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Diglycidyl ether of bisphenol-A epoxy resin–polyether sulfone/polyether sulfone ether ketone blends: phase morphology, fracture toughness and thermo-mechanical properties

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Abstract The properties of diglycidyl ether of bisphenol-A epoxy resin toughened with poly(ether sulfone ether ketone) (PESEK) and poly(ether sulfone) (PES) polymers were investigated. PESEK was synthesised by the nucleophilic substitution reaction of 4,4'-difluorobenzophenone with dihydroxydiphenylsulfone using sulfolane as solvent and potassium carbonate as catalyst at 230 °C. The T_g–composition behaviour of the homogeneous epoxy resin/PESEK blend was modelled using Fox, Gordon–Taylor and Kelley–Bueche equations. A single relaxation near the glass transition of epoxy resin was observed in all the blend systems. From dynamic mechanical analysis, the crosslink density of the blends was found to decrease with increase in the thermoplastic concentration. The storage modulus of the epoxy/PESEK blends was lower than that of neat resin, whilst it is higher for epoxy/PES blends up to glass transition temperature, thereafter it decreases. Scanning electron microscopic studies of the blends revealed a homogeneous morphology. The homogeneity of the blends was attributed to the similarity in chemical structure of the modifier and the cured epoxy network and due to the H-bonding interactions between the blend components. The fracture toughness of epoxy resin increased on blending with PESEK and PES. The increase in fracture toughness was due to the increase in ductility of the matrix. The thermal stability of the blends was comparable to that of neat epoxy resin.

Keywords Epoxy resin · Poly(ether sulfone ether ketone) · Fracture toughness · Morphology

Introduction

Epoxy resins are being used for multitudes of applications in day-to-day life. They are well known for good thermal and mechanical properties, excellent adhesion to various substrates and easy processability [1, 2]. The ability of epoxy group to react with a large number of reactive groups imparts versatility to the resin. By proper choice of the curing agent and curing conditions, it is possible to tune the ultimate properties of the cured resin according to end use. The cured resins give rise to highly crosslinked three dimensional network structures, which impart epoxy resin its characteristic properties. But this highly crosslinked structure itself becomes a drawback when it comes to structural applications. These materials are brittle and easily fail under impact. The inborn brittle nature of epoxy resin made it necessary to toughen them for many structural applications. Addition of reactively terminated rubbers has been reported to increase the fracture toughness of epoxy resin [3–8]. Different toughening mechanisms like rubber particle tearing, matrix shear yielding, cavitation, shear banding etc. were responsible for the improvement in fracture toughness of epoxy resin [9]. But rubber toughening is ineffective in multifunctional epoxy systems like tetraglycidyl diaminodiphenyl methane (TGDDM) because of high crosslink density. Also, rubber toughening resulted in decreased thermal stability and modulus. Hence, high performance engineering thermoplastics have been used

for toughening epoxy resins. The factors affecting the properties of the blends were extensively studied [10–19]. Among the various thermoplastic-toughened epoxy resin systems, polysulfone-modified epoxy resin was the most extensively studied system. Bucknall and Partridge [20] were the first to report on the toughening of a diamine-cured trifunctional and tetrafunctional epoxy resin with PES. Even though they have not obtained the expected toughness enhancement, later on, other researchers succeeded in getting good toughness enhancement. One of the earlier studies involving toughening of DGEBA resin was reported by Hedrick et al. [21]. They used a low molecular weight phenolic hydroxyl-terminated PES to get 100% increase in fracture toughness. Later, a number of studies were conducted on the phase behaviour, cure kinetics, rheological properties, morphology, mechanical, thermal and fracture toughness of DGEBA/polysulfone blends. Various functionalised PES was also used to enhance the fracture toughness [22–29]. Unlike polysulfones, poly (ether ether ketone) (PEEK)/epoxy blends is a much less studied system. Owing to the difficulty in processing, commercial PEEK is seldom blended with epoxy resin. Instead of the semi-crystalline PEEK, functionalised PEEK or PEEK with pendent bulky groups were used to toughen epoxy resin. The properties were strongly dependent on the morphology of the blends [19, 30, 31]. Recently, we had synthesised a series of PEEK polymers with pendent alkyl groups and used them as toughening agents for epoxy resin. It was found that these polymers are effective in improving the toughness of DGEBA epoxy resin cured with DDS and the cure kinetics followed auto-catalytic mechanism [32, 33]. For the above said systems, pendent groups were introduced on the PEEK backbone resulting in decreased crystallinity and improved processability. We synthesised another PEEK polymer with sulfone group in the polymer chain and was used for toughening DGEBA epoxy resin. The mechanical properties, thermal properties, morphology and fracture toughness were investigated and compared with a commercial PES-modified epoxy resin.

Experimental

Materials

High purity dihydroxydiphenylsulfone (DHDPS) (Aldrich), 4,4'-difluorobenzophenone (DFBP) (Spectrochem), potassium carbonate (Qualigens), sulfolane (Aldrich) and toluene (Qualigens) were used for the synthesis. DHDPS and DFBP were vacuum-dried at 80 and 60 °C, respectively. Potassium carbonate was dried at 400 °C in a muffle furnace before using. Sulfolane was distilled under reduced pressure and stored over molecular sieves. Toluene was distilled over sodium and stored over sodium wire. A diglycidyl ether of bisphenol–A (DGEBA) epoxy resin (LY 556, Ciba Geigy) with epoxide equivalent weight 188.68 and the curing agent 4,4'-diaminodiphenylsulfone (DDS) (Merck) were used as received. The chemical structures of DGEBA and DDS are given in Fig. 1. A commercial grade polyether sulfone (PES), (P3500, Gharda Chemicals) with glass transition temperature 200 °C was used as received.

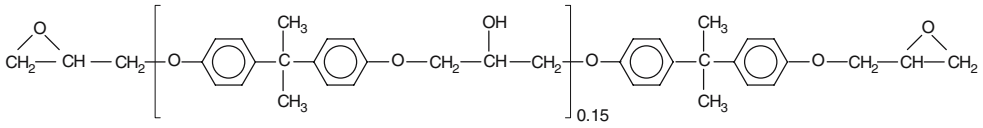
Synthesis of PESEK

Poly(ether sulfone ether ketone) (PESEK) was synthesised by the nucleophilic substitution reaction of DFBP with DHDPS as reported in our earlier paper as per Scheme 1 [34, 35]. A typical procedure for the synthesis of PESEK is as follows. The synthesis was conducted in a clean and dry four-necked flask equipped with a mechanical stirrer, thermowell, nitrogen inlet and Dean–Stark trap outfitted with a condenser. The flask was purged with dry nitrogen before starting the reaction. The flask was charged with 45 g (0.18 mol) of DHDPS, 29.8 g (0.22 mol) of potassium carbonate, 320 ml sulfolane and 150 ml toluene. The reaction mixture was refluxed at 120–160 °C for 4 h with constant stirring under nitrogen atmosphere. Water formed during reaction was removed as azeotrope with toluene through the Dean–Stark trap. After 4 h, the reaction temperature was brought down to 100 °C and 39.2 g (0.18 mol) of DFBP and 100 ml sulfolane were added to the flask. The reaction mixture was further heated at 230 °C for 3 h and cooled to room temperature. The viscous polymer solution was precipitated in large excess of methanol at room temperature with constant stirring. The precipitated polymer was filtered and purified by refluxing with water repeatedly followed by soxhlet extraction with methanol. The resultant product was dried under vacuum at 120 °C for 24 h and characterised using various analytical techniques.

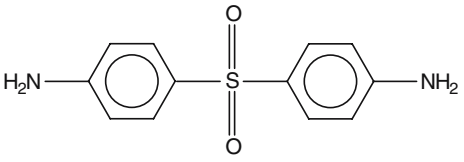
Blend preparation

The blends were prepared by melt mixing. PESEK was dissolved in epoxy resin at 180 °C with constant stirring. After complete dissolution, stoichiometric amount of DDS was added and dissolved completely. The ternary solution was evacuated in a vacuum oven at 180 °C. After evacuation, the mixture was transferred into an open mould kept at 180 °C. The blend was cured in an air convection oven at 180 °C for 3 h and post-cured at 200 °C for 2 h. After post-curing, the blends were allowed to cool slowly to room temperature. For preparing epoxy/PES blends, required amount of PES was dissolved in epoxy resin at 120 °C and the rest of the process is same as in the case of epoxy/PESEK blends. Blends with 0, 5, 10 and 15 phr modifier were prepared.

Fig. 1 Chemical structures of epoxy resin and DDS



Diglycidyl ether of bisphenol-A



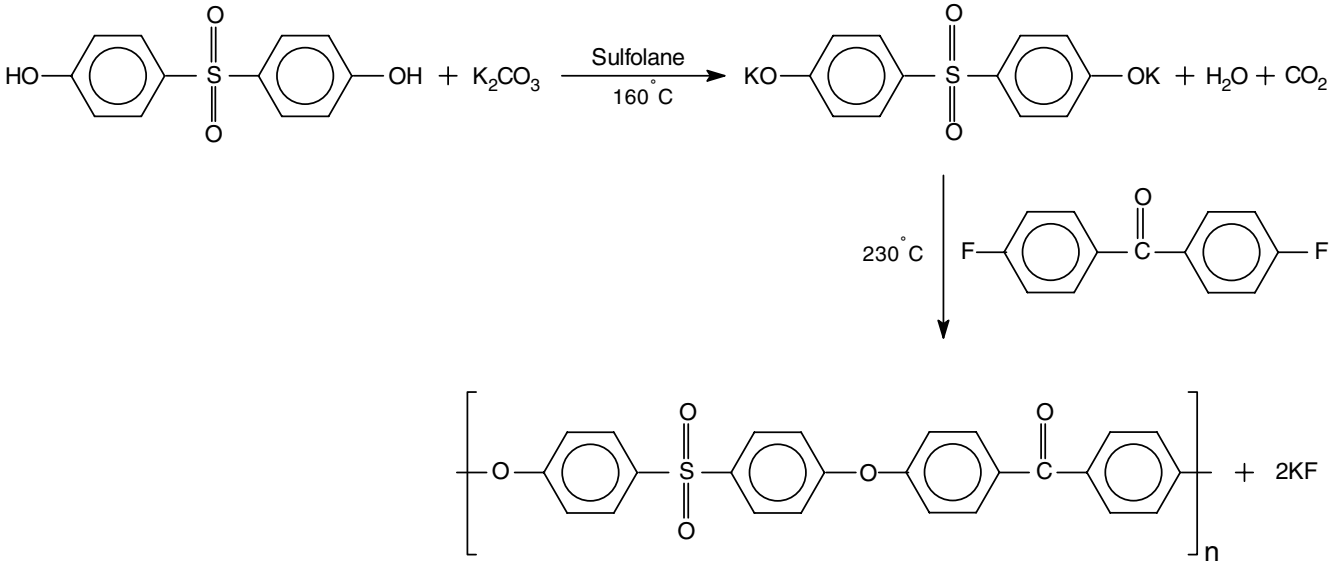
4,4'-diaminodiphenyl sulfone

Characterisation

The molecular weight and molecular weight distribution of PESEK was determined using gel permeation chromatography (GPC). A Waters Alliance separation module in conjunction with Waters 410 differential refractive index detector was used. The machine was calibrated using polystyrene standard. The analysis was done using chloroform as solvent at a flow rate of 1 ml/min. The inherent viscosity of PESEK was determined for 0.4% polymer solution in concentrated sulphuric acid at room temperature using Ubbelhode suspended level viscometer. The ^{13}C NMR spectrum of PESEK was recorded using Bruker Avance-300 spectrometer. $CDCl_3$ was used as solvent and tetramethylsilane as an internal standard. The FTIR spectrum of the polymer in KBr pellets was recorded using a Perkin Elmer Spectrum GXA FTIR spectrometer.

DSC analysis

The glass transition temperature of pristine epoxy and uncured epoxy/PESEK blends were determined using TA instruments model 2920 differential scanning calorimeter. To determine the T_g of PESEK, the sample was heated from 0 °C to 250 °C at a heating rate of 10 °C/min in nitrogen atmosphere and to determine the T_g of pristine epoxy and uncured DGEBA/PESEK blends, the samples were heated from −50 to 200 °C at a heating rate of 10 °C/min in nitrogen atmosphere.



Scheme 1 Synthesis of poly(ether sulfone ether ketone)

Mechanical properties

Tensile and flexural properties

Specimens for mechanical testing were machined to the required dimensions from cast laminates by cutting with a diamond wheel cutter. Tensile measurements were done according to ASTM D638 using a universal testing machine (Model TNE 5000) at a crosshead speed of 10 mm/min. Rectangular specimens of 100×10×3 mm were used for determining flexural strength. The flexural measurements were done at a crosshead speed of 10 mm/min as per ASTM D790. Flexural strength was calculated using Eq. 1.

$$\textit{Flexural strength} = \frac{3PL}{2bd^2} \tag{1}$$

where, P is the load at break, L is the span length, b and d are the breadth and the thickness of the specimen, respectively.

Fracture toughness

Fracture toughness of the modified and unmodified resin was determined according to ASTM STP410. The fracture toughness was expressed as stress intensity factor (K_{Ic}). Rectangular specimens of 100×35×3 mm were used for fracture toughness measurements. A notch of 5 mm was made on one edge of the specimen. A natural crack was made by pressing a fresh razor blade into the notch. The analysis was done in tension mode. The fracture toughness was calculated using Eq. 2.

$$\textit{Stress intensity factor}, K_{IC} = \frac{QPa^{1/2}}{bd} \tag{2}$$

where P is the load at the initiation of crack, a is the crack length, b is the breadth of the specimen, d is the thickness of the specimen and Q is a geometry constant. Q was calculated using Eq. 3.

$$Q = 1.99 - 0.41(a/b) + 18.7(a/b)^2 - 38.48(a/b)^3 + 53.85(a/b)^4 \tag{3}$$

Scanning electron microscopy

The fracture surfaces of cryogenically fractured specimens and failed specimens from fracture toughness measurement were analysed using a Hitachi model S-2400 scanning electron microscope. The cryogenically fractured surfaces of DGEBA/PESEK and DGEBA/PES blends were etched with chloroform and dimethylsulfoxide (DMSO), respectively, for 24 h to remove the thermoplastic phase. The specimens were dried in vacuum overnight to remove the solvent. All the specimens were sputter coated with gold before taking the micrographs.

Dynamic mechanical thermal analysis

The viscoelastic properties of the neat resin as well as the blends were measured using TA Instruments DMA 2980 dynamic mechanical thermal analyser or a Rheometric Scientific (ARES) machine equipped with 2 K STD transducer. Rectangular specimens of 60×10×3 mm were used for the analysis. The analysis was done in dual cantilever mode at a frequency of 10 Hz. The samples were heated from room temperature to 275 °C at a heating rate of 3 °C/min.

Thermogravimetric analysis

The thermal stability of epoxy/PESEK blend was analysed by thermogravimetric studies using TA Instruments model SDT 2960 thermal analyser. The samples were heated from room temperature to 900 °C at a heating rate of 20 °C/min in nitrogen atmosphere.

Results and discussion

The general reaction scheme for the synthesis of PESEK is given in Scheme 1. The synthesis was carried out in sulfolane using DHDPS and DFBP as the monomers. The FTIR spectrum of PESEK showed characteristics peaks at 1,290–1,370 cm^{-1}, 1,220–1,225 cm^{-1} and 1,600–1,670 cm^{-1} due to sulfone group, ϕ–O stretching and ϕ–CO stretching vibrations, respectively. The ^{13}C NMR spectrum of PESEK along with peak assignments is shown in Fig. 2. The spectrum showed nine peaks due to nine distinguishable carbon atoms in the polymer. The peak due to carbonyl carbon was observed in the range 193.8 ppm. The other peaks are due to aromatic ring carbons. The number average molecular weight ($\overline{M}_n$), weight average molecular weight ($\overline{M}_w$) and polydispersity index of PESEK were found to be 8,500, 17,800 and 2.19, respectively, from GPC measurements. The glass transition temperature of the polymer was 192 °C from DSC analysis.

Miscibility of blends

Blends of DGEBA epoxy resin with PESEK and PES were prepared by melt mixing. Both the blend systems were transparent indicating homogeneous behaviour. Yamanaka

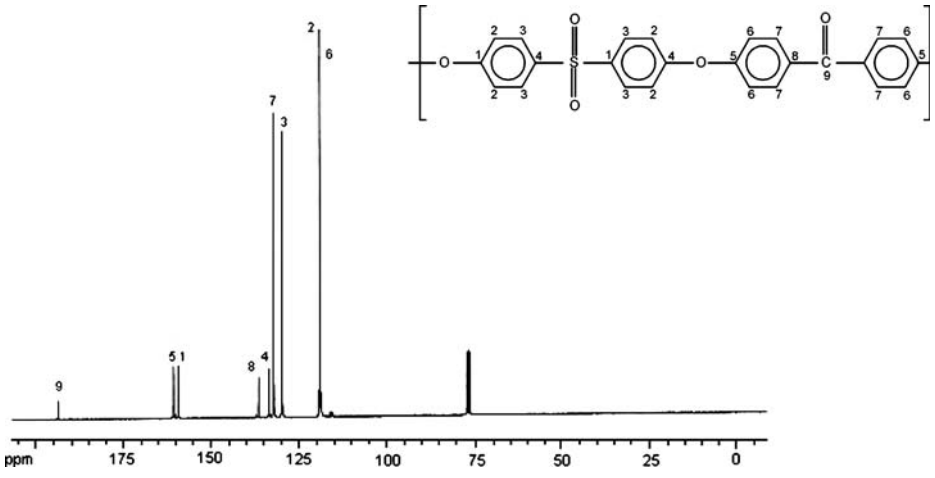


Fig. 2 ^{13}C NMR spectrum of PESEK

and Inoue [36] reported that PES formed homogeneous blends with DGEBA epoxy resin. Hence, the miscibility of DGEBA/PESEK blend was further studied by DSC. The binary blends exhibited a single T_g between the glass transitions of pure epoxy resin (−17 °C) and PESEK (192 °C). Several empirical equations like Gordon–Taylor [37], Kelley–Bueche [38] and Fox equation [39] as given by Eqs. 4, 5 and 6, respectively, are used to predict the T_g of homogeneous systems.

$$T_g = \frac{w_1 T_{g1} + k w_2 T_{g2}}{w_1 + k w_2} \tag{4}$$

$$T_g = \frac{v_1 T_{g1} + k w_2 T_{g2}}{v_1 + k v_2} \tag{5}$$

$$\frac{1}{T_g} = \frac{w_1}{T_{g1}} + \frac{w_2}{T_{g2}} \tag{6}$$

where T_g is the glass transition temperature of the blend, T_{g1} and T_{g2} are the glass transition temperatures, w_1 and w_2 are the weight fractions and v_1 and v_2 are the volume fractions of components 1 and 2, respectively, and k is an adjustable parameter. A plot of the experimental and theoretical glass transition temperatures is shown in Fig. 3. From the figure, it is seen that Kelley–Bueche and Gordon–Taylor equations gave good correlation with experimental values whereas Fox equation deviated maximum from the experimental values. According to Prud'homme and co-workers, [40, 41] the value of k in Gordon–Taylor equation is an indication of the interaction between the blend components. A k value of 0.24 gave the best fit in the present system. This indicated weak interaction between the blend components. In spite of the weak interactions, the blend was miscible. Hence, the reason for miscibility was entropic in origin due to the low molecular weight of epoxy prepolymer.

Dynamic mechanical thermal analysis

The tanδ against temperature plot of DGEBA/PESEK and DGEBA/PES blends are shown in Fig. 4a,b, respectively. A well-defined glass transition peak was observed for both the neat resin and the blends. This may be either due to the homogeneous phase behaviour of the blends or due to the close proximity of the glass transitions of PESEK or PES with that of cured epoxy resin. The molecular weight between crosslinks M_c was calculated using the following equation [42].

$$M_c = \frac{3.9 \times 10^4}{T_g - T_{g0}} \tag{7}$$

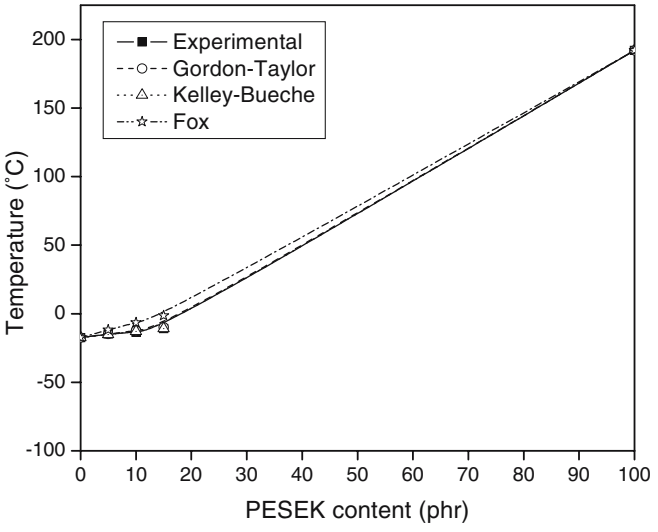


Fig. 3 T_g–composition behaviour of DGEBA/PESEK blends

where, T_g is the glass transition temperature of the crosslinked epoxy resin and T_{g0} is the glass transition temperature of the uncrosslinked polymer having the same chemical composition as the crosslinked polymer. The value of T_{g0} was taken as 91 °C for DGEBA/DDS system [43]. The effective crosslink density of the blends (ν_e) was calculated using the following equation [44].

$$\textit{Effective crosslink density}, \nu_e = \frac{\rho N_A}{M_c} \quad (8)$$

where, ρ is the density and N_A is Avogadro's number.

The T_g, molecular weight between crosslinks and effective crosslink density are given in Table 1. The molecular weight between crosslinks increased and crosslink density decreased with the addition of PESEK or PES to epoxy resin. The increase in M_c indicated decrease in the crosslink density of epoxy resin as shown in Table 1. Therefore, the reduction in T_g was due to the decrease in crosslink density of epoxy resin. The tanδ values from 50 to 125 °C are shown as inset in Fig. 4a,b. A relaxation called ω-relaxation due to the lower crosslink density sites in the epoxy network or due to the β-relaxation overtones in the regions of higher crosslink density matrix which are occluded in the lower crosslink density matrix could be seen in this region [45, 46]. The absence of relaxation peak for neat epoxy and 10 phr PESEK may be due to experimental error. The variation of storage modulus with temperature for epoxy/PESEK and epoxy/PES blends is shown in Fig. 5a,b, respectively. The storage modulus of PESEK-modified epoxy resin was lower than that of neat epoxy resin whilst the storage modulus of epoxy/PES blends was higher than that of neat epoxy resin till the glass transition region and thereafter it lowers. The loss modulus of the blends was lower than that of neat resin at room temperature (Fig. 6a,b). The ω-relaxation above room temperature due to lower crosslink density sites is clear in the loss modulus curves.

Table 1 T_g, M_c and crosslink density of the blends from dynamic mechanical thermal analysis

Blend composition (phr)	T_g (°C)	M_c (g/mol)	$\nu_e \times 10^{27}$ chains/m^3
PESEK			
0	220	302	2.39
5	209	331	2.19
10	217	310	2.33
15	213	320	2.21
PES			
0	233	276	2.59
5	225	291	2.19
10	229	282	2.33
15	217	309	2.26

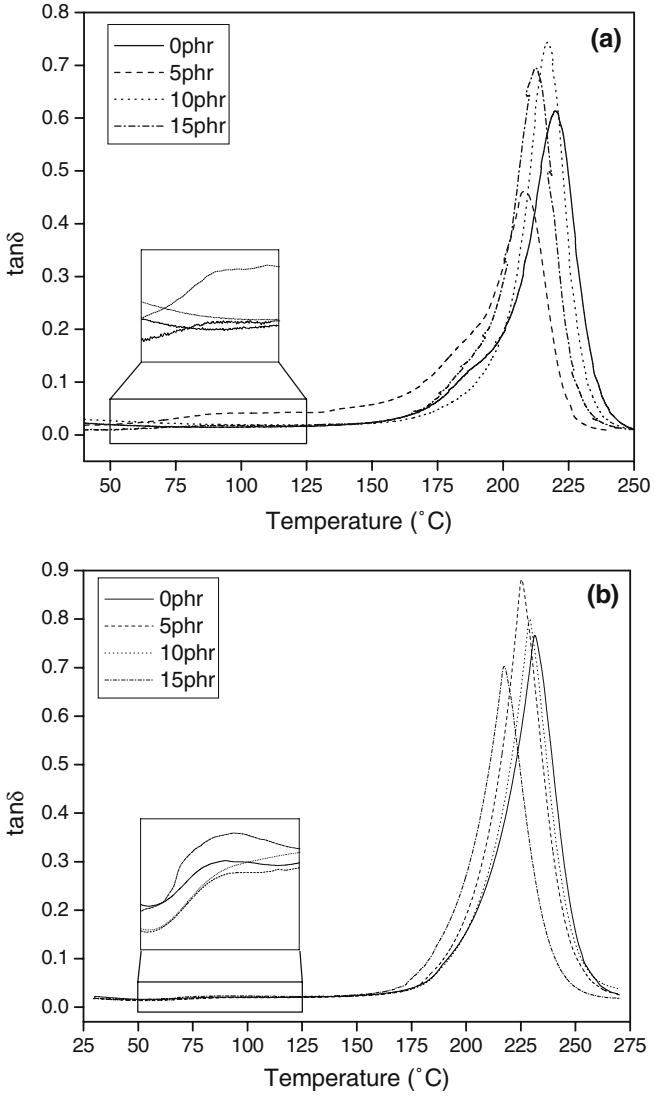


Fig. 4 tanδ against temperature plot for **a** DGEBA/PESEK and **b** DGEBA/PES blends

Scanning electron microscopy studies

The cured blends were visually transparent. This is in contrast to hydroxyl terminated PEEK with pendent tert-butyl (PEEKTOH) group toughened epoxy resin where the transparent solution became opaque on curing with DDS [33]. The visual transparency indicated homogeneity of the blends after curing. The scanning electron micrographs of unmodified epoxy resin, cryogenically fractured surfaces of DGEBA/PESEK and DGEBA/PES blends are given in Figs. 7, 8(a–c) and 9(a–c), respectively. The fracture surfaces of DGEBA/PESEK and DGEBA/PES blends were extracted with chloroform and DMSO, respectively. The fracture surface of epoxy resin revealed no heteroge-

neity. No evidence of phase separation was seen on the fracture surface confirming the homogeneity of the blends. But Hedrick et al. [47] reported that DDS-cured epoxy/PSF blends were heterogeneous. The miscibility in the blend systems was due to several reasons. One may be due to H-bonding between the blend components and another may be due to the gelation of epoxy resin before phase separation. A finite time is required for the phase separation of thermoplastic. This time is increasing during cure because the increase in viscosity caused by the increase in molecular weight of epoxy. Because the curing temperature was 180 °C, curing reaction was faster and, therefore, there was a rapid viscosity build up. Hence, gelation of the blends occurred in a short time. Consequently, vitrification of epoxy halts phase separation in the blends.

Mechanical properties

Tensile and flexural properties

The tensile and flexural properties of the blends are summarised in Table 2. The tensile strength increased with the addition of PESEK and PES to epoxy resin. Addition of PES (15 phr) gave maximum increase in tensile strength whilst the Young's modulus, flexural strength and flexural modulus were slightly lower than that of unmodified epoxy resin. The tensile stress–strain curves for the blends are shown in Fig. 10a,b. No yields were observed in the figure. An increase in strain was observed in the blends. Similar behaviour was observed in the flexural stress–strain curves of the blends

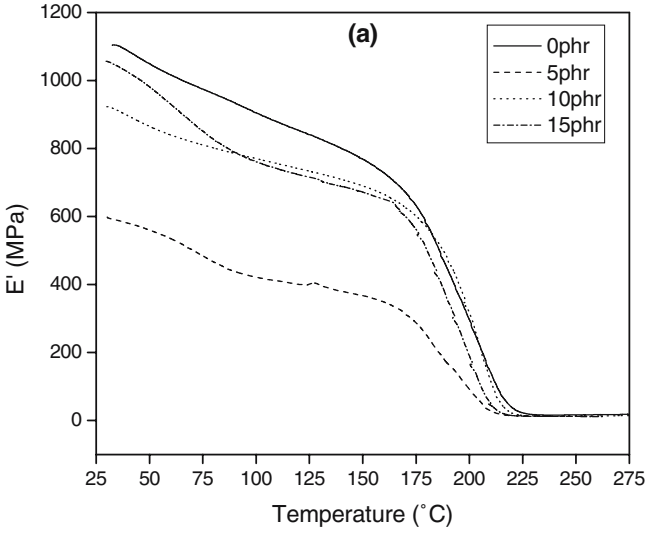


Fig. 5 Storage modulus against temperature plot for **a** DGEBA/PESEK and **b** DGEBA/PES blends

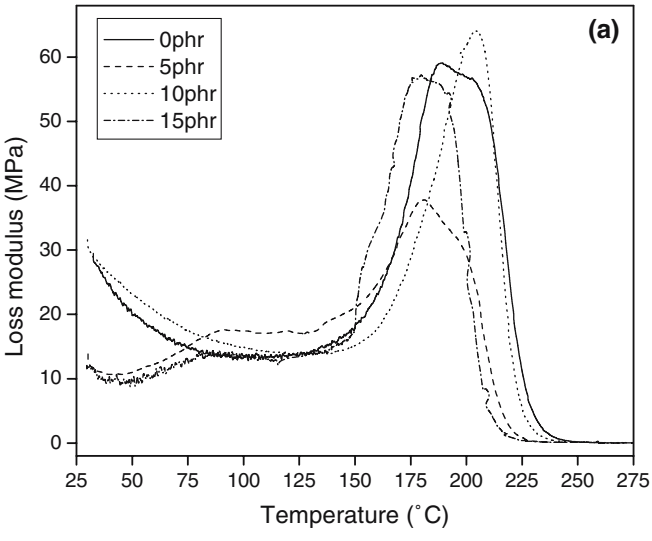


Fig. 6 Loss modulus against temperature plot for **a** DGEBA/PESEK and **b** DGEBA/PES blends

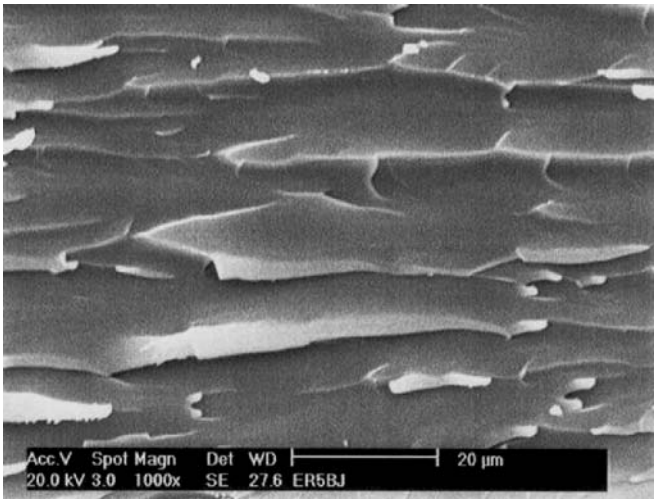


Fig. 7 Scanning electron micrograph of unmodified epoxy resin

(Fig. 11a,b). The properties of epoxy/PES blends were found to be better than that of epoxy/PESEK blends. This may be due to the higher molecular weight of PES compared to PESEK.

Fracture toughness

The fracture toughness expressed as stress intensity factor (K_{Ic}) of the blends is shown in Fig. 12. The fracture toughness increased with the addition of PESEK or PES to epoxy resin. The increase in fracture toughness was more in PES-toughened system compared to PESEK-toughened system. This may be due to more amorphous and high molecular weight of PES. In our earlier systems epoxy/PEEKTOH [34], the increase in fracture toughness was found to be more than twofold. This is due to the better interaction between terminal hydroxyl groups of PEEKTOH with epoxy resin and reaction induced phase separation, thereby several energy-absorbing mechanisms played a role in toughening the blends. Such factors were absent in the present system; hence, the increase in fracture toughness is not very high. Huang et al. [48] attributed the increase in fracture toughness of homogeneous diamonodiphenylmethane-cured epoxy/PES blends due to the decrease in crosslink density of epoxy resin. The scanning electron micrographs of failed surfaces of PES-modified epoxy resin are shown in Fig. 13. The fracture surfaces were rough and river marks are formed on the surface. These are evidences for ductile nature of the crack.

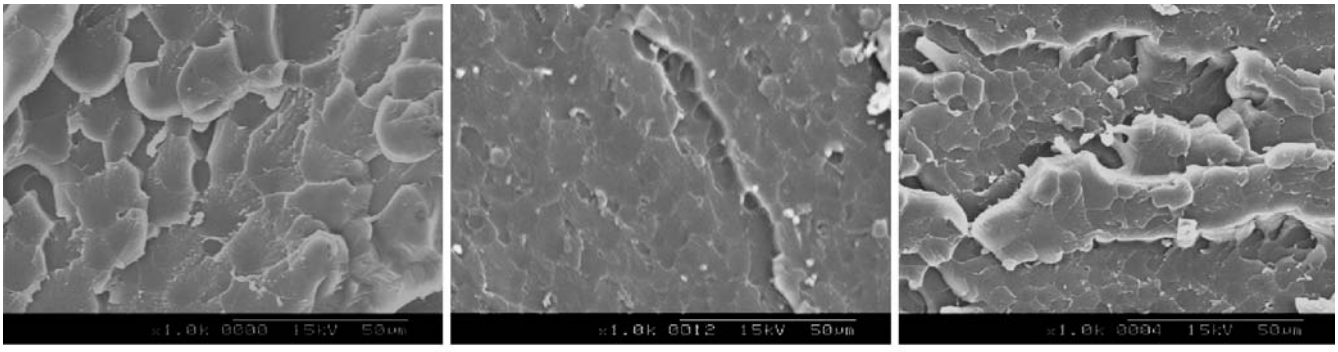


Fig. 8 Scanning electron micrographs of **a** 5 phr, **b** 10 phr and **c** 15 phr DGEBA/PESEK blends

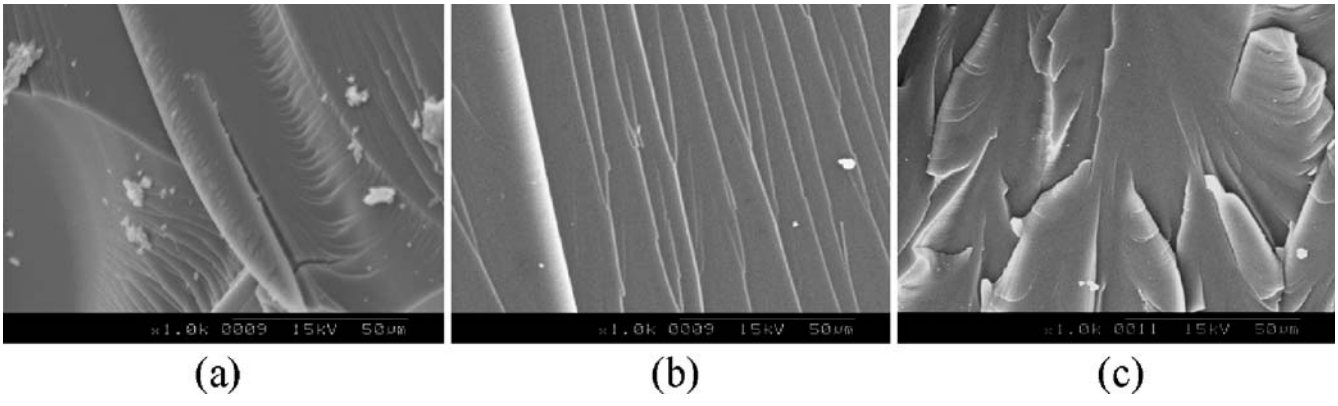


Fig. 9 Scanning electron micrographs of **a** 5 phr, **b** 10 phr and **c** 15 phr DGEBA/PES blends

Table 2 Mechanical properties of blend

Composition (phr)	Tensile strength (MPa)	Young's modulus (GPa)	Flexural strength (MPa)	Flexural modulus (GPa)
Epoxy resin	60±4	1.70±0.12	122±6	2.95±0.11
DGEBA-PESEK				
5	66±3	1.39±0.06	105±2	2.74±0.13
10	64±2	1.30±0.05	109±3	2.74±0.10
15	63±2	1.40±0.07	118±2	2.72±0.08
DGEBA-PES				
5	80±6	1.55±0.07	115±8	2.85±0.14
10	79±5	1.55±0.09	123±9	3.06±0.11
15	77±4	1.27±0.03	109±7	2.69±0.12

Thermal stability

The thermal stability of the blends was analysed using TGA. Epoxy resin toughened with PES was reported to be stable up to 360 °C [49]. Hence, we investigated the thermal stability of PESEK-modified epoxy resin. The initial decomposition temperature (IDT) and the temperature at maximum rate of decomposition (T_{max}) for the blends tabulated in Table 3 remained close to that of unmodified epoxy resin. Kinetic investigation is one of the most important applications of thermal analysis. Activation energy (E) for decomposition was calculated using non-isothermal integral equations viz; Coats–Redfern [50] equation. The main advantage of non-isothermal techniques is that the kinetic values for the whole temperature

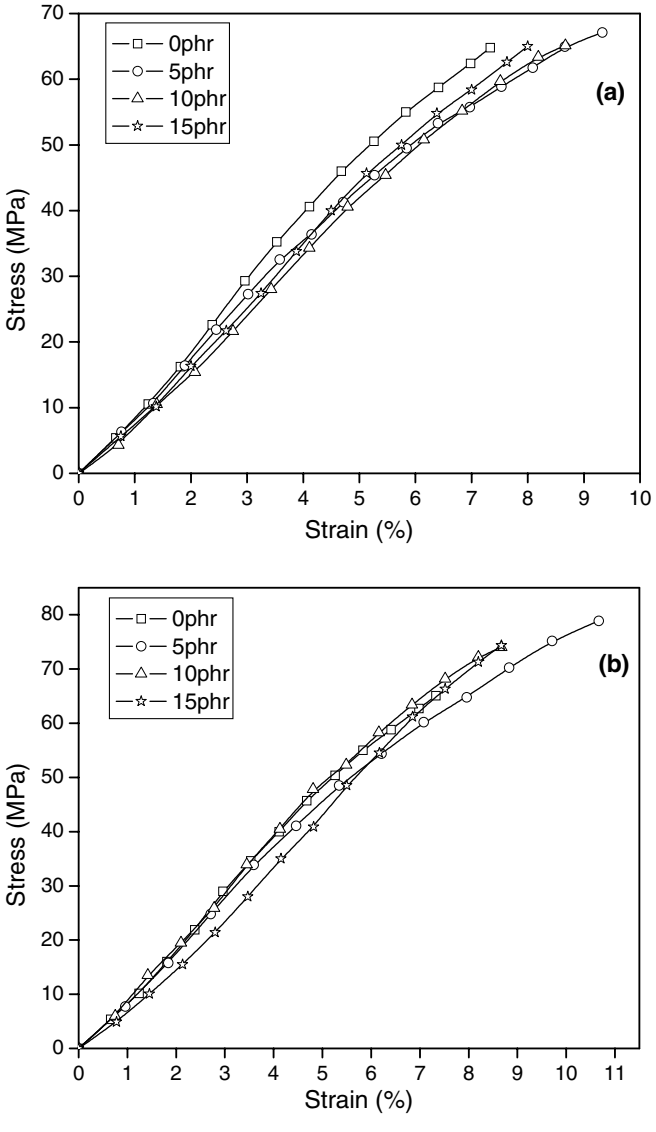


Fig. 10 Tensile stress–strain curves for **a** DGERBA/PESEK and **b** DGEBA/PES blends

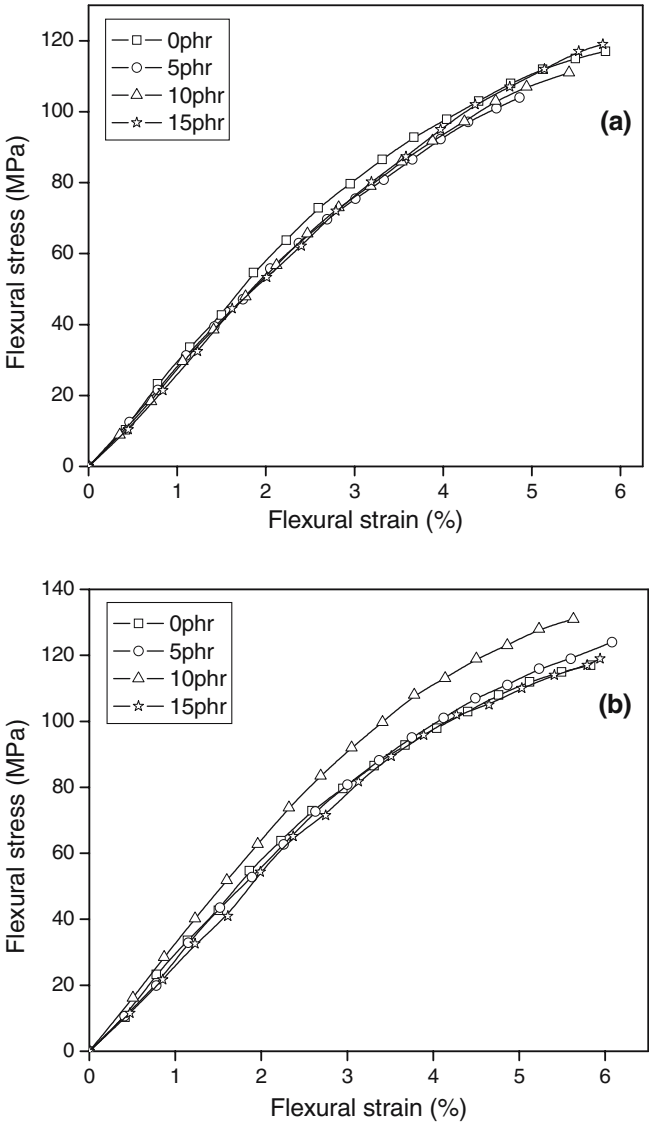


Fig. 11 Flexural stress–strain curves for **a** DGERBA/PESEK and **b** DGEBA/PES blends

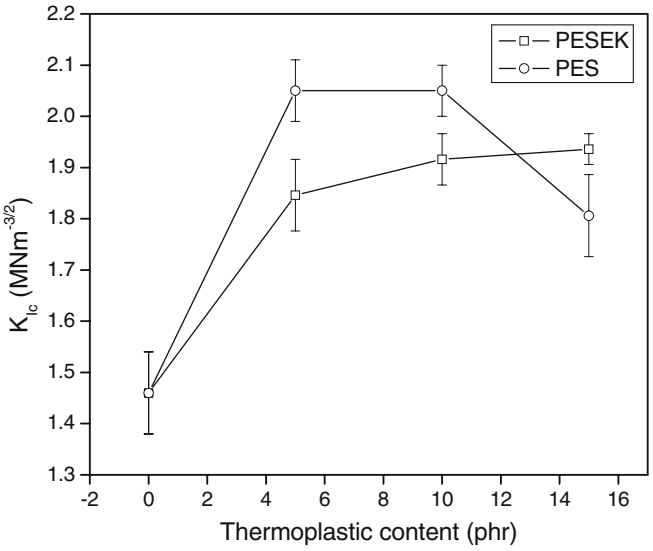


Fig. 12 Fracture toughness of PESEK- and PES-toughened epoxy resin

range could be obtained from a single measurement. The Coats–Redfern theory given in Eq. 9 was used to compute the activation energy.

$$1n\left[g(\alpha)/T^2\right] = 1n\left\{\left(AR/\varphi E\right)\left(1-2RT/E\right)\right\} - E/RT \qquad (9)$$

where, $g(\alpha) = \left\{\frac{1-(1-\alpha)^{1-n}}{1-n}\right\}$ for $(n \neq 1)$ and

$$g(\alpha) = -1n(1-\alpha) \, for \, (n \neq 1)$$

where, α is the fraction decomposed at temperature T, φ is the heating rate, R is the gas constant and A is the Arrhenius factor. Best fit (correlation coefficient r>0.99) was obtained for n=1. The activation energy was determined from the plot of ln[−ln(1−α)/T^2)] against the reciprocal of absolute temperature (1/T). Activation energy was calculated from the slope of the kinetic plot. The activation energy was slightly higher than that of neat epoxy resin. Overall, the thermal stability of the blends was comparable to that of neat epoxy resin.

Table 3 Initial decomposition temperature, T_{max} and activation energy for decomposition of DGEBA/PESEK blends

PESEK content (phr)	IDT (°C)	T_{max} (°C)	E (kJ/mol)	Correlation coefficient
0	401	430	280	0.9971
5	404	427	282	0.9982
10	404	425	281	0.9960
15	404	423	304	0.9981

Conclusions

A commercial PES and PEEK with sulfone group in the polymer chain synthesised from DFBP and DHDPS were used to toughen DGEBA resin cured with DDS. The blends formed homogeneous systems before curing. Uncured epoxy/PESEK blends exhibited single composition dependent T_g. Good correlation with experimental values was obtained using Gordon–Taylor and Kelley–Bueche equations. The initial miscibility was entropic in origin. Dynamic mechanical spectrum of the blends cured with DDS showed a single relaxation near the T_g of epoxy resin. Glass transition temperature of epoxy resin decreased with the addition of thermoplastic to epoxy resin. The molecular weight between crosslinks increased with the addition of PESEK or PES indicating decrease in crosslink density. The storage modulus and loss modulus was dependent on the composition of the blends. Scanning electron micrographs of the blends revealed no evidence for phase separation. The homogeneity of the blends was due to the similarity in chemical structure of the modifiers and the cured epoxy resin. H-bonding interactions between the

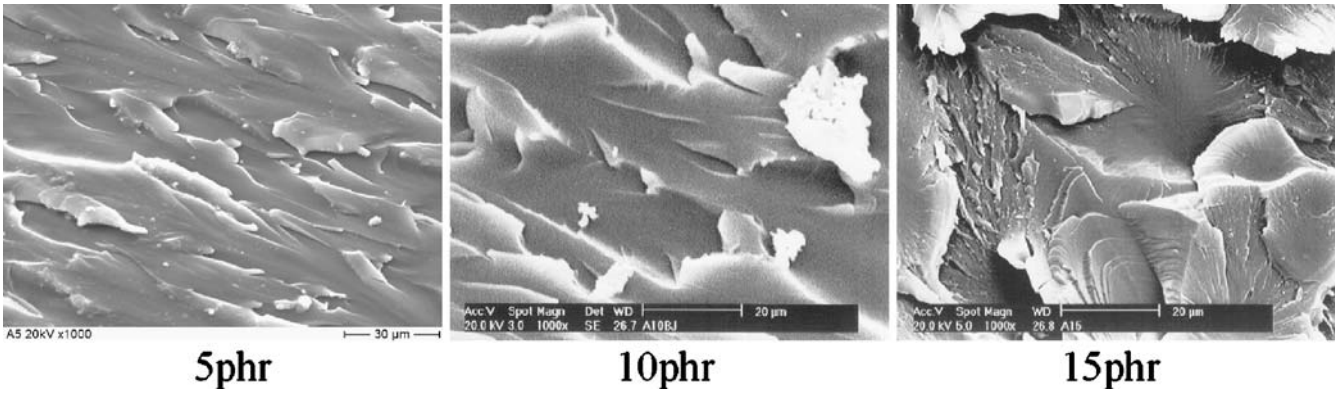


Fig. 13 Scanning electron micrographs of failed surfaces of PES-modified epoxy resin

modifiers and epoxy resin also favoured miscibility. Tensile strength of the blends increased with the addition of PESEK and PES. Addition of PESEK or PES to epoxy resin increased the fracture toughness of epoxy resin. The increase in toughness was due to the ductility of the blends. Thermogravimetric analysis revealed no decrease in the thermal stability of epoxy resin with the addition of PESEK.

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