Research Article

Thermal Decomposition Behavior of Melaminium Benzoate Dihydrate

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Crystals of melaminium benzoate dihydrate (MBDH) have been grown from aqueous solution by slow solvent evaporation method at room temperature. Powder X-ray diffraction analysis confirms that MBDH crystallizes in the monoclinic system (C2/c). Thermal decomposition behavior of MBDH has been studied by thermogravimetric analysis at three different heating rates: 10, 15, and 20°C/min. Nonisothermal studies of MBDH revealed that the decomposition occurs in three stages. The values of effective activation energy (Ea) and preexponential factor (ln A) of each stage of thermal decomposition for all heating rates were calculated by model free methods: Arrhenius, Flynn-Wall, Friedman, Kissinger, and Kim-Park methods. A significant variation of effective activation energy (Ea) with conversion (α) indicates that the process is kinetically complex. The linear relationship between the A and Ea values was established (compensation effect). Avrami-Erofeev model (A3), contracting cylinder (R2), and Avrami-Erofeev model (A4) were accepted by stages I, II, and III, respectively. DSC has also been performed.

1. Introduction

Supramolecular chemistry is the chemistry of molecular aggregates assembled via noncovalent interactions [1]. The design and synthesis of supramolecular polymeric networks, especially those constructed by hydrogen bonding and intermolecular weak interactions, have attracted many researchers due to their physical properties and potential applications in functional materials. Melamine and its organic and inorganic complexes or salts can develop supramolecular structures via multiple hydrogen bonds containing components that contain complementary arrays of hydrogen bonding sites [2–5]. The crystal structure of melaminium benzoate dihydrate was already reported [6]. The asymmetric unit of melaminium benzoate dihydrate (C3H7N6+ ⋅ C6H5COO− ⋅ 2H2O) consists of singly protonated melaminium cations, benzoate anions, and water molecules. The components are linked by hydrogen bonds into a three-dimensional framework structure. Several researchers have already studied the thermal behavior of melamine and its salts [7–12]. The presence of triazine ring in the melamine structure gives improved hydrolytic and thermal stability [13]. TGA is a commonly used technique to determine characteristics of thermal decomposition kinetics and thermal stability of polymers and its composites. This can be done by either single heating rate program like Coats-Redfern, Freeman-Carroll, and Chang or multiple heating rate programs like Flynn-Wall, Friedman, Kissinger, and Kim-Park [14–17]. To estimate kinetic parameters for the thermal decomposition of polymer composites, multiple heating rate method is recommended by the ICTAC committee [18].

2. Experimental Procedure

2.1. Preparation of MBDH. MBDH crystal was synthesized from melamine and benzoic acid in the stoichiometric ratio...
1:1. To the hot solution of melamine, benzoic acid solution was added gently and stirred continuously well for 5 hours to get the homogenous solution. Then the solution was allowed to evaporate at room temperature, which yielded needle shaped crystals within a period of 20–25 days.

2.2. Characterization. The grown crystals of MBDH have been characterized by X-ray powder diffraction technique using Rich Seifert X-ray powder diffractometer with CuK\(_{\alpha}\) radiation of \(\lambda = 1.5406 \text{ Å}\). The 2\(\theta\) range was analyzed from 10\(^{\circ}\) to 70\(^{\circ}\) by employing the reflection mode for scanning. The detector used was a scintillation counter. The thermal behavior of the crystal was determined by thermogravimetric analysis and differential thermal analysis using an SDT Q6000 V8.2 Built 100 thermal analyzer at a heating rate of 10, 15 and 20\(^{\circ}\)C/min under nitrogen atmosphere in the temperature range of 30–1000\(^{\circ}\)C. DSC was carried out on NETZSCH DSC 204 analyzer with an initial mass of 3.850 mg in the temperature range 0–120\(^{\circ}\)C.

3. Results and Discussion

3.1. X-Ray Powder Diffraction Analysis. Figure 1 shows the indexed X-ray powder diffraction pattern for the grown MBDH crystal. From the study, it is confirmed that the title crystal crystallizes in monoclinic system (C2\(\text{I}_\text{c}\)) with the lattice parameters \(a = 21.878 \pm 0.039 \text{ Å}, b = 9.859 \pm 0.023 \text{ Å}, c = 12.547 \pm 0.027 \text{ Å}, \alpha = 90.00 \pm 0.00^{\circ}, \beta = 99.02 \pm 0.24^{\circ}, \gamma = 90.00 \pm 0.00^{\circ}, \text{ and } V = 2672.92 \text{ Å}^3\) and it agrees very well with the earlier literature [6]. The prominent peaks have been indexed.

3.2. Thermal Analysis. TG-DTG curves of MBDH at three different heating rates 10, 15, and 20\(^{\circ}\)C/min in the temperature range of 30–1000\(^{\circ}\)C are shown in Figure 2 and it seems that TG curve exhibits mass losses in three stages involving dehydration and decomposition. For 10\(^{\circ}\)C/min, the initial mass is taken as 1.3490 mg. The first stage of decomposition takes place in the temperature range of 68.48\(^{\circ}\)C to 111.86\(^{\circ}\)C with a weight loss of 4.691% and is due to the liberation of two water molecules from the structure of MBDH. The corresponding exothermic peak is seen at 63.04° C. A rapid weight loss starts at 124.65°C and continues up to 173.45° C with a weight loss of 41.78%. This mass loss is attributed to the decomposition of benzoate anions. It exactly matches with an exothermic peak at 169.05°C in DTG curve. And the remaining 37.78%
Table 1: Activation energies of thermal degradation of MBDH by Arrhenius, Kissinger, and Kim-Park methods.

| Method    | Heating rate/°C min⁻¹ | Stage I | Stage II | Stage III |
|-----------|------------------------|---------|----------|-----------|
|           |                        | \( E_a / \text{kJ mol}^{-1} \) | ln \( A / \text{s}^{-1} \) | \( E_a / \text{kJ mol}^{-1} \) | ln \( A / \text{s}^{-1} \) |
| Arrhenius | 10                     | 41.92   | 13.60    | 89.97     | 27.52     | 115.11    | 27.82     |
|           | 15                     | 40.01   | 12.25    | 62.96     | 20.15     | 85.32     | 21.25     |
|           | 20                     | 29.27   | 8.02     | 63.41     | 20.64     | 82.59     | 21.02     |
| Kissinger |                        | 83.54   | 20.67    | 122.48    | 26.39     | 184.23    | 26.01     |
| Kim-Park  |                        | 78.93   | 45.65    | 129.84    | 37.88     | 199.81    | 44.56     |

The temperature dependent function is generally assumed to follow an Arrhenius type dependency:

\[
\ln k = \ln A - \frac{E_a}{RT},
\]

where \( k \) is the rate constant, \( A \) is the preexponential factor, \( E_a \) is the activation energy, and \( R \) and \( T \) are the gas constant and temperature, respectively.
Dehydration was governed by Avrami-Erofeev model (A3), decomposition of benzoate anion was governed by contracting cylinder (R2) then non-isothermal decomposition of MBDH using TG data.

Figure 6: Flynn-Wall plot for stage III in nitrogen atmosphere for the nonisothermal decomposition of MBDH using TG data.

A typical plot of α versus temperature for stages I, II, and III is shown in Figure 3. It is seen that all α-T curves have the same shapes. From the slope of linear Arrhenius plots of ln k versus 1/T for the thermal decomposition of MBDH at three different heating rates, the activation energies (E_a) for all stages were calculated and listed in Table 1. Activation energies of the decomposition complex were also calculated by Kissinger and Kim-Park. Both methods yield similar calculation results, which are therefore reasonable (Table 1).

Flynn-Wall plots for three different heating rates against the temperature for the stages I, II, and III are shown in Figures 4, 5, and 6, respectively, and the straight lines obtained are nearly parallel to each other. At each heating rate, the temperatures were determined corresponding to the degree of conversion α within the range 0.1 to 0.9 in intervals of 0.1. Activation energy (E_a) is calculated from the slope of lnβ versus 1/T for a fixed mass loss and it is given in Table 2. We have also calculated the activation energies by Friedman method for all the three stages and they are given in Table 2. The calculated values of the activation energy in the Flynn-Wall method very well agree with the Friedman. If E_a changes with α, the process is complex and the shape of E_a-α curve may provide the information on the reaction mechanism [20, 21]. With increasing heating rate, TG curves shifted to higher temperature which is a typical case of thermally activated heterogenous process. The mass loss depends on the heating rate. Mass loss is very small at the lowest heating rate and high at the highest heating rate.

Figure 7(a) shows the dependence of the apparent activation energy (E_a) on the degree of conversion (α) obtained by Flynn-Wall method. Dependence of effective activation energy (E_a) with extent of conversion (α) is used to identify its kinetic scheme; that is, these values are used for input to multistep for model fitting purposes. Kinetic compensation effect was observed in many isothermal processes. There is a linear relationship between ln A and E_a:

\[
\ln A = aE_a + b, \tag{4}
\]

where a and b are called compensation parameters. Figure 7(b) shows the linear relationship between ln A and E_a and hence it is clear that compensation effect is valid for the thermal decomposition of MBDH.

Best models can be selected by introducing the various analytical forms of g(α) and f(α) functions at all heating rates (β) which in turn depend on the value of statistical parameters R. A plot of ln g(α)/T^2 versus 1000/T that gives straight line for all the three stages is shown in Figure 8 accompanied by a correlation value 0.9−0.99. Dehydration was governed by Avrami-Erofeev model (A3), decomposition of benzoate anion was governed by contracting cylinder (R2)

| α    | Stage I | Stage II | Stage III | Stage I | Stage II | Stage III |
|------|---------|----------|-----------|---------|----------|-----------|
|      | E_a [kJ mol^{-1}] ln A [s^{-1}] E_a [kJ mol^{-1}] ln A [s^{-1}] E_a [kJ mol^{-1}] ln A [s^{-1}] | E_a [kJ mol^{-1}] ln A [s^{-1}] E_a [kJ mol^{-1}] ln A [s^{-1}] E_a [kJ mol^{-1}] ln A [s^{-1}] | E_a [kJ mol^{-1}] ln A [s^{-1}] E_a [kJ mol^{-1}] ln A [s^{-1}] E_a [kJ mol^{-1}] ln A [s^{-1}] |
| 0.1  | 43.59   | 11.26    | 42.13     | 12.87   | 95.37    | 21.48     | 11.65     | 3.77    | 47.79    | 14.25    | 30.83    | 7.56     |
| 0.2  | 45.76   | 11.93    | 56.68     | 16.50   | 88.32    | 19.86     | 19.34     | 6.46    | 49.82    | 14.88    | 37.36    | 9.08     |
| 0.3  | 48.62   | 12.82    | 70.04     | 19.87   | 82.49    | 18.54     | 25.13     | 8.47    | 43.99    | 13.35    | 40.44    | 9.81     |
| 0.4  | 48.49   | 12.71    | 82.44     | 22.99   | 78.93    | 17.71     | 27.34     | 9.22    | 28.57    | 9.21     | 42.56    | 10.33    |
| 0.5  | 48.86   | 12.76    | 93.02     | 25.64   | 75.54    | 16.94     | 27.22     | 9.16    | 14.43    | 3.39     | 41.78    | 10.21    |
| 0.6  | 45.91   | 11.72    | 62.34     | 17.55   | 72.73    | 16.29     | 24.75     | 8.28    | 14.91    | 2.42     | 36.62    | 9.10     |
| 0.7  | 34.27   | 7.88     | 113.93    | 30.86   | 69.78    | 15.64     | 19.56     | 6.46    | 61.59    | 14.98    | 23.71    | 6.29     |
| 0.8  | 12.25   | 1.19     | 122.09    | 32.86   | 66.45    | 14.91     | 12.79     | 4.09    | 91.21    | 22.93    | 8.92     | 0.92     |
| 0.9  | 39.89   | 14.88    | 130.86    | 35.00   | 62.41    | 14.05     | 11.02     | 1.25    | 79.69    | 19.94    | 44.27    | 8.54     |

Figure 7(b) shows the linear relationship between ln A and E_a.
model, and melaminium cation decomposition was accepted by Avrami-Erofeev model (A4).

3.3. Phase Transition. Figure 9 shows the DSC traces of MBDH. Differential Scanning Calorimetry measurements indicate clearly the occurrence of phase transition of the first order at approximately 368 and 358 K for heating and cooling, respectively, which is accompanied by a big thermal effect of 385 J/g. The peak at 95°C is due to the water of crystallization of MBDH. The phase transition of the benzoate anion occurs at 158.6°C and 167.3°C for heating and cooling, respectively, accompanied by a thermal effect of 17.54 J/g and 2.049 J/g. The third stage of thermal decomposition is the elimination of melamine which usually occurs at ~500–600°C. In the present study, it is not the objective to find out the decomposition temperature of the final compound. The thermal stability of melamine is naturally higher since it has strong intermolecular hydrogen bonding which is expected to be present in these structures because of water of crystallization.

4. Conclusions

Single crystals of melaminium benzoate dihydrate (MBDH) crystallize in the monoclinic system (C2/c). TG-DTG measurements were carried out at three different heating rates: 10, 15, and 20°C/min. Model free methods, Arrhenius,
Flynn-Wall, Friedman, Kissinger, and Kim-Park methods were employed. All methods yield almost similar results. It is found that Kissinger and Kim-Park are the most suitable methods to find effective activation energy. Effective activation is nearly constant for stage I whereas it varies strongly with extent of conversion for the stages II and III indicating that the process is dominated by multistep mechanism. The compensation effect is valid for the thermal decomposition of MB DH. From the results, it is concluded that Avrami Erofeev model (A3) is the most probable kinetic model for the thermal decomposition of MB DH for the dehydration stage, contracting cylinder (R2) for the benzoate anion decomposition, and Avrami-Erofeev model (A4) for the decomposition of melaminium cation.

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