and strain energy up to 60% at 10 phr loading, with a reduction of about 9% in flexural strength and stiffness. Considering enhancement of energy along with reduction of mechanical strength and stiffness, 10 phr polyol in epoxy resin may be considered as optimum loading.

- $\text{NH}_2$ -MWCNTs incorporation at a very low concentration in polyol/epoxy composites increased flexural properties of composites as well as fracture toughness significantly. Flexural test results indicate maximum improvement in strength, modulus and strain energy of about 18%, 16% and 99%, respectively at 0.3 wt.% loading of MWCNTs in 10 phr polyol/epoxy nanocomposites. Maximum ductility of epoxy resin is obtained without any reduction in properties when  $\text{NH}_2$ -MWCNTs and 10 phr polyether polyol was added to epoxy resin.
- A combination of mechanisms including particle cavitation, shear yielding, plastic deformation due to polyol-toughening and crack deflection, inability to break nanotubes, energy absorption by nanotubes pull-out due to MWCNTs may induce a synergistic approach to improve the ductility and other properties as well in epoxy systems.
- Overall, this work showed that amino-functionalized MWCNTs and polyether polyol can significantly improve the mechanical properties of epoxy systems under quasi-static loading conditions.

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