Tailoring the toughness and CTE of high temperature bisphenol E cyanate ester (BECy) resin

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Abstract. The objective of the present work is to enhancing the toughness and minimizing the CTE of a special class of bisphenol E cyanate ester (BECy) resin by blending it with a thermoplastic toughening agent. Poly(ether sulfone) was chosen as a high temperature resistant thermoplastic resin to enhance the thermo-mechanical properties of BECy. The influence of poly(ether sulfone)/BECy blend composition on the morphology and phase behavior was studied using scanning electron microscopy and dynamic mechanical analysis. The mechanical properties of the blends were evaluated by flexural tests, which demonstrated significant enhancement in the material's toughness with an increase in PES concentration from 0 to 15 wt%. The coefficient of thermal expansion of pure BECy was reduced from 61 to 48 ppm/°C in the blends with PES, emphasizing the multi-functional benefits of PES as a toughening agent in BECy.

Keywords: thermosetting resins, bisphenol E cyanate ester, polymer matrix composites, injection repair, polymer blends and alloys

1. Introduction

The growing demand for strong and lightweight materials from polymer matrix composites (PMCs) has driven recent interest in engineering their functional properties. Under extreme service conditions, the toughness and the coefficient of thermal expansion (CTE) of the polymer matrix play an important role in controlling the durability of composite materials. Polycyanurates are used extensively to manufacture structural composites because of their excellent mechanical, thermal, and adhesive properties. Cyanate ester monomers with two or more cyanate ester ($-\text{O}-\text{C}\equiv\text{N}$) functional groups undergo a thermally initiated cyclotrimerization reaction to form densely packed cross-linked thermosets [1, 2]. Because of their high crosslinking density they exhibit high glass transition temperatures, moderate fracture toughness after cure, low toxicity, and long-

term stability [3]. The properties of dicyanate ester resins meet several service requirements for applications in extreme environments. Polycyanurates are also widely used in electronic circuit boards because of their low dielectric constant [4]. Another major advantage of cyanate ester resins is the ease of processability compared to typical thermoset resins used to manufacture polymer matrix composites (PMCs). The low room temperature viscosity and good compatibility with the reinforcing fibers phase makes them matrix resin of choice for PMCs. Bisphenol E cyanate ester (BECy) is considered a unique polycyanurate resin for composite applications because of its distinctive combination of high T_g and low viscosity at room temperature [5, 6]. BECy's low viscosity, caused by the rotational flexibility of the BECy monomer structure (Figure 1), makes it easy to process at low temperatures [1].

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Figure 1. BECy monomer transforming into a cross-linked networked structure (cured)

Good fiber wetting together with a glass transition temperature of 270°C when fully cured qualifies BECy for high service temperature applications. In our previous work, it was demonstrated that BECy outperformed a bisphenol A-based bifunctional epoxy in all mechanical tests, even at high temperatures (200°C) [7]. Bisphenol E cyanate ester resin was also identified as a unique adhesive for injection repair of damages in high temperature polymer matrix composites [8]. However, the inherent brittle behavior of BECy is a major disadvantage in functional applications. In addition, when BECy is used as the matrix resin in carbon fiber reinforced polymer composites, the high CTE of BECy (~60 ppm/°C) when compared to nearly negligible CTE of carbon fiber, results in a significant mismatch in the thermal expansivities of BECy and the reinforcing fiber phase. This mismatch in CTE results in residual stress in the composites leading to loss in dimensional stability of the produced parts.

While the current efforts to develop new thermoset resins with advanced thermal and mechanical properties were based on new synthesis routes [9, 10], blending of polymers offers a simple and easy alternative over complex synthesis techniques. Multi-phase polymer blends prepared to create or improve desired functional properties in thermoset polymers are considered potential alternatives in the literature [11–14]. In the present work, poly(ether sulfone)

Figure 2. Molecular structure of poly(ether sulfone)

(PES) was used as a high temperature resistant thermoplastic toughening agent for BECy. The molecular structure of PES is shown in Figure 2. PES is a well-known engineering thermoplastic with good mechanical and thermal stability at elevated temperatures [15]. Typical applications of PES include high temperature coating formulations, advanced high temperature composites, and specialty adhesives. In a recent work, Grishchuk *et al.* [16] have investigated the influence of blending PES in a tetrafunctional, anhydride hardened epoxy resin. The phase behavior and fracture mechanical of these thermoplastic-thermoset blends have been studied. Blending of this high performance engineering thermoplastic with BECy could reduce the brittleness of BECy without sacrificing its modulus and glass transition temperature (T_g). In addition to the improvement in toughness, the low CTE of PES compared to BECy is expected to reduce the CTE of BECy.

The objective of the work presented here was to study the toughening mechanism of BECy/PES blends for high temperature service applications. The phase behavior of BECy and PES blends was investigated qualitatively using SEM and thermo-mechanical techniques. Further, the CTE of BECy is engineered by blending with PES.

2. Experimental

2.1. Materials

Bisphenol E cyanate ester (BECy) was purchased from Tencate Technologies, Almelo, The Netherlands. Poly(ether sulfone) (RADEL A-304P) was kindly supplied by Solvay Advanced Polymers, Alpharetta, GA, USA. A melt mixing technique was used to blend BECy and PES following a procedure described earlier [14]. During the melt mixing procedure, pure BECy was initially heated to 160°C in a round bottom flask followed by blending PES in different blend concentrations of 5, 10, 15, 20 and 30 wt% in BECy. Using a mechanical stirrer, both blend components were continuously stirred until a clear, transparent solution was observed. A liquid

phase organometallic-based catalyst (EX-1510-B, Tencate Technologies, Almelo, The Netherlands) was added as a curing agent to cure the clear solutions (3 ppm). A standard curing schedule consisting of a pre-cure at 180°C for 2 h followed by a post-cure at 250°C for 2 h was used for all the samples.

2.2. Thermal analysis

The influence of blend composition on the phase behavior was studied by dynamic mechanical analysis (DMA). The temperature dependent dynamic mechanical properties were characterized by using a DMA Q-800 from TA Instruments, New Castle, DE, USA. DMA tests were conducted on 12×6×0.5 mm samples in tensile mode geometry between 30 to 320°C. A heating rate of 3°C/min, frequency of 1 Hz and a strain amplitude of 0.05% was used for the tests. The thermal stability of the neat polymers and their blends were determined by thermogravimetric analysis (TGA) using a TGA-Q50 from TA Instruments. TGA results were obtained in air for a temperature range from room temperature (*RT*) to 700°C at a heating rate of 20°C/min. The CTE of the samples was measured using a Q-400 thermo mechanical analyzer (TMA) from TA Instruments. The thermomechanical properties of the composites were characterized using the second heating scan of a heat/cool/heat cycle performed at 5°C/min from 25 to 320°C.

2.3. Mechanical properties

Specimens for flexural tests were machined from a 60×40×20 mm bulk sample using a slow-speed diamond edge saw. Flexural specimens with dimensions of 50×30×1 mm were tested in three-point bending mode with a span length of 30 mm. The flexural tests were performed using an Instron universal testing machine (model 4502), Norwood, MA, USA with a crosshead speed of 1 mm/min.

2.4. Morphology

The fracture surfaces of the flexural specimens were examined by scanning electron microscopy (SEM) using a Hitachi S-2460N, Japan. The SEM images were collected using backscattered electron signals from a working distance of 25 mm. Fracture morphology images of the blends were correlated with the mechanical properties of the samples.

3. Results and discussion

3.1. Morphology of BECy/PES blends

The phase morphologies of BECy/PES blends prepared by melt mixing were investigated by SEM analysis. During the sample preparation process, pre-cured BECy and PES blends were completely miscible, forming a clear solution. However, after curing, the samples appeared to lose their transparency. The change in the transparency of BECy/PES blends after curing was attributed to cure-induced phase separation in the blends. Figure 3 depicts the morphologies of the fracture surfaces of the investigated samples. The dark and light areas correspond to BECy and PES phases, respectively. Pure BECy samples exhibited a smooth fracture surface with traces of shear bands in the SEM micrographs, whereas BECy/PES blends showed microphase separation in all blend compositions. A systematic change in the microstructure was observed with an increase in PES concentration in the blends. Similar morphologies were observed previously in thermoset/thermoplastic blends tailored to improve the toughness of the materials [11, 14]. The PES minor phase initially appeared to form finely dispersed, spherical nano-domains inside the continuous BECy phase. With an increase in PES concentration from 5 to 15 wt%, the size and number of these PES micro domains increased along with a simultaneous decrease of the BECy phase. At 20 wt% PES, the BECy phase underwent a morphological transformation from a continuous to a discontinuous structure, revealing composition-dependent phase inversion.

The SEM micrographs of blends with high PES concentrations (blends containing 30 wt% of PES) exhibited large BECy micro domains distributed inside the separated BECy/PES microphase structure. Due to large discrepancy in the phase separation, a low magnification SEM micrograph is used in Figure 3f, to present a representative local morphology of 30 wt% PES sample. In general, such morphologies are identified as non-uniform phase separated morphologies. The observed inhomogeneity in the microstructure of blends with high PES concentration was primarily driven by the viscosity of the un-cured resin. Uniform distribution of the binary phases in 30 wt% PES sample may be hindered due to the high viscosity of the melt. To overcome this problem, various research groups previ-

Figure 3. SEM micrographs of BECy/PES blends containing: a) 0, b) 5, c) 10, d) 15, e) 20, and f) 30 wt% PES

ously used solution casting techniques as an approach to achieve an equilibrium microstructure in blends, even at high PES concentrations [12, 17].

3.2. Dynamic mechanical analysis

The dynamic mechanical properties of BECy/PES blends were studied to understand the effect of phase separation on their temperature-dependent mechanical properties. The loss modulus (E'') and storage modulus (E') curves of BECy/PES blends are shown in Figure 4.

The influence of blend composition on the T_g behavior of the PES-rich phase was determined from the loss modulus (E'') curves. Figure 4a shows a decrease in T_g peak intensity with an increase in PES concentration. At low PES concentrations (0 to 15 wt%), as BECy formed a continuous phase with finely dispersed PES micro domains, the physical interactions between PES and the surrounding BECy phase hindered the segmental relaxation in the PES phase, resulting in reduced relaxation peak intensity in the blends [18].

The loss modulus curve of pure BECy exhibited a single peak at 270°C, indicating the glass transition (T_g) temperature of BECy. Blending PES with BECy resulted in a decrease in T_g compared to BECy, together with a simultaneous reduction in peak

intensity. The E'' curve showed a secondary peak at a lower temperature corresponding to the T_g of PES. With an increase in weight percent of PES in the blends, the secondary peak intensity gradually increased, approaching the T_g of the PES-rich phase near 240°C. The presence of two distinct T_g 's verified phase separation of the blends. The composition-dependent changes in glass transition temperatures of the BECy and PES phases are listed in Table 1. Generally, immiscible polymer blends show multiple glass transition peaks, whereas miscible blends show a single transition peak in the E'' curve [19, 20]. However, for partially miscible blends, the T_g peak becomes broader and the peak positions shift to either higher or lower temperatures [21, 22]. With the T_g of the PES (240°C) below the T_g of the BECy (270°C), a reduction in T_g for the BECy-rich phase was expected. With an increase in PES composition in the blends from 0 to 15 wt%, the T_g of the BECy-rich phase was reduced from 270 to 258.

As the peak position of T_g is primarily controlled by the mobility of the polymer chain segments, the presence of PES chains inside the cross-linked network of BECy may increase the segmental mobility, resulting in a shift of the T_g of BECy-rich phase to lower temperatures. Another potential reason for the

observed shift in the T_g behavior of the BECy-rich phase is the crosslinking density. Blending PES with BECy monomer may have adversely affected on the cure behavior of BECy, resulting in a lower crosslinking density. The degree of cure in BECy may be significantly affected by the functional groups on the blend component [23]. As glass transition temperature in thermoset polymers is directly proportional to the crosslinking density, the observed change in the glass transition temperature of the BECy-rich phase can be directly related to its inherent crosslinking density.

Figure 4. Influence of blend composition on the dynamic mechanical properties; a) temperature-dependent loss modulus (E'') curves of BECy/PES blends with different blend compositions; b) temperature-dependent storage modulus (E') of blends

The dynamic mechanical storage modulus (E') is used as another valuable tool to describe the influence of blend composition on the stiffness of a material over a broad temperature range. The changes in the storage modulus with PES concentration in the blends is shown in Figure 4b. The E' curves of pure BECy and BECy/PES blends showed an extended glassy plateau until the temperature reached the glass transition temperature of the inherent phases. The modulus of the material measured at 50°C within the glassy regime is listed in Table 1. With an increase in PES concentration from 0 to 10 wt%, a slight reduction in glassy modulus from 2.27 to 2.10 GPa was observed for the blends. Further increase in PES content above 10 wt% resulted in a significant reduction in modulus from 2.10 to 1.12 GPa. The composition-dependent change in the modulus of the blends was attributed to the phase separated microstructure. At low PES concentrations, as the BECy phase formed a continuous phase, the mechanical properties were primarily dominated by the properties of BECy. However, at high PES concentrations, the transition in the morphology of the blends from a continuous to a discontinuous BECy phase resulted decrease in the storage modulus of the blends, as the modulus of PES is lower than that of BECy.

3.3. Influence of PES concentration on flexural properties of BECy/PES blends

In order to further investigate the influence of PES concentration on the mechanical properties of BECy/PES blends, flexural properties were evaluated using three-point bending tests. Flexural stress and ultimate strain to break are shown in Figure 5a and 5b, respectively. The toughness of the samples was determined by the area under the corresponding flexural stress-strain curves in Figure 5c. With an increase in PES concentration, the flexural mechanical properties (flexural stress, ultimate strain, and toughness)

Table 1. Influence of blend composition on storage modulus (E') and glass transition temperature of BECy and PES phases

Samples	Storage modulus, E' at 50°C [MPa]	Glass transition temperature, T_g [°C]	
		BECy-rich phase	PES-rich phase
BECy	2.27	270	NA
BECy/PES 95/05	2.19	267	243
BECy/PES 90/10	2.10	261	240
BECy/PES 85/15	1.67	258	240
BECy/PES 80/20	1.22	267	247
BECy/PES 70/30	2.57	265	240

increased initially, followed by a significant drop at high PES concentrations (above 15 wt%). In general, the mechanical properties of phase separated polymer blends primarily depend on the interfacial adhesion between the binary phases. Strong interactions between the binary phases provide a synergetic effect and maintain the best bulk material properties from both blend components. In addition to these physical interactions, the crosslinking density of the BECy phase may further influence the mechanical properties. Park *et al.* [24] observed a composition dependent decrease in crosslinking density of epoxy resins after blending with PES. In a more recent work, we reported that the crosslinking density of

pure BECy has a significant influence on the mechanical properties [25].

In the present work, the pronounced enhancement in mechanical properties of blends of BECy with 0 to 10 wt% PES was attributed to the strong interfacial adhesion between the binary phases and the optimum crosslinking density of the BECy phase in the blends. However, in the intermediate PES concentration range (5 to 15 wt%), the observed nominal decrease in mechanical properties was caused by the decrease in crosslinking density of the BECy phase. At higher PES concentrations (20–30 wt%), the significant decrease in mechanical properties was attributed to the transition of the blends from a continuous to a discontinuous BECy phase, as observed in the SEM micrographs. Therefore, in BECy/PES blends, the transition in phase morphology and the change in crosslinking density of the BECy phase were determined to be the root causes for the observed change in mechanical properties of the blends.

3.4. Influence of PES concentration on the thermal stability of the blends

Cyanate ester resins are well recognized as excellent high temperature resistant materials [26]. Blending cyanate esters with thermoplastic polymers may significantly reduce their ultimate thermal stability because most thermoplastic polymers are less stable at elevated temperatures. However, PES is classified under polysulfones which are known to be thermoplastic polymers with high thermal stability. Therefore, PES was selected as a potential candidate to enhance the physical and mechanical properties of BECy without sacrificing its thermal stability. The thermal stability of BECy, PES, and their blends were investigated using thermogravimetric analysis (TGA) and the corresponding TGA and derivative TGA traces are shown in Figure 6a and 6b, respectively. Table 2 shows the temperature at which 5% weight loss measured from the TGA curve and the maximum degradation temperatures ($T_{\max}$) determined by the peak position of the derivative TGA curve. The TGA curves reveal that both BECy and PES decompose in two steps, with major mass loss at 436°C for BECy and 524°C for PES. Figure 6a and Table 2 show that pure PES exhibits higher thermal stability than BECy. However, blending of PES with BECy did not improve the thermal stability, neither in the initial (5 % weight loss) nor in the maximum

Figure 5. Influence of blend composition on the flexural properties: change in a) flexural stress; b) flexural strain; c) flexural toughness

Table 2. TGA analysis of BECy, PES, and their blends

Samples	5 % weight loss temperature [°C]	Stage 1: $T_{\max}$ from derivative TGA peak	Stage 2: $T_{\max}$ from derivative TGA peak
BECy	412	436	516
BECy/PES 85/15	417	437	516
BECy/PES 70/30	390	438	514
PES	482	524	612

Figure 6. Thermogravimetric analysis (TGA) of pure BECy, PES, and their blends (BECy/PES 85/15, BECy/PES 70/30); a) TGA curves of BECy/PES blends illustrating the onset of thermal degradation; b) DTG curves of BECy/PES blends showing the shift in $T_{\max}$ with blend composition

($T_{\max}$) decomposition stages. In fact, a slight decrease in the initial decomposition temperature in the BECy/PES 70/30 blend was observed when compared to pure BECy. In thermoset polymers the crosslinking density plays a significant role in controlling their thermal stability; therefore, the slight drop in the initial decomposition temperature in the blends may be associated with the decrease in crosslinking density.

3.5. Influence of PES on the CTE of blends with BECy

Cyclic, high temperature thermo-mechanical loading of polymer matrix composites results in residual stresses in the composites caused by the mismatch in CTE between polymer matrix and reinforcing

phase [27]. Therefore, low CTE polymer resins are preferred for high temperature resistant polymer matrix composite materials. In general, the residual thermal stresses in composites negatively influence dimensional stability, resulting in decreasing structural strength of the composites. As PES exhibits a considerably lower CTE (~ 25 ppm/°C) than BECy (~ 60 ppm/°C) at room temperature, blending PES with BECy reduced the CTE of BECy-rich phase along while improving the toughness of the composites. The CTE values determined from the slopes of the thermal strain curves, both in the glassy and rubbery range, are plotted in Figure 7. In the glassy region, the CTE ranged between 100 and 150°C, and in rubbery region, it ranged between 250 and 300°C. The glassy CTE of BECy decreased from 61 to 48 ppm/°C with PES concentration increasing from 0 to 30 wt%, while the rubbery CTE increased from 209 to 229 ppm/°C. The rubbery CTE values were much higher than glassy CTE because of the high segmental motion of the polymer chains above T_g . In this temperature range, most thermoplastic polymers show terminal relaxation with liquid-like flow behavior, whereas in thermosets the segmental mobility is constrained by the cross-linked network. Therefore, the observed difference in CTE between BECy and BECy/PES in the rubbery region is primarily caused by the onset of terminal relaxation in the PES phase.

Figure 7. Influence of BECy/PES blend composition on the coefficient of thermal expansion (CTE) in the glassy and rubbery regions

4. Conclusions

The present work successfully explored the possibility of incorporation of poly(ether sulfone) (PES) into bisphenol E cyanate ester (BECy) resin by a simple blending process. The microphase separation in the blends observed by SEM images revealed both BECy and PES are forming miscible blends at all concentrations. DMA and TGA tests showed that the toughness of BECy resin increased considerably without significantly sacrificing the glass transition temperature after blending with PES. BECy/PES blends exhibited a reduction in CTE with increasing PES concentration, indicating that this blending strategy may be a simple alternative to the development of new polymer resins for the production of dimensionally stable, high temperature resistant composite materials.

References

- [1] Hamerton I.: Chemistry and technology of cyanate ester resins. Chapman and Hall, London (1994).
- [2] Grigat E., Pütter R.: Synthesis and reactions of cyanic esters. *Angewandte Chemie International Edition in English*, **6**, 206–218 (1967).
DOI: [10.1002/anie.196702061](https://doi.org/10.1002/anie.196702061)
- [3] Russell A. J., Bowers C. P.: Resin requirements for successful repair of delaminations. in 'Proceedings of the 36th international SAMPE symposium, San Diego, California' 2279–2290 (1991).
- [4] Kubens R., Schultheis H., Wolf R., Grigat E.: Aromatische Cyansaureester als Grundstoff für neue Harze in der Laminieretechnik. *Kunststoffe*, **58**, 827–832 (1968).
- [5] Shimp D. A., Craig Jr. W. M.: New liquid dicyanate monomer for rapid impregnation of reinforcing fibers. in 'Proceedings of the 34th international SAMPE symposium, Reno, USA', 1336–1346 (1989).
- [6] Sheng X., Akinc M., Kessler M. R.: Rheology and dynamic mechanical analysis of bisphenol E cyanate ester/alumina nanocomposites. *Polymer Engineering and Science*, **50**, 302–311 (2010).
DOI: [10.1002/pen.21543](https://doi.org/10.1002/pen.21543)
- [7] Thunga M., Lio W. Y., Akinc M., Kessler M. R.: Adhesive repair of bismaleimide/carbon fiber composites with bisphenol E cyanate ester. *Composites Science and Technology*, **71**, 239–245 (2011).
DOI: [10.1016/j.compscitech.2010.11.021](https://doi.org/10.1016/j.compscitech.2010.11.021)
- [8] Thunga M., Larson K., Lio W. Y., Weerasekera T., Akinc M., Kessler M. R.: Low viscosity cyanate ester resin for the injection repair of hole-edge delaminations in bismaleimide/carbon fiber composites. *Composites Part A: Applied Science and Manufacturing*, **52**, 31–37 (2013).
DOI: [10.1016/j.compositesa.2013.05.001](https://doi.org/10.1016/j.compositesa.2013.05.001)
- [9] Srinivasan S. A., McGrath J. E.: Amorphous phenolphthalein-based poly(arylene ether) modified cyanate ester networks: 1. Effect of molecular weight and backbone chemistry on morphology and toughenability. *Polymer*, **39**, 2415–2427 (1998).
DOI: [10.1016/S0032-3861\(97\)00598-3](https://doi.org/10.1016/S0032-3861(97)00598-3)
- [10] Srinivasan S. A., McGrath J. E.: Amorphous bisphenol A based poly(arylene ether) modified cyanate ester networks. *High Performance Polymers*, **5**, 259–274 (1993).
DOI: [10.1088/0954-0083/5/4/001](https://doi.org/10.1088/0954-0083/5/4/001)
- [11] Kinloch A. J., Taylor A. C.: The toughening of cyanate-ester polymers: Part II Chemical modification. *Journal of Materials Science*, **38**, 65–79 (2003).
DOI: [10.1023/A:1021109731672](https://doi.org/10.1023/A:1021109731672)
- [12] Wooster T. J., Abrol S., Hey J. M., MacFarlane D. M.: The effect of particle matrix adhesion on the mechanical properties of silica filled cyanate ester composites. *Macromolecular Materials and Engineering*, **289**, 872–879 (2004).
DOI: [10.1002/mame.200400127](https://doi.org/10.1002/mame.200400127)
- [13] Hwang J. W., Park S. D., Cho K., Kim J. K., Park C. E., Oh T. S.: Toughening of cyanate ester resins with cyanated polysulfones. *Polymer*, **38**, 1835–1843 (1997).
DOI: [10.1016/S0032-3861\(96\)00715-X](https://doi.org/10.1016/S0032-3861(96)00715-X)
- [14] Woo E. M., Shimp D. A., Seferis J. C.: Phase structure and toughening mechanism of a thermoplastic-modified aryl dicyanate. *Polymer*, **35**, 1658–1665 (1994).
DOI: [10.1016/0032-3861\(94\)90839-7](https://doi.org/10.1016/0032-3861(94)90839-7)
- [15] Bucknall C. B., Partridge I. K.: Phase separation in crosslinked resins containing polymeric modifiers. *Polymer Engineering and Science*, **26**, 54–62 (1986).
DOI: [10.1002/pen.760260110](https://doi.org/10.1002/pen.760260110)
- [16] Grishchuk S., Gryshchuk O., Weber M., Karger-Kocsis J.: Structure and toughness of polyethersulfone (PESU)-modified anhydride-cured tetrafunctional epoxy resin: Effect of PESU molecular mass. *Journal of Applied Polymer Science*, **123**, 1193–1200 (2012).
DOI: [10.1002/app.34610](https://doi.org/10.1002/app.34610)
- [17] Woo E. M., Su C. C., Kuo J-F., Seferis J. C.: Model with experimental evidences for the morphology of binary blends of a thermosetting polycyanate with thermoplastics. *Macromolecules*, **27**, 5291–5296 (1994).
DOI: [10.1021/ma00097a008](https://doi.org/10.1021/ma00097a008)
- [18] Pan Y., Xu Y., An L., Lu H., Yang Y., Chen W., Nutt S.: Hybrid network structure and mechanical properties of rodlike silicate/cyanate ester nanocomposites. *Macromolecules*, **41**, 9245–9258 (2008).
DOI: [10.1021/ma800819s](https://doi.org/10.1021/ma800819s)
- [19] Varughese K. T., Nando G. B., De P. P., De S. K.: Miscible blends from rigid poly(vinyl chloride) and epoxidized natural rubber. *Journal of Materials Science*, **23**, 3894–3902 (1988).
DOI: [10.1007/BF01106811](https://doi.org/10.1007/BF01106811)

- [20] Thomas S., Gupta B. R., De S. K.: Studies on morphology, mechanical properties and failure mode of blends of plasticized poly(vinyl chloride) and thermoplastic copolyester elastomer. *Journal of Vinyl Technology*, **9**, 71–85 (1987).
DOI: [10.1002/vnl.730090209](https://doi.org/10.1002/vnl.730090209)
- [21] Zhang X-R., Ma C-Y., Ke L., Jiang D.: Influence of compatibilization on the mechanical behavior and morphology of polyethersulfone/polycarbonate blends. *High Performance Polymers*, **23**, 212–218 (2011).
DOI: [10.1177/0954008311401440](https://doi.org/10.1177/0954008311401440)
- [22] Thunga M., Satapathy B. K., Staudinger U., Weidisch R., Abdel-Goad M., Janke A., Knoll K.: Dynamic mechanical and rheological properties of binary S–(S/B)–S triblock copolymer blends. *Journal of Polymer Science Part B: Polymer Physics*, **46**, 329–343 (2007).
DOI: [10.1002/polb.21304](https://doi.org/10.1002/polb.21304)
- [23] Fainleib A., Bardash L., Boiteux G.: Catalytic effect of carbon nanotubes on polymerization of cyanate ester resins. *Express Polymer Letters*, **3**, 477–482 (2009).
DOI: [10.3144/expresspolymlett.2009.59](https://doi.org/10.3144/expresspolymlett.2009.59)
- [24] Park S-J., Li K., Jin F-L.: Thermal stabilities and mechanical interfacial properties of polyethersulfone-modified epoxy resin. *Journal of Industrial and Engineering Chemistry*, **11**, 720–725 (2005).
- [25] Bauer A., Thunga M., Obusek K., Akinc M., Kessler M. R.: Bisphenol E cyanate ester as a novel resin for repairing BMI/carbon fiber composites: Influence of cure temperature on adhesive bond strength. *Polymer*, **54**, 3994–4002 (2013).
DOI: [10.1016/j.polymer.2013.05.030](https://doi.org/10.1016/j.polymer.2013.05.030)
- [26] Ramirez M. L., Walters R., Lyon R. E., Savitski E. P.: Thermal decomposition of cyanate ester resins. *Polymer Degradation and Stability*, **78**, 73–82 (2002).
DOI: [10.1016/S0141-3910\(02\)00121-0](https://doi.org/10.1016/S0141-3910(02)00121-0)
- [27] Badrinarayanan P., Rogalski M. K., Kessler M. R.: Carbon fiber-reinforced cyanate ester/nano-ZrW₂O₈ composites with tailored thermal expansion. *ACS Applied Materials and Interfaces*, **4**, 510–517 (2012).
DOI: [10.1021/am201165q](https://doi.org/10.1021/am201165q)