

Kinetics Study of Imidazole-Cured Epoxy-Phenol Resins

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ABSTRACT: The reaction kinetics of diglycidyl ether of bisphenol A (DGEBA) cured with different concentrations of imidazole and bisphenol A (BPA) were investigated by using differential scanning calorimetry. Both dynamic and isothermal DSC were studied. Two initiation mechanisms were found to play roles in the curing reactions. One was based on adduct formation of epoxy groups with pyridine-type nitrogen and the other was based on ionic complexes of imidazole and BPA. The subsequent propagation was composed of three main reactions, viz. the epoxide/phenol reaction, the acid/base reaction, and the epoxide/R-O⁻ reaction. A generalized kinetics model was developed and used to predict the conversion of epoxide groups using a wide range of imidazole and BPA concentrations, and cure temperature. © 1999 John Wiley & Sons, Inc. *J Polym Sci A: Polym Chem* 37: 3233–3242, 1999

Keywords: Epoxy; imidazole; cure kinetics; cure mechanisms

INTRODUCTION

In recent years there has been a great increase in the number of applications of epoxy-phenol resins, especially in the electronics industry as encapsulating and packaging materials.^{1–3} Nowadays the chip sizes have become larger, while the dimensions of devices inside the chip have become smaller and the structure of chips has become more delicate. Molding compounds need to have much more stringent properties like higher thermal resistance, higher moisture resistance, lower thermal expansion coefficient, and lower modulus.⁴ Encapsulants formulated out of epoxy-phenol resins are transfer-molded to form the protective shell outside integrated circuits. During the polymerization, the molecular weight increases and the crosslinked structure builds up, which governs the rheological and mechanical properties of the cured resins. Thus it was particularly important to understand thoroughly the cure ki-

netics because of its effect on stress distribution in the IC packaging during processing. There have been several existing publications, reviewed as below.

Shechter and Wynstra⁵ were the first to examine the uncatalyzed epoxy-phenol reaction. They found that the reaction is sluggish at 200°C and was found to proceed at reasonable rate only at higher temperatures. In the meanwhile epoxide disappeared at a faster rate than phenol, with about 60% of the reaction being between epoxide and phenol, and the remaining 40% being between epoxide and the secondary hydroxyl resulted from the epoxide-phenol reaction. However, this reaction procedure is too slow for high-speed integrated circuit packaging purposes, which require the reaction to be essentially completed in a few minutes at temperatures around 170°C. Shechter and Wynstra found that some catalysts like tertiary amines or potassium hydroxide could improve the epoxy-phenol reaction selectivity and substantially lower the activation energy.

Sorokin and Shode^{6,7} proposed two mechanisms for creating ionic species which were poten-

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tially capable of further propagating the reaction. The acidity of the phenol used and the basicity of the tertiary amine selected determined which one of the two mechanisms dominated the propagation reactions. All Sorokin's work on the epoxy-phenol reaction was carried out with a phenol/epoxy ratio > 1 . So no side reactions were observed from his studies.

In addition to the main epoxy-phenol reaction, Gagnebien, Madec, and Marechal⁸ proposed three other possible mechanisms in epoxy-phenol reactions catalyzed by tertiary amines. First is epoxy homopolymerization as initiated by the free tertiary amine. Second is a branching reaction. Third is a zwitterion catalyzed branching reaction. The selectivity of reactions depended on the kind of catalyst used.

Hale and Macosko⁹ studied the imidazole-cured epoxy-phenol reaction. They showed that the selectivity of imidazoles strongly depends on their concentration. If a low amount of imidazole is used, the reaction takes place exclusively through the addition of phenol to epoxide even if the latter is used in excess. However a larger amount of imidazole causes secondary hydroxyl groups to react with epoxide. But the reaction of secondary hydroxyl with epoxide is prevented to any significant extent as long any phenol remains in the reaction mixture. In addition, some information has been published about the use of imidazoles for catalyzing the homopolymerization of epoxide.^{10–16}

Among the previous studies in the publications above, both detailed and quantitative reaction mechanisms have been proposed for tertiary amine catalyzed epoxy-phenol reactions. However, there could not be found any generalized kinetic mechanisms for the imidazole catalyzed epoxy-phenol reaction which can explain the cure reaction qualitatively and predict the conversion quantitatively over a wide range of reaction conditions. This is essential in order to understand the chemorheology and the structure buildup during transfer molding. The objective of this study is to examine the kinetics of imidazole cure of epoxy-phenol resins at different epoxy/phenol molar ratios by using the differential scanning calorimetric (DSC) technique.^{17,18} Based on the previous studies described above, we combined the reaction mechanisms for tertiary amine catalysis and for imidazole catalysis and proposed a generalized kinetics model which can quantitatively predict the conversion of epoxide for a wide range of

DGEBA/BPA/imidazole molar ratios and cure temperatures. By use of the numerical skills, all the reaction rate constants were properly tuned and discussed in this paper.

EXPERIMENTAL

Materials

The epoxy resin (DER332), a nearly pure form of the diglycidyl ether of bisphenol A (DGEBA), was supplied by the Dow Chemical Company. The epoxide equivalent weight (EEW) of DER332, determined by titration, was 174 g/mol-epoxide. The difunctional phenol, bisphenol A (BPA) with a purity $> 99\%$, was obtained from the Tokyo Chemical Industry Company. The imidazole, 2-ethyl-4-methyl-imidazole (2,4EMI) with a purity $> 99\%$, was obtained from Acros Organics. All materials were stored in a desiccator and used as received without further purification.

Sample Preparation

Different molar ratios of BPA/epoxide and 2,4EMI were dissolved separately in spectrometric grade acetone. Both of the solutions were added, mixed well by rigorous stirring, and the acetone was evaporated under vacuum at 30°C for 10 minutes. The resultant mixture was immersed in ice water immediately to minimize further cure reaction before kinetics studies. The prepared samples were surveyed from room temperature to 320°C by thermogravimetric analysis (TGA). The results of TGA showed that the total weight loss caused by residual acetone loss and thermal degradation of resultant mixture is less than 1%.

Differential Scanning Calorimeter (DSC) Analysis

Both dynamic and isothermal differential scanning calorimetry were performed by using a TA Instruments (TA-2010) DSC under nitrogen atmosphere. The DSC enthalpy and temperature scale were calibrated using a high purity indium sample. Dynamic scans from 2.5°C to 20°C/min over a temperature range of 25–320°C were used to cure the 2,4EMI/BPA/epoxide samples. Isothermal studies were also performed at four fixed temperatures (90°C, 95°C, 100°C, 110°C), holding for various periods of time. Both dynamic and

isothermal samples were quenched to -40°C and scanned up to 300°C at a heating rate $20^{\circ}\text{C}/\text{min}$ to detect the residual heat of reaction and glass transition temperature (T_g).

RESULTS AND DISCUSSION

Reaction Mechanisms

Based on the previous studies of Gagnebien, Mader, and Marechal,⁸ Heise,¹⁹ and Biernath and Soane,²⁰ our proposed curing mechanisms are shown in Figure 1. There are two initiation mechanisms. The first one starts with adduct ion of the pyridine-type nitrogen with the epoxy (1.1, 1.2). The second results from the ionic nature of the 2,4EMI-phenol interaction (1.4, 1.5). The following propagation steps consist of three main reaction mechanisms, the epoxide/phenol reaction (1.6), the acid-base reaction (1.3, 1.7), and the epoxide/R-O⁻ reaction (1.8, 1.9).

DSC Analysis

The reaction kinetics were studied using DSC because the amount of heat evolved during reaction is related to the number of reacting epoxide molecules.¹⁸ Both dynamic and isothermal traces were employed to analyze the DGEBA/BPA/2,4EMI reaction.

Dynamic Studies

The DSC dynamic traces for 100/6 molar ratio of DGEBA and 2,4EMI cured with different concentrations of BPA are illustrated in Figure 2. For DGEBA cured with 100% molar ratio of BPA, there is enough phenol to consume all epoxides to give linear aromatic ether chains with secondary hydroxyl groups. The DSC thermogram exhibited a single exotherm as showed in Figure 2. As the BPA concentration is lowered, some epoxide groups are unreacted after the initial epoxide/phenol reaction. These free epoxides could react with R-O⁻ to form aliphatic ethers. Consequently DGEBA cured with 60% molar ratio of BPA exhibits two exothermic peaks. As the BPA concentration is lowered below 40% molar ratio, the epoxide/phenol reaction appears as a low temperature exotherm shoulder and the epoxide/R-O⁻ reaction as a large exothermic peak. This is characterized by a high heat flow corresponding to a higher reaction rate.

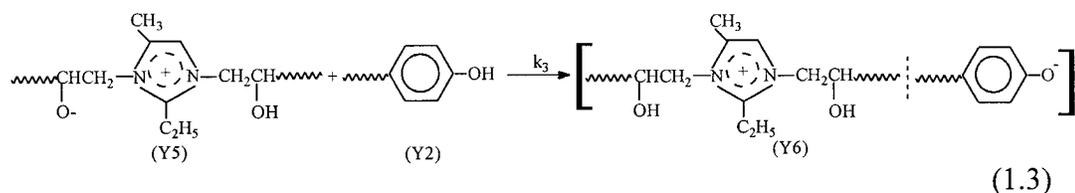
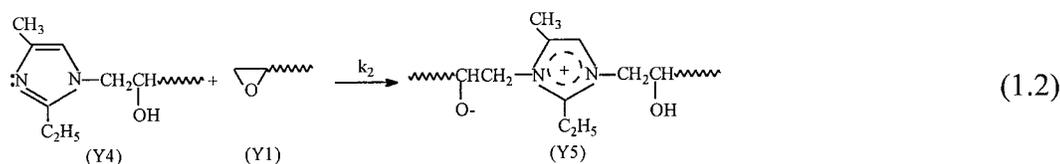
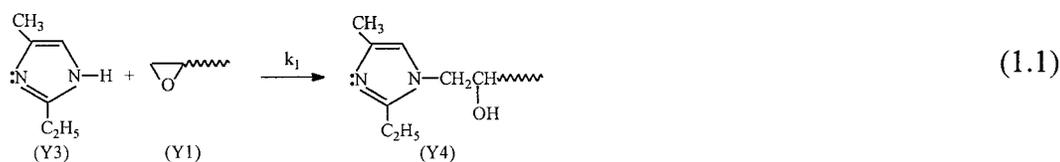
The dynamic DSC scan was used to analyze curing reactions that exhibit several exotherms.¹⁷ The reaction heat was determined for five different heating rates varying from $2.5^{\circ}\text{C}/\text{min}$ to $20^{\circ}\text{C}/\text{min}$ over a temperature range of 25°C – 300°C . The measured results were plotted versus different heating rates. The best fitting line was obtained by linear regression. The total heat of reaction, ΔH_{tot} , was obtained by extrapolating the best fitting line to zero heating rate. Total heat of reaction obtained this way is summarized in Table I. As can be seen from the table, the heat of reaction for a range of DGEBA/BPA/2,4EMI compositions varied between 76 and 88 kJ/mol-epoxide. These values agreed very well with those obtained by Enikolopiyan²¹ and Hale.²² As shown in Table I, the total heats of reaction do not vary significantly with BPA concentration, indicating that the heats of reaction for the two etherification reactions are almost the same. Hence thermal conversion could be related directly to the conversion of epoxide group.¹⁸

Both dynamic and isothermal samples were scanned after the initial curing to 300°C at $20^{\circ}\text{C}/\text{min}$ to determine T_g . T_g of the cured resins is a strong function of BPA concentration as shown in Table I. As the BPA concentration is lowered, more epoxide groups become available for the chain branching, epoxide/R-O⁻ reaction, which increases the crosslinking density of the resultant resins and results in a higher T_g . For 100% molar ratio of BPA, the T_g is between 69 and 75°C , while for 25% molar ratio of BPA, the T_g value is around 140°C .

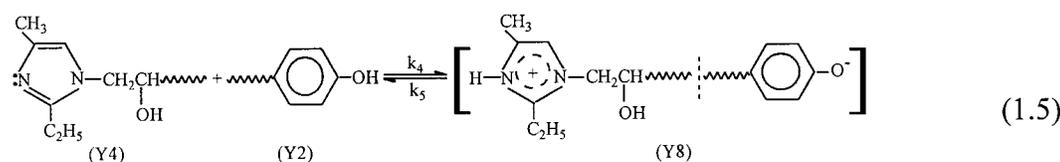
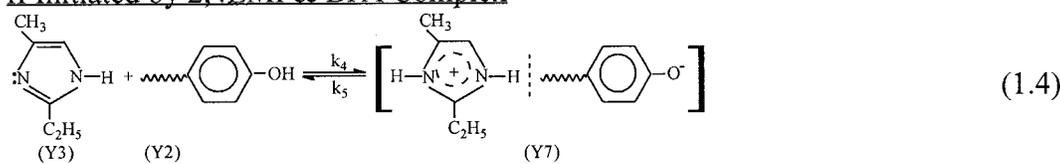
Isothermal Studies

On the basis of the above dynamic DSC studies, isothermal DSC scans were performed at four different temperatures (90 , 95 , 100 , and 110°C). The isothermal DSC thermograms for 100/6 molar ratio of DGEBA and 2,4EMI cured with different concentrations of BPA are showed in Figure 3. There are two distinct exothermic peaks. The first one corresponds to the epoxide/phenol reaction while the second can be attributed to the epoxide/R-O⁻ reaction. Increasing the BPA concentration delays the occurrence of the epoxide/R-O⁻ reaction since the required time to react all the phenol groups is increased. And the area under the second peak decreases because fewer epoxide molecules are left after the epoxide/phenol reaction.

I. Initiated by 1:1 adduct & 2:1 adduct



II Initiated by 2,4EMI & BPA Complex



III. Propagation

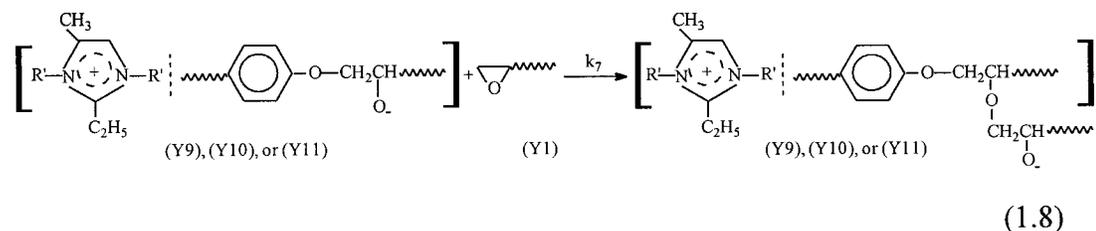
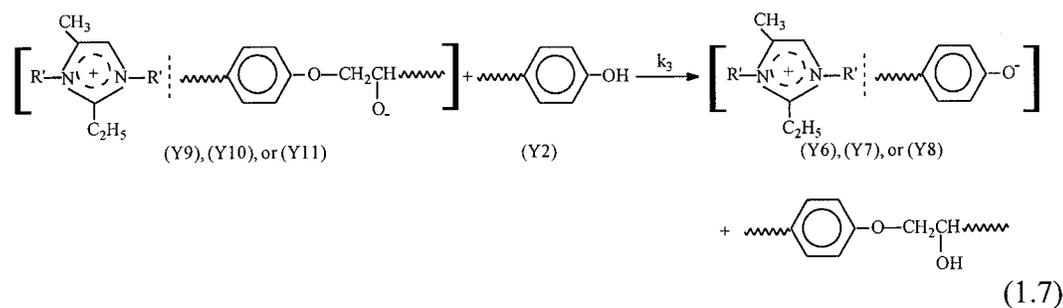
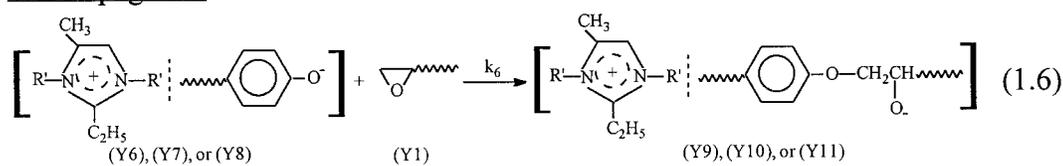


Figure 1. Reaction mechanisms proposed for DGEBA cured with 2,4EMI and BPA.

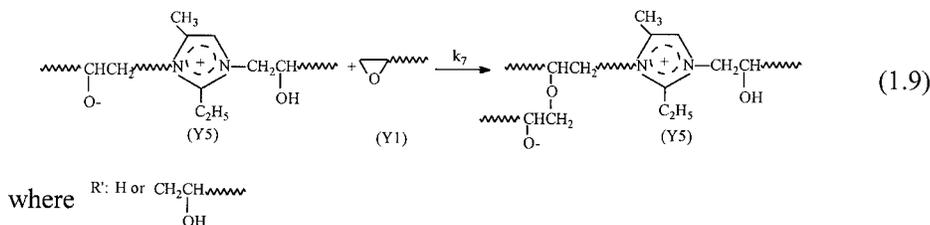


Figure 1. (Continued from previous page)

The thermal conversion during the isothermal reaction can be expressed as:

$$X(t) = \Delta H_{t_0 \text{ to } t} / \Delta H_{\text{total}} \quad (1)$$

where $X(t)$ is the thermal conversion at time t , ΔH_{total} is the total heat of reaction determined from dynamic DSC studies, and $\Delta H_{t_0 \text{ to } t}$ is the heat of reaction from initial time t_0 to time t during the isothermal reaction.

Figure 4 shows the influence of BPA concentrations on isothermal reactions. There is an obvious transition when BPA molar ratio is less than 40% as shown in Figure 4. The lower time interval slope is dominated by the value of the rate constant of the epoxide/phenol reaction and the higher time interval slope represents that of the epoxide/R-O⁻ reaction. If the BPA molar ratio is higher than 80%, most of the epoxide groups are

consumed by the epoxide/phenol reaction, so no transition can be expected up to 70% conversion (i.e., $\ln(1-X) = -1.2$). The rate of the epoxide/phenol reaction is also accelerated if the BPA concentration is increased.

The influence of 2,4EMI concentrations are shown in Figure 5. As the 2,4EMI concentration is increased, both epoxide/phenol and epoxide/R-O⁻ reaction rates increase because more active ionic centers are formed which take part in the subsequent propagation reactions.

Increasing isothermal temperature accelerates both the epoxide/phenol and the epoxide/R-O⁻ reaction. These results are shown in Figure 6.

Kinetics Modeling and Theoretical Approaches

The reaction mechanisms shown in Figure 1 can be expressed as the following mathematical scheme: (where “ y_1 ” species are identified in Figure 1)

$$\frac{dy_1}{dt} = -k_1 y_1 y_3 - k_2 y_1 y_4 - k_6 y_1 (y_6 + y_7 + y_8) - k_7 y_1 (y_5 + y_9 + y_{10} + y_{11}) \quad (2)$$

$$\frac{dy_2}{dt} = -k_3 y_2 y_5 - k_4 y_2 (y_3 + y_4) + k_5 (y_7 + y_8) - k_3 y_2 (y_9 + y_{10} + y_{11}) \quad (3)$$

$$\frac{dy_3}{dt} = -k_1 y_1 y_3 - k_4 y_2 y_3 + k_5 y_7 \quad (4)$$

$$\frac{dy_4}{dt} = k_1 y_1 y_3 - k_2 y_1 y_4 - k_4 y_2 y_4 + k_5 y_8 \quad (5)$$

$$\frac{dy_5}{dt} = k_2 y_1 y_4 - k_3 y_2 y_5 \quad (6)$$

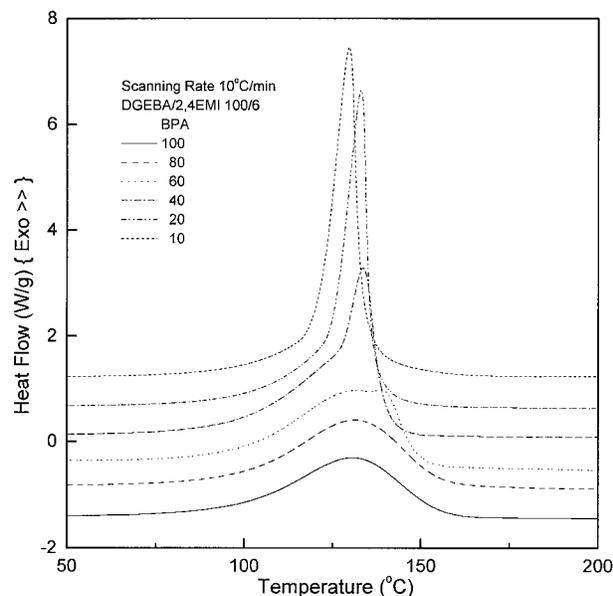


Figure 2. DSC dynamic traces at 10°C/min for the cure of DGEBA with 6% molar ratio of 2,4EMI and various molar ratios of BPA.

Table I. The Heat of Reaction (ΔH_{tot}) and Glass Transition Temperature (T_g) for Different DGEBA/BPA/2,4EMI Resin Compositions (where DGEBA: 100)

2,4EMI BPA	2		4		6	
	ΔH_{tot} (KJ/mole-epoxide)	T_g (°C)	ΔH_{tot} (KJ/mole-epoxide)	T_g (°C)	ΔH_{tot} (KJ/mole-epoxide)	T_g (°C)
100	76.7866	74.8	78.7094	72.2	77.2882	69.7
80	78.9602	85.0	79.1692	79.8	78.5840	76.6
60	82.0116	94.9	80.3814	91.2	78.9184	83.7
40	80.5068	111.9	81.7608	106.0	79.1274	96.7
20	81.7608	132.6	82.1370	129.9	82.2624	115.5
10	85.6064	132.3	87.6128	131.9	84.5614	125.7

$$\frac{dy_6}{dt} = k_3 y_2 (y_5 + y_9) - k_6 y_1 y_6 \quad (7)$$

$$\frac{dy_{10}}{dt} = k_6 y_1 y_7 - k_3 y_2 y_{10} \quad (11)$$

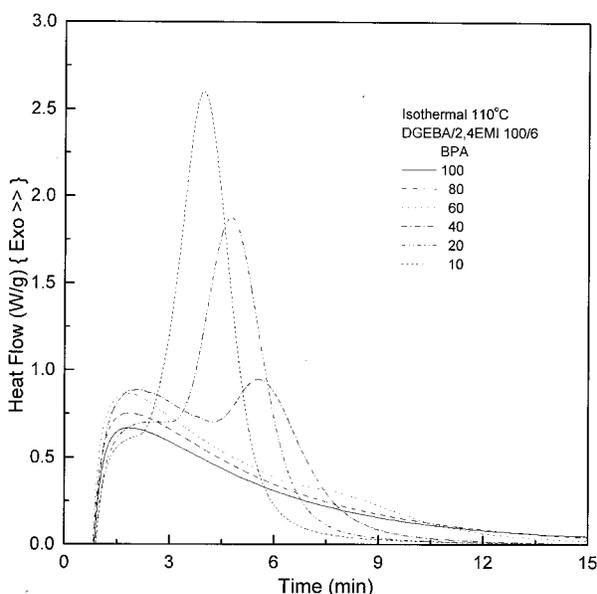
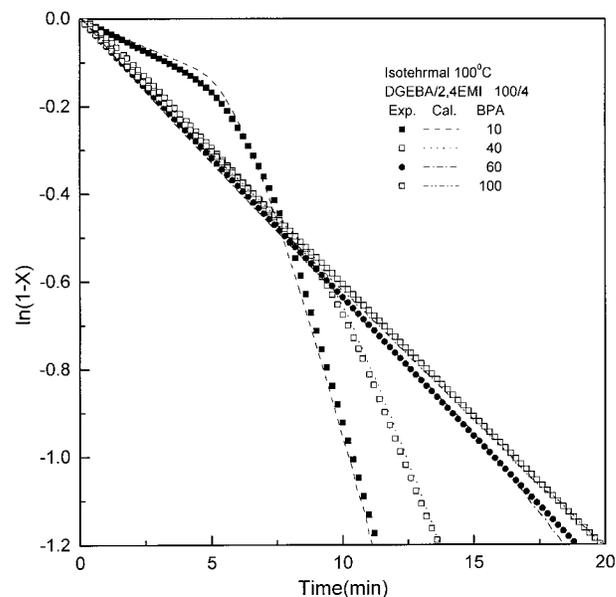
$$\frac{dy_7}{dt} = k_4 y_2 y_3 - k_5 y_7 - k_6 y_1 y_7 + k_3 y_2 y_{10} \quad (8)$$

$$\frac{dy_{11}}{dt} = k_6 y_1 y_8 - k_3 y_2 y_{11} \quad (12)$$

$$\frac{dy_8}{dt} = k_4 y_2 y_4 - k_5 y_8 - k_6 y_1 y_8 + k_3 y_2 y_{11} \quad (9)$$

$$\frac{dy_9}{dt} = k_6 y_1 y_6 - k_3 y_2 y_9 \quad (10)$$

The adaptive step-size of Cash—Karp Runge—Kutta method²³ was selected for the numerical procedure to solve ordinary differential eqs (2) to (13), programmed in Fortran language, and then executed by a Pentium II-233 microprocessor. All the parameters used in calculation were listed in

**Figure 3.** DSC isothermal thermograms for DGEBA cured with 6% molar ratio of 2,4EMI and various molar ratios of BPA at 110°C.**Figure 4.** Comparison of the model results with the experimental epoxide conversion curves for DGEBA cured with 4% molar ratio of 2,4EMI and different molar ratios of BPA at 100°C.

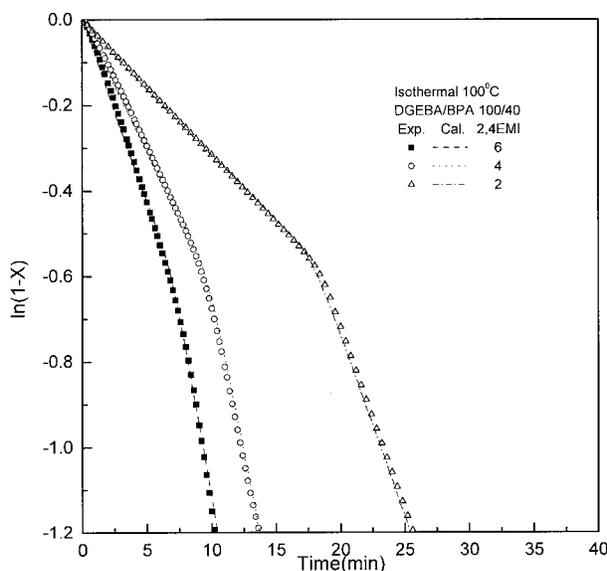


Figure 5. Comparison of the model results with the experimental epoxide conversion curves for DGEBA cured with 40% molar ratio of BPA and different molar ratios of 2,4EMI at 100°C.

Table II. The concentration profiles of y_1 to y_{11} versus time can be simultaneously calculated. Then the conversion of epoxide (X) can be calculated as $X = \frac{1-y_1(t)}{y_1^0}$ where y_1^0 is the initial concentration of epoxide and $y_1(t)$ is the concentration of epoxide at time t . The comparisons between theoretical and empirical results are plotted in Figures 4 to 6. With proper tuning parameters, all experimental data could be simulated by the proposed kinetics model very well.

Reaction rate constants k_1 and k_2 represent the adduct formation of pyridine-type nitrogen with epoxide group and were referred from the previous studies of Heise.¹⁹

The constant k_3 represents the rate constant of an acid-base reaction between an alkoxide ion and a phenolic hydroxyl group to create a secondary hydroxyl group and a phenoxide ion as shown in Figure 1. In the presence of unreacted phenolic hydroxyls, the anionic homo-polymerization, i.e. the epoxide/ $R-O^-$ reaction, is suppressed since the alkoxide ion is a stronger base than phenoxide ion. It means that the rate of acid-base reaction is higher than the rates of the etherification reaction; therefore, the epoxide/phenol and the epoxide/ $R-O^-$ reaction occur separately. The optimum value of k_3 was found from the conversion rate curves as showed in Figure 7. The slope of the curve between point A and B depended on the

value of k_3 selected. The value also influenced the curvature at point B. The optimum curve fitting results of k_3 are listed in Table II. They are a strong function of reaction temperature but are insensitive to concentration changes of 2,4EMI or BPA. The activation energy for k_3 is only ca. 39 kJ/mol, which is less than that of the etherification reaction.¹⁹

The reaction rate constant k_4 was determined from the initial slope change as shown in Figure 7. The rate constant k_4 represents the forward part of an equilibrium reaction which results in complexes between the pyridine-type nitrogen of 2,4EMI and the phenolic hydroxyl of BPA. Since the energy gap for the complex formation is very small, its activation energy is less than that of other reactions in this system. In our calculations, the value of k_4 was set as 5×10^{-2} (L/mol-sec) and assumed to be insensitive to the concentration changes of 2,4EMI or BPA, and reaction temperatures.

The reaction rate constant k_5 represents the backward part of the previously mentioned equilibrium. Its value influences the whole reaction time period, especially in the final reaction stage. When species Y2, Y3, and Y4 (Fig. 1) are consumed to form active phenoxide ions, their concentrations decrease. The backward reaction gradually becomes important since more phenox-

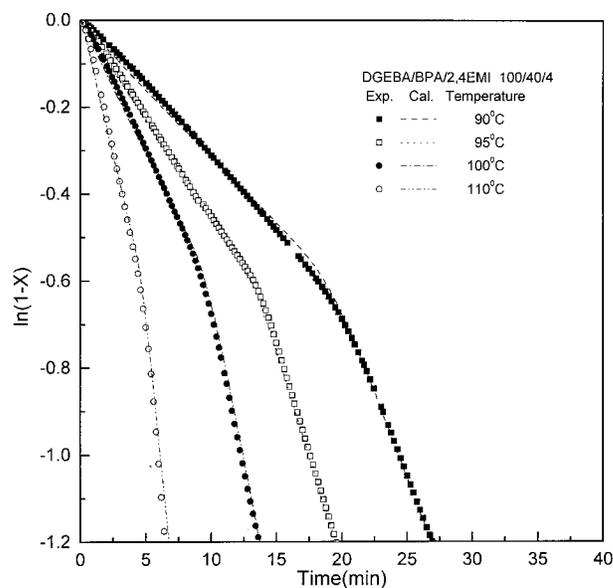


Figure 6. Comparison of the model results with the experimental epoxide conversion curves for DGEBA cured with 40% molar ratio of BPA and 4% molar ratio of 2,4EMI at different isothermal temperatures.

Table II. Reaction Rate Constants Used in Calculation and Activation Energies Determined from Isothermal DSC Result

k_1 and k_2 (L/mol-sec) ²²				k_3 (L/mol-sec)		
Ln(A)	E_a (KJ/mol)			Ln(A)	E_a (KJ/mol)	
18.33	74			13.52	38.35	

Molar Ratio DGEBA/BPA/2,4EMI	Ln(A)	$\frac{k_6 \text{ (L/mol-sec)}}{E_a \text{ (KJ/mol)}}$	R	Ln(A)	$\frac{k_7 \text{ (L/mol-sec)}}{E_a \text{ (KJ/mol)}}$	R
100/10/6	28.26	108.78	-0.995	20.40	74.58	-0.997
100/10/4	29.91	113.05	-0.999	17.07	64.70	-0.995
100/10/2	25.26	97.61	-0.999	17.98	67.73	-0.996
100/20/6	20.30	81.94	-0.998	19.37	72.40	-0.999
100/20/4	23.47	91.05	-0.997	16.34	62.89	-0.999
100/20/2	21.99	85.57	-0.998	15.75	60.95	-0.999
100/40/6	20.40	79.81	-0.998	21.46	80.07	-0.997
100/40/4	20.62	80.18	-1.000	20.73	77.36	-0.992
100/40/2	20.45	79.45	-0.999	16.15	62.81	-0.994
100/60/6	20.06	78.01	-1.000	21.15	80.96	-0.999
100/60/4	20.43	79.04	-0.999	23.21	86.81	-0.998
100/60/2	20.00	77.59	-0.999	21.82	81.40	-0.998
100/80/6	21.35	81.67	-0.998	21.35	81.67	-0.998
100/80/4	21.35	81.42	-0.998	21.35	81.42	-0.998
100/80/2	20.29	78.17	-0.997	20.29	78.17	-0.997
100/100/6	20.68	79.34	-0.998	20.68	79.34	-0.998
100/100/4	20.69	79.30	-0.997	20.69	79.30	-0.997
100/100/2	20.72	79.29	-0.999	20.72	79.29	-0.999

ide anions of species Y7 and Y8 convert back into Y2, Y3, and Y4. Therefore, the apparent reaction rate gradually slows down. The reverse reaction would cause a serious deviation from experimental results unless the value of k_5 is small enough. In the model calculation, k_5 was selected as 10^{-7} (1/sec) and assumed to be insensitive to reaction temperature and concentration changes of 2,4EMI and BPA.

The optimum reaction rate constant k_6 and its activation energy is listed in Table II. The values of k_6 decide the occurrence of the second peak and the height of the plateau between point A and B as shown in Figure 7. And the results indicate that the rate constant k_6 is a strong function of reaction temperature, and 2,4EMI and BPA concentrations. Sorokin's^{6,7} studies showed that the degree of ionization of the binary complex is directly proportional to the acidity of phenol and the basicity of the pyridine-type nitrogen in 2,4EMI. The degree of ionization of binary complexes would dominate the subsequent propagation rate constant k_6 . As the BPA concentration is increased and that of 2,4EMI is decreased, the

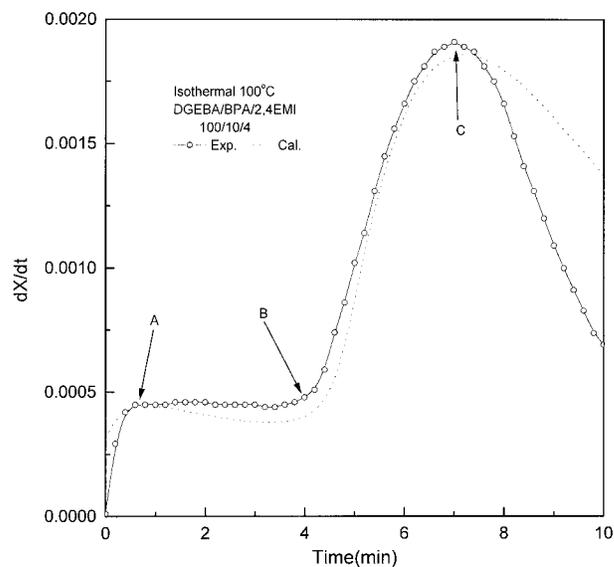


Figure 7. Comparison of the model results with the experimental epoxide conversion rate curve for DGEBA cured with 4% molar ratio of 2,4EMI and 10% molar ratio of BPA at 100°C.

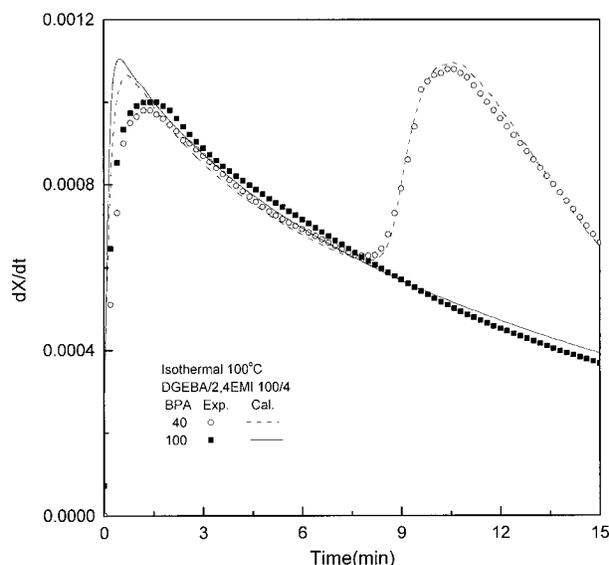


Figure 8. Comparison of the model results with the experimental epoxide conversion rate curve for DGEBA cured with 4% molar ratio of 2,4EMI and 40%, 100% molar ratio of BPA at 100°C.

polarity of the reaction system is raised and consequently k_6 becomes larger. The activation energies of rate constant k_6 are between 78 and 109 kJ/mol. This finding agrees with the studies of Heise.¹⁹

Table II lists the most suitable reaction rate constant k_7 . The slope of the conversion rate curve during the time period between point B and C in Figure 7 determines the optimum value of k_7 . It is a strong function of reaction temperature and BPA concentration. Since increasing the BPA concentration delays the initiation of epoxide/ $R-O^-$ reaction, the average molecular weight per ionic propagating chain is increased. The steric obstacle becomes more serious if the BPA concentration is raised; therefore, the reaction rate constant is decreased proportional to the BPA concentration increase. The activation energies of reaction rate constant k_7 were between 60 and 82 kJ/mol, which is a little less than that of k_6 . As the BPA molar ratio increased higher than 80%, no obvious second exotherm peak was seen from the isothermal DSC traces. So the tuning of k_7 became difficult and insensitive. In Table II, k_7 was assumed to be the same as k_6 in numerical calculations if the BPA molar ratio was higher than 80%.

Figures 7 and 8 show the comparison of conversion rate between model calculations and experimental results from isothermal DSC traces at

different BPA concentrations. There is a little deviation between experimental and theoretical curves in the initial period of time. It might be caused by the instrument's measuring error, since a time period is needed for the thermal controller of the DSC to reach the desired set-point temperature.

CONCLUSIONS

The reaction kinetics of imidazole cured epoxide-phenol resins were studied both by dynamic and isothermal DSC. There were two initiation mechanisms. The first was from adduct reactions of pyridine-type nitrogen. The second stemmed from the ionic complexes of 2,4EMI/BPA interaction. A generalized kinetic model was proposed and all parameters needed for computation were properly tuned from the conversion rate curves. The rate constant of the acid/base reaction was higher than that of the etherification, since the alkoxide ion is a stronger base than the phenoxide ion. The optimum value of k_3 from parameter tuning (see text) agrees with this principle very well. And the activation energy of the rate constant k_3 was 39 kJ/mol, which is less than that of the etherification reaction. The rate constant k_6 is found to be a strong function of the molar ratio of BPA and 2,4EMI. The reason is that the degree of ionization of binary complexes (Y6, Y7, and Y8) was proportional to the acidity of the phenol and the basicity of the pyridine-type nitrogen in 2,4EMI. With proper tuning parameters, our kinetic model can predict the conversion of epoxide groups for a wide range of imidazole and BPA concentrations, and cure temperatures.

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