Curing Behavior and Mechanism of Diglycidyl Ether of Bisphenol-A in the Presence of Poly (Amide–Amidic Acid) and 4,4′-Diaminodiphenylsulfone

HAIMING CHEN, PEIHONG CONG, CHAO SU, AND TONGSHENG LI

State Key Laboratory of Molecular Engineering of Polymers, Department of Macromolecular Science, Fudan University, Shanghai 200433, People’s Republic of China

Poly (amide-amidic acid) (PAA) and 4, 4′-diaminodiphenylsulfone (DDS) with varying molar ratios were used as co-curing agents to cure diglycidyl ether of bisphenol-A (DGEBA). The curing process was investigated. The differences between PAA and the conventional curing agents are discussed relative to the curing behavior and mechanism when cured with DGEBA. It was found that a lower temperature was needed to cure DGEBA when PAA was used as co-curing agent with DDS. There was only one step during the curing process of DGEBA and PAA, compared with the conventional curing agents (two steps). The activation energy (E) of the curing process of DGEBA with the co-curing agents, computed using model free estimations, was lower than that with DDS and PAA individually.

Keywords cure kinetics, curing behavior, curing mechanism, epoxy resin, poly (amide-amidic acid)

1. Introduction

Epoxy resins are widely used in many fields ranging from high-performance composites to electric and electronic insulation, protective coatings, and structural adhesives because of their good properties of high bonding strength, excellent thermal resistance, high mechanical strength, and outstanding dielectric and aging characteristics. [1–3] Epoxides must be cured before being put into use, which is usually accomplished by a reaction of epoxy oligomers with active-hydrogen compounds (generally named curing agents). [2] The curing behavior and the properties of epoxides greatly depend on the molecular structure and content of curing agents. [4,5]

Poly (amide–imide)s (PAIs) are a kind of thermoplastic engineering plastic with high thermal resistance and high strength due to its chemical structure consisting of a high

Received 10 October 2012; accepted 24 July 2013.
Address correspondence to Tongsheng Li, State Key Laboratory of Molecular Engineering of Polymers, Department of Macromolecular Science, Fudan University, Shanghai 200433, People’s Republic of China. E-mail: lits@fudan.edu.cn
proportion of aromatic rings, double bonds, and heterocyclic imide structure along the polymer backbone.[6–8] The thermal and mechanical properties of PAIs are both better than that of epoxides. Generally, PAIs are obtained by the way of chemical or thermal imidization of poly(amide–amidic acid)s (PAAs).[6] There are three active-hydrogens in each structural unit of PAA: two come from secondary amides and one comes from carboxylic acid. As a result, it is feasible that the active-hydrogen of PAAs react with epoxy groups under proper conditions. In other words, PAAs can be used as curing agents of epoxides. By this means, aromatic rings, double bonds, and heterocyclic imide structure along the PAA polymer backbone can be introduced to the cross-linked network of epoxides, because of which, it can be expected that the thermal resistance and mechanic strength will be improved. Our former work has demonstrated that PAA can cure tetraglycidyl 4, 4′-diaminodiphenylmethane (TGDDM). What’s more, the fracture toughness and tensile strength of the PAA cured TGDDM were greatly improved compared with the one cross-linked by DDS.[9]

The study of the curing behavior, curing mechanism, and curing kinetics contribute both a better knowledge of the curing process and can improve the quality of the final product. As a result, these three factors of the curing process of epoxides by various curing agents have been extensively investigated.[10–15] Hong et al.[12], for instance, investigated the curing behavior of the epoxy/dicyandiamide/2-methylimidazole system with intercalated clays; they found that the curing behavior and mechanism were affected by the curing temperature and the type of intercalated clay. Cheng et al.[13] studied the curing behavior of a trifunctional epoxy resin cured by 4,4′-diaminodiphenylmethane. It was shown that the curing reaction was both dependent on the curing temperature and curing time, and the curing temperature had more effect on the curing reaction than the curing time. Zhang et al.[14] investigated the influence of heating rate on the curing behavior of a thermoplastic-modified multifunctional epoxy system; they found that a greater heating rate caused higher epoxy conversion. Thomas et al.[15] studied the effects of a liquid rubber inclusion on the cure kinetic of modified DGEBA-based epoxy resin and found that the inclusion of a large wt% of carboxyl-terminated butadiene-co-acrylonitrile decreased the cross-linking density of the thermoset matrix.

Among the methods of kinetic equations and analysis, several kinds of isoconversional methods (Kissinger-Akahira-Sunose method, Ozawa-Flynn-Wall method and Fireman method) are the most widely used to estimate the activation energy (E). The apparent activation energy can be determined using these model free-estimations without the need to define a specific model for the reaction run.

In this paper, PAA was selected to cure DGEBA alone, or with DDS as a co-curing agent. A systematic work was done to make a thorough inquiry of the curing behavior and mechanism of DGEBA with PAA and DDS.

2. Experimental

2.1. Materials

DGEBA was supplied by Shanghai Resin Factory Co., Ltd., (China). PAA, with an Mw of 34,000, was supplied by Olong Electrical Insulation Materials Co. Ltd., (China) while the conventional curing agent (DDS) and dimethyl acetamide (DMAc) solvent were both supplied by Sinopharm Chemical Reagent Co., Ltd., (China). The chemical structures of the materials are shown in Table 1.
2.2. Sample Preparation

Theoretically, there are three active-hydrogens (one comes from carboxyl and the other two come from secondary amides) that can react with the epoxy groups in each structural unit of PAA. However, only a fraction of the secondary amides and the carboxyls in the ortho position of the phenyl ring took part in the thermal imidization during the curing process. Therefore, when we calculated the amount of PAA used to cure DGEBA, we assumed that there were two active-hydrogens in every constitutional unit of PAA. And, obviously, the number of active-hydrogens in DDS is four.

The samples used for DSC analysis were obtained by mixing stoichiometric amounts of DGEBA with DDS and PAA in varying molar ratios of active-hydrogen in a minimum amount of DMAc. Molar ratios of epoxy group and active-hydrogen in DDS and PAA were 1:1:0, 1:0.75:0.25, 1:0.5:0.5, 1:0.25:0.75, and 1:0:1. The sample designations are shown in Table 2. Considering DMAc is a high boiling solvent, the following steps were performed to evaporate it. First, the resulting solutions were sprayed with 0.2 MPa high-purity nitrogen gas using a spray gun on a few pieces of 80°C heated clean aluminum foils. We sprayed six times in order to get a film with a thickness of 30 to 60 μm; the aluminum foils were then heated at 80°C to evaporate most of the DMAc in a blowing oven between each time we sprayed. The sprayed aluminum foils were then put in a vacuum oven at 80°C for 4 h to evaporate the remaining DMAc. The freshly prepared samples were used for DSC analysis.

### Table 1

<table>
<thead>
<tr>
<th>Materials</th>
<th>Chemical formulas</th>
</tr>
</thead>
<tbody>
<tr>
<td>DGEBA</td>
<td><img src="https://example.com/dgeba_formula.png" alt="DGEBA Chemical Formula" /></td>
</tr>
<tr>
<td>PAA</td>
<td><img src="https://example.com/paa_formula.png" alt="PAA Chemical Formula" /></td>
</tr>
<tr>
<td>DDS</td>
<td><img src="https://example.com/dds_formula.png" alt="DDS Chemical Formula" /></td>
</tr>
</tbody>
</table>

### Table 2

<table>
<thead>
<tr>
<th>Molar ratios of epoxy groups and active-hydrogens of DDS and PAA</th>
<th>Sample designation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1:1:0</td>
<td>ED</td>
</tr>
<tr>
<td>1:0.75:0.25</td>
<td>EDP-3:1</td>
</tr>
<tr>
<td>1:0.5:0.5</td>
<td>EDP-1:1</td>
</tr>
<tr>
<td>1:0.25:0.75</td>
<td>EDP-1:3</td>
</tr>
<tr>
<td>1:0:1</td>
<td>EP</td>
</tr>
</tbody>
</table>
within four hours of removal from the oven. For FT-IR analysis, DGEBA/DDS/PAA blends were cured at 100°C for 1 h, 160°C for 2 h, 180°C for 2 h, and followed by 200°C for 2 h in an air-oven. Powdered samples were removed by scraping with a razor blade and mixed with HBr and pressed into a pellet.

2.3. DSC Analysis

4 ± 1 mg of freshly prepared samples were sealed in several alumina crucibles, followed by scanning in a differential scanning calorimeter (DSC-60A, Shimadzu Co. Ltd., Japan), calibrated with an indium standard, and operating in a dynamic mode. Nonisothermal scans were performed at heating rates of 2.5, 5, 10, and 20°C/min from 50°C to a maximum of 350°C, with a stream of N₂ at a flow rate of 40 ml/min protecting the DSC cell, for curing behavior and kinetic analysis.

2.4. FT-IR Analysis

The analysis was conducted in a Fourier transform infrared spectroscopy spectrometer (FT-IR, NEXUS-470, Thermo Nicolet, USA) using the samples in KBr pellets.

3. Results and Discussion

3.1. Curing Behavior

DGEBA was cured with PAA and/or DDS. The curing behavior was investigated using DSC (Figs. 1 and 2). The exothermic peak is characteristic of the curing reaction. This peak is mainly attributed to the TGDDM/DDS or TGDDM/PAA copolymerization. Several interesting dependences were found in the data presented in Figs. 1 and 2. The temperature where the first detectable heat was released \( T_{\text{onset}} \), the peak exotherm temperature \( T_p \), and the temperature of the end of the curing exotherm \( T_{\text{end}} \) changed depending on the curing agents used. The values of \( T_{\text{onset}} \) and \( T_p \) decreased at first and then increased slightly with the increase of PAA content in the curing agents. The minimum values of \( T_{\text{onset}} \) and \( T_p \) were obtained when the molar ratios of active-hydrogen of DDS and PAA were 0.75:0.25. The value of \( T_{\text{end}} \) decreased for ratios from 1:0 to 0.5:0.5 at first and then increased slightly from 0.5:0.5 to 0:1. It can be explained that, first, PAA acted as a catalyst because of the carboxyl and secondary amide groups in PAA. It was reported in our previous work.\(^{[16]}\) However, an increase of PAA content blocks the access between DGEBA and DDS by decreasing the likelihood of reactions between DGEBA’s epoxy functional groups and DDS’s primary amide groups. The heat of curing, calculated by measurement of the areas under the exothermic peaks (\( \delta H \)) decreased with increasing PAA. It can be explained that the active functional groups per-unit mass of PAA (such as secondary amides) that can react with epoxy groups are about 2/3 less than that of per-unit mass of DDS (primary and secondary amines). What’s more, the crosslinking density decreased with PAA content in the mixed curing agent increasing.

3.2. Curing Mechanism

To further understand the curing behaviors of DGEBA with PAA and DDS, FT-IR analysis was performed. The results are shown in Fig. 3. The band at 915 cm\(^{-1}\) belongs to the asymmetric stretching vibration transmission peak of the epoxy groups of TGDDM. No
Curing Behavior and Mechanism of DGEBA/DDS/PAA

Figure 1. DSC scans of DGEBA in the presence of various active-hydrogen molar ratios of DDS/PAA.

Figure 2. Results of DSC scans of DGEBA in the presence of various active-hydrogen molar ratios of DDS/PAA.
peak at this position, or a very small one, was observed in the spectra of all the samples, indicating that almost all the epoxy groups were involved in the curing reaction. The band at 1380 cm$^{-1}$ was attributed to the C–N stretching vibrations of the aromatic imides while that at 1780 cm$^{-1}$ was assigned to the C=O asymmetric stretching of aromatic imides. These two bands were present when there was PAA in the mixed curing agents in the range of our sample designation. In addition, the areas ratio of the band at 1380 cm$^{-1}$ was calculated by the ratio of the areas of the bands at 1380 cm$^{-1}$ to 1513 cm$^{-1}$ (attributing

![FT-IR spectra of DGEBA cured with various active-hydrogen molar ratios of DDS/PAA.](image)

**Figure 3.** FT-IR spectra of DGEBA cured with various active-hydrogen molar ratios of DDS/PAA.

<table>
<thead>
<tr>
<th>Areas ratios</th>
<th>Sample designation</th>
<th>$A_{1380}/A_{1513}$</th>
<th>$A_{1780}/A_{1513}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ED</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>EDP-3:1</td>
<td>0.207</td>
<td>0.071</td>
</tr>
<tr>
<td></td>
<td>EDP-1:1</td>
<td>0.297</td>
<td>0.094</td>
</tr>
<tr>
<td></td>
<td>EDP-1:3</td>
<td>0.343</td>
<td>0.126</td>
</tr>
<tr>
<td></td>
<td>EP</td>
<td>0.482</td>
<td>0.368</td>
</tr>
</tbody>
</table>

$A_{1380}$ and $A_{1513}$ are the areas of the bands at 1380 cm$^{-1}$ and 1513 cm$^{-1}$, respectively, $A_{1380}/A_{1513}$ is the ratio of the areas of the bands at 1380 cm$^{-1}$ and 1513 cm$^{-1}$.

$A_{1780}$ is the area of the band at 1780 cm$^{-1}$, $A_{1380}/A_{1513}$ is the ratio of the areas of the bands at 1780 cm$^{-1}$ and 1513 cm$^{-1}$.
Curing Behavior and Mechanism of DGEBA/DDS/PAA

To the stretching vibration of the skeleton of phenyl ring, the band is almost the same in different samples, the same for 1780 cm\(^{-1}\). The ratios are listed in the Table 3. Obviously, the areas ratio of the two bands increased with increasing PAA in the mixed curing agents. The band at 1535 cm\(^{-1}\) was attributed to the in-plane bending vibration of secondary amide N–H. There was a weak shoulder peak at 1535 cm\(^{-1}\) in the spectrum of EP, while it was hard to identify this band in the other spectra. This indicated that there was an important amount of nonreacted secondary amide groups in the cross-linked network of DGEBA cured with PAA only. However, almost all the secondary amide groups of PAA participated in chemical reactions during the curing process when PAA acted as a co-curing agent.

The bands at 1098 cm\(^{-1}\) and 1240 cm\(^{-1}\) are the characteristics transmission peaks of aliphatic ether and aromatic ether, respectively. The band at 1240 cm\(^{-1}\) was present in all spectra because of the aromatic ether groups of DGEBA. The band at 1098 cm\(^{-1}\) was also present in all spectra, although there are no aliphatic ether groups in either the epoxy or the curing agents we used. The explanation is that aliphatic ether was generated during the curing reaction, and only the reaction of hydroxyl and epoxy groups can generate aliphatic ethers. It was also noticed that the intensity of the transmission peak of the aliphatic ether decreased with increasing PAA in the mixed curing agents. It was likely that an increase in PAA content reduced the molecular motions during the curing process and consequently involved a decrease of the likelihood of reactions between DGEBA’s epoxy functional groups and hydroxyls generated during the curing process.

There is more steric hindrance for secondary amines than primary amines when they react with epoxy groups. Leon et al.\([17]\) found that although there was no great selectivity between the reaction of primary amines with epoxy groups and that of secondary amines with epoxy groups, only a small number of the reactions of the secondary amines with epoxy groups took place in the first stage when the majority of the primary amines reacted with the epoxy groups. In addition, from the point of view of the kinetics of the reaction, the activation energy \((E)\) of the reaction of the epoxy groups with primary amines was lower than that with secondary amines or secondary amides. Results of the activation energy \((E)\) calculated using the three different model free estimations (Details of the three model free estimations are given in section “3.3. Kinetic equations and analysis”) are given in Table 4. From Table 4, it is obvious that the activation energy \((E)\) of the reaction of the epoxy groups with primary amines was lower than that with secondary amides. As a result, it was likely that the reaction of epoxy groups with primary amines, leading to the formation of numerous macromolecules with linear chain structures, mainly took place in the first stage of the curing reaction. In the second stage, the epoxy groups reacted with secondary amines or amides, giving rise to the formation of three dimensional network structures.

<table>
<thead>
<tr>
<th>E of Samples Method</th>
<th>E (KJ/mol) EDP-1:0</th>
<th>EDP-0:1</th>
</tr>
</thead>
<tbody>
<tr>
<td>KAS method</td>
<td>65.44</td>
<td>69.71</td>
</tr>
<tr>
<td>OFW method</td>
<td>81.01</td>
<td>97.87</td>
</tr>
<tr>
<td>Friedman method</td>
<td>72.84</td>
<td>103.16</td>
</tr>
</tbody>
</table>

Table 4

Results of the activation energy \((E)\) calculated using the three different model-free estimations
On the basis of the analysis above, the following conclusion could be generated. The curing process of DGEBA with DDS can be divided into two stages (Scheme 1, process one). Stage one: the dominating reaction in this stage was that primary amine groups reacted with epoxy groups, leading to the formation of a mass of molecules with predominantly linear backbone chain structures (M1). In addition, a small fraction of secondary amines from DDS reacted with epoxy groups, leading to the formation of a few E branches at this stage. Stage two: the reaction of secondary amines from DDS and epoxy groups giving rise to the formation of the three dimensional network structures mainly took place in this stage. In contrast, there was only one stage in the curing process of DGEBA with PAA, or to speak more precisely, the main reaction was the reaction of secondary amides in the M2 linear chains with epoxy groups leading to the formation of the three dimensional network structures (Scheme 1, process two).

Based on the conclusion above, it was probable that the differences among the DGEBA’s cured with the mixed curing agents, either in the curing process or the cross-linked
products, lay in the differences of the macromolecules with linear chain structures generated in stage one to some extent. There were a mass of aromatic ether and methylene groups in the skeleton of the linear macromolecular chain of M1; by contrast, five-membered imide rings and benzene accounted for a high proportion in the skeleton of the linear macromolecular chain of PAA and PAI (M2). As a result, the strength of the macromolecular chains of M2 was higher than that of M1.[18]

3.3. Kinetic Equations and Analysis

3.3.1. Kinetic Equations. Generally, there are two kinds of methods (isothermal and non-isothermal) to study chemical kinetics. The nonisothermal method is more complicated and more accurate than the isothermal method. As a result, the nonisothermal method is commonly used in kinetic analysis. The temperature usually increases according to a constant heating rate in the nonisothermal process:

$$\beta = \frac{dT}{dt} = T_0 + \beta t$$  \hspace{1cm} (1)

where $\beta$ is the constant heating rate, $T$ is the temperature in Kelvin, $t$ is the time, and $T_0$ is the initial temperature.

In this study, three kinds of model-free methods [Kissinger–Akahira–Sunose (KAS) method, Friedman method, and Ozawa–Flynn–Wall (OFW) method] were employed to study the curing kinetics. Using these model-free methods (also named isoconversional methods), the values of $E$ can be determined without the need to define a specific model for the reaction. Finally, the reaction order was determined by the Crane equation:

$$\frac{d \ln \beta}{d(1/T_p)} = -\frac{E}{nR}$$  \hspace{1cm} (2)

where $T_p$ is the temperature of the peak position of the exotherm, $E$ is the activation energy, $R$ is the gas constant, and $n$ is the reaction order.

The KAS method assumes that $\ln(\beta)$ and $1/T_p$ have the relation shown in the following equation:

$$\frac{\ln \beta}{T_p^2} = \ln \left(\frac{AR}{E}\right) - \frac{E}{RT_p}$$  \hspace{1cm} (3)

where $A$ is the pre-exponential factor.

It can be seen from the equation that a plot of the dependence of $\ln(\beta/T_p^2)$ on $f(1/T_p)$ results in a straight line with the slope $m = -E/R$ from which the value of the activation energy ($E$) can be obtained.

The Ozawa–Flynn–Wall method assumes the following relation to determine $E$ for the $n$th-order reaction $f(a)$:

$$\ln \beta = \text{const} - 1.052 \frac{E}{RT}$$  \hspace{1cm} (4)

It can be seen from the equation that $\ln \beta$ and $1/T$ are in a straight-line relation with a slope $m = -1.052E/R$ at a fixed degree of conversion $a$ of a series of measurements at the heating rates $\beta$. $T$ in the equation stands for the temperature in Kelvin at which the conversion $a$ is reached at the heating rate $\beta$. The value of $E$ can be determined from the slope of the straight line.
Figure 4. DSC scans of the sample ED at different heating rates of 2.5, 5, 10, and 20°C/min from 50°C to a maximum of 350°C.

Another isoconversional procedure, introduced by Friedman, proposed that the logarithm of the conversion rate \( \frac{d\alpha}{dt} \) (with \( a \) given) and the reciprocal temperature has the relationship shown below:

\[
\frac{d\alpha}{dt} = A \exp \left( -\frac{E}{RT} \right) f(a) \tag{5}
\]

\[
\ln \left( \frac{d\alpha}{dt} \right) = \ln f(a) + \ln A - \frac{E}{RT} \tag{6}
\]

\( f(a) \) is a constant for a given \( a \) at different heating rates; as a result, the plot of the dependence \( \ln(\frac{d\alpha}{dt}) = f(1/T) \) results in a straight line with the slope \( m = -E/R \) from which the \( E \) can be obtained assuming a first-order reaction.

3.3.2. Kinetic analysis. The results of the nonisothermal DSC scans at different heating rates are shown in Figs. 4–6 for samples ED, EDP-1:1, and EP, respectively. The values of the activation energy \( (E) \) computed using the three isoconversional methods for DGEBA cured with DDS and PAA at the three different active-hydrogen molar ratios of 1:0, 0.5:0.5, and 0:1 are listed in Table 5. It can be seen that there were some differences among the values computed by the three isoconversional methods for all of the samples. This can be attributed to the different approximations or assumptions made in these isoconversional
methods in order to present the kinetic parameters in a more calculable and more efficient way. However, the values obtained by all three of the methods for DGEBA cured with DDS and PAA in an active-hydrogen molar ratio of 0.5:0.5 were lower than those for DGEBA cured with DDS or PAA individually. In addition, the values computed by the three methods for DGEBA cured with PAA were higher than those for DGEBA cured with

\[
\text{Table 5}
\]

The values of the activation energy \((E)\) and reaction order \((n)\) computed using the three model free estimations for DGEBA cured with DDS and PAA in active-hydrogen molar ratios of 1:0, 0.5:0.5, and 0:1

<table>
<thead>
<tr>
<th>Methods</th>
<th>Parameters</th>
<th>EDP-1:0</th>
<th>EDP-1:1</th>
<th>EDP-0:1</th>
</tr>
</thead>
<tbody>
<tr>
<td>KAS method</td>
<td>(E) (KJ/mol)</td>
<td>65.44</td>
<td>54.31</td>
<td>69.71</td>
</tr>
<tr>
<td></td>
<td>Reaction order ((n))</td>
<td>0.88</td>
<td>0.87</td>
<td>0.90</td>
</tr>
<tr>
<td>OFW method</td>
<td>(E) (KJ/mol)</td>
<td>81.01</td>
<td>60.26</td>
<td>97.87</td>
</tr>
<tr>
<td></td>
<td>Reaction order ((n))</td>
<td>1.30</td>
<td>0.91</td>
<td>1.31</td>
</tr>
<tr>
<td>Friedman method</td>
<td>(E) (KJ/mol)</td>
<td>72.84</td>
<td>47.49</td>
<td>103.16</td>
</tr>
<tr>
<td></td>
<td>Reaction order ((n))</td>
<td>1.17</td>
<td>0.72</td>
<td>1.38</td>
</tr>
</tbody>
</table>
Figure 6. DSC scans of the sample EP at different heating rates of 2.5, 5, 10, and 20 °C/min from 50 °C to a maximum of 350 °C.

DDS. It was likely that PAA could catalyze the reaction of epoxy groups with primary amines because of the carboxyl and secondary amide groups in PAA, thus contributing to the decrease of the activation energy ($E$), compared with that of DGEBA cured with DDS. There were a large number of primary amines in DDS that could react more easily with epoxides than the secondary amides of PAA, resulting in a decrease of activation energy ($E$) of DGEBA cured with DDS compared with PAA. The reaction order was not an integer number, demonstrating that complex reactions took place during the curing process. The variation of activation energy ($E$) computed with Friedman method is shown in Fig. 7. Different trends of the activation energy ($E$) as a function of the degree of conversion ($\alpha$) were obtained. The variation of the activation energy ($E$) with the degree of conversion indicated the presence of a complex reaction path.

4. Conclusions

Systematic research was undertaken to make a thorough inquiry of the curing process and mechanism of DGEBA with PAA and/or DDS. The cure temperature decreased when DGEBA was cured with the co-curing agents composed of PAA and DDS, compared with the ones cured with PAA or DDS individually. We suggest this is because the PAA in the co-curing agent can catalyze the reaction of PAA and DDS. However, too much PAA in the co-curing agent (molar ratios of active-hydrogens of DDS and PAA less than 0.5:0.5) increased the cure temperature because the likelihood of reactions between DGEBA's
Figure 7. The activation energy (E) as a function of degree of the conversion for the curing process of DGEBA cured with DDS and PAA in active-hydrogen molar ratios of 1:0, 0.5:0.5, and 0:1.

epoxy functional groups and DDS’s primary amide groups were blocked by PAA. The kinetic analysis found that the activation energy (E) of DGEBA cured with DDS and PAA with active-hydrogen molar ratios of 0.5:0.5, computed by Friedman method, was 47.49 KJ/mol, much lower than that cured with DDS (72.84 KJ/mol) or PAA (103.16 KJ/mol) individually. This result further confirmed that PAA in the co-curing agent can catalyze the reaction of PAA and DDS.

References


