

Hydrolytic Degradation Studies on Poly(Phosphate Ester)s

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Received 10 May 2001; accepted 12 April 2002

ABSTRACT: Eight poly(phosphate ester)s comprising five homopolymers (polymers I–V), two copolymers (polymers VI and VII), and one terpolymer (polymer VIII) were synthesized by interfacial polycondensation of phenyl phosphorodichloridate with various bisphenols. The polymers were characterized by spectroscopic techniques. The copolymer and terpolymer ratios were determined by $^1\text{H-NMR}$ spectroscopy. The molecular weights of the polymers were de-

termined by end-group analysis using $^{31}\text{P-NMR}$ spectroscopy. Accelerated hydrolytic degradation studies under alkali-catalyzed conditions showed that the polymer from biphenol (polymer IV) is the most stable and the polymer from thiodiphenol (polymer V) is the least stable. The products of hydrolytic degradation were analyzed and a suitable mechanism for the degradation of the polymers proposed. © 2002 Wiley Periodicals, Inc. *J Appl Polym Sci* 87: 626–631, 2003

INTRODUCTION

Hydrolytically degradable polymers are potentially biodegradable. Biodegradable polymers have applications in medicine and as environment-friendly plastics.^{1–3} Of all the polymers studied as biodegradable polymers, very little work has been reported on poly(phosphate ester)s. The phosphate ester linkages are hydrolyzable, similar to carboxylic esters. Leong et al. were the first to report on poly(phosphate ester)s as biodegradable polymers for applications as drug-delivery devices.^{4,5} The first report on the kinetics of the hydrolysis of poly(phosphate ester)s was given by Basen and Penczek.⁶ In this article, we report on the synthesis of eight poly(phosphate ester)s and their accelerated hydrolytic degradation under alkali-catalyzed conditions. The polymer from bisphenol A (polymer I) was studied by Leong et al., while the other polymers that we synthesized have not been studied so far. We also studied the hydrolytic degradation of polymer I in detail and it was reported in a separate article.⁷

Poly(phosphate ester)s are also an important class of organophosphorus polymers because of their flame-retardant property.^{8–11} Kishore et al. synthesized a number of poly(phosphate ester)s and studied their flammability and thermal stability.^{12–17}

EXPERIMENTAL

Materials

Phosphorus oxychloride (Spectrochem, India) and phenol (Glaxo Laboratories, India) were used after distilla-

tion. The bisphenols, bisphenol A (Kochlight Laboratories), bisphenol S (Aldrich, Milwaukee, WI), 4,4'-thiodiphenol (Aldrich), phenolphthalein (E. Merck, India), 4,4'-dihydroxybiphenyl (Fluka), and the phase-transfer catalyst tetrabutylammonium bromide (Loba Chemie, India) were used as such. Dichloromethane solvent (LR grade) was kept over calcium chloride (anhydrous) for 24 h and then distilled over phosphorus pentoxide to make it dry. Solvents like chloroform (LR grade) and petroleum ether (commercial grade) were distilled prior to use.

Synthesis of poly(phosphate ester)s

Phenyl phosphorodichloridate was prepared from phosphorus oxychloride and phenol as reported earlier.^{18,19} All the polymers were synthesized by interfacial polycondensation of phenyl phosphorodichloridate with bisphenols in the presence of a phase-transfer catalyst. The procedure followed by Leong et al. was followed with certain modifications.²⁰ A typical procedure for the synthesis of homopolymers (polymers I–V) is given here.

Bisphenol (0.07 m), sodium hydroxide (0.2 m), and tetrabutylammonium bromide (10 mol %, 0.007 m) were placed in a three-necked round-bottom flask attached with a nitrogen inlet, addition funnel, and mechanical stirrer. The mixture in the flask was first made to dissolve in 120 mL of water by stirring. Then, while stirring the mixture rapidly, freshly distilled phenyl phosphorodichloridate (0.067 m, 10 mL), dissolved in 100 mL of dry dichloromethane solvent, was added rapidly to the mixture. After the addition was complete, the reaction mixture was vigorously stirred for another 0.5 h.

During the work-up, the organic phase was separated from the aqueous layer in a separatory funnel and washed four times with distilled water to remove

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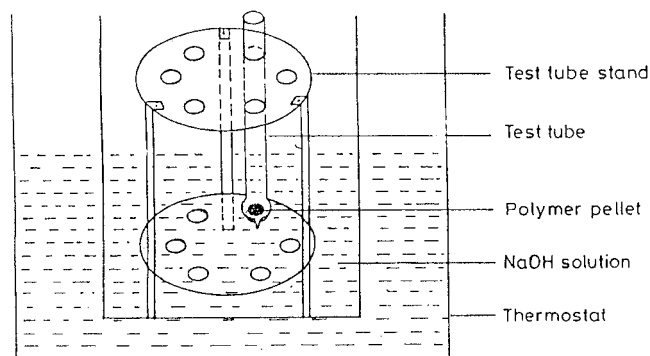


Figure 1 Experimental setup for hydrolytic degradation studies.

the traces of alkali completely. The polymer solution was then passed through anhydrous sodium sulfate to remove traces of water, concentrated, and then poured into a large excess of petroleum ether to precipitate the polymer. The polymer was washed again with ice-cold water to remove traces of the phase-transfer catalyst and then dried under a vacuum. The copolymers and terpolymer were synthesized in a similar manner except that the feed ratio of the bisphenols was 50 : 50% for the copolymers and 33.33% each for the terpolymer. The yields of the polymers ranged from a low of 54% for polymer III and a high of 82% for polymers V and VII. All the polymers were white powdery solids, except the polymer from biphenol (polymer IV), which was a gummy solid.

Hydrolytic degradation studies

About 250 mg of the finely powdered polymer was compressed in a die and made as a pellet. The pellet dimensions are a diameter of 10 mm and thickness of 2.6 mm. Ten such pellets were used for a single experiment.

First, the initial weights of the pellets were recorded. The 10 pellets were placed each in numbered test tubes (125 × 12 mm) with a bulge and a small hole at the bottom. The test tubes were placed in a circular stainless-steel stand with 10 holes. The stand was then placed inside a 2-L beaker containing the sodium hydroxide solution. The whole setup was then placed in a thermostat (Fig. 1). To start the experiment, the thermostat was brought to the desired temperature (37°C) and then the 2-L beaker containing only the sodium hydroxide solution (6M) was kept in the beaker to attain thermal equilibrium. After 1 h, the stand containing the test tubes and pellets was placed inside the beaker. The sodium hydroxide solution rose into the test tubes through the holes at the bottom of the test tube.

The test tubes were removed one at a time, after given time intervals, and the pellets were washed with distilled water. They were then placed in a 1% HCl solution for about 2 min and then washed again with

distilled water until the washings were neutral to pH paper. If the pellet was intact, it was removed from the test tube, its surface wiped with a tissue paper, and then put back into the test tube. If the pellet was broken, it was left as such. Then, the test tubes with the pellets were dried in a vacuum desiccator for 36 h and then their final weights calculated. From the difference between initial and final weights of the pellets, the percentage of weight loss was calculated.

The polymer from biphenol (polymer IV) could not be made as a pellet. Hence, a thin film was made by dissolving the polymer in dichloromethane and casting it on to a glass plate and evaporating the solvent. A small section of the film was cut. The film dimensions were 1.2 × 1.2 cm. The film was weighed and placed at the bottom of a test tube containing the sodium hydroxide solution. Then, the test tube was placed inside a beaker containing water. The beaker was then placed in a thermostat. After 6 h, the film was washed with water, 1% HCl, and again water. Then, it was dried under a vacuum and its final weight recorded.

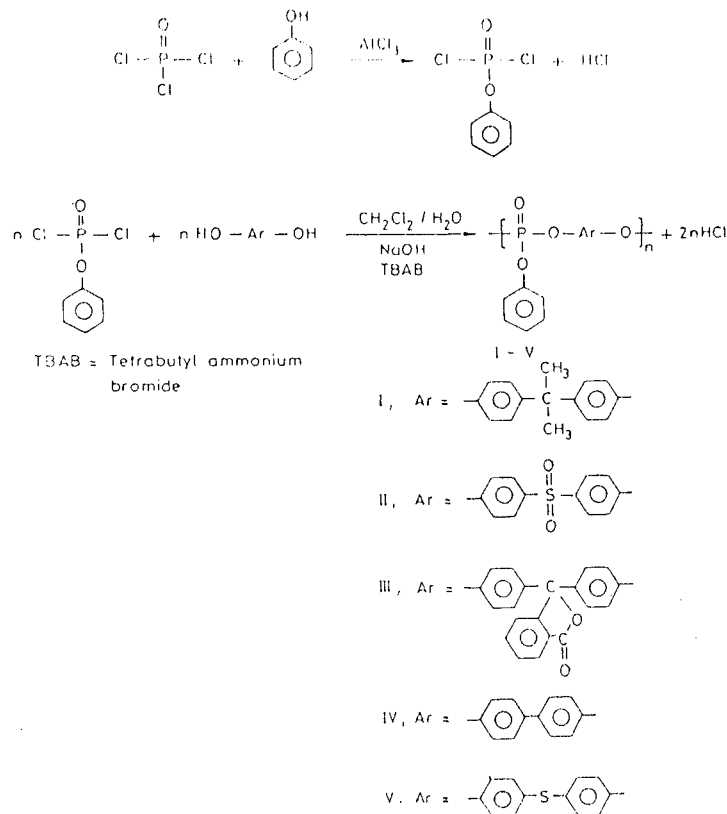
Procedure for extraction of degradation products

To determine the degradation products formed during the hydrolytic degradation, in one of the polymers, that is, in polymer I, the sodium hydroxide solution was taken after the experiment was completed and neutralized with an equivalent amount of HCl. On neutralizing, a white solid precipitated out. This solid was filtered and the filtrate extracted with chloroform solvent three times to extract the organic products dissolved in the aqueous solution. The chloroform solutions were collected and dried over calcium chloride and then the chloroform evaporated. The resulting residue and the filtered solid were analyzed by TLC, NMR spectroscopy, and mass spectrometry.

RESULTS AND DISCUSSION

Synthesis of poly(phosphate ester)s

The various poly(phosphate ester)s were synthesized from phenyl phosphorodichloridate and different bisphenols. Five homopolymers (polymers I–V) were synthesized by interfacial polycondensation of phenyl phosphorodichloridate with bisphenol A, bisphenol S, phenolphthalein, biphenol, and thiodiphenol, respectively (Scheme 1). Two copolymers (polymers VI and VII) were synthesized from phenyl phosphorodichloridate and a mixture of bisphenol A with biphenol (polymer VI) and bisphenol A with thiodiphenol (polymer VII) (Scheme 2). A terpolymer was synthesized from phenyl phosphorodichloridate and a mixture of three bisphenols, that is, bisphenol A, biphenol, and thiodiphenol (polymer VIII) (Scheme 2). The



Scheme 1 Synthesis of phenyl phosphorodichloridate and homopolymers (I-V).

synthesis of all the homopolymers was reported earlier.^{12,14,19}

Characterization of the polymers

All the polymers were characterized by FTIR and ¹H-, ¹³C-, and ³¹P-NMR spectroscopy. The spectroscopic results for the poly(phosphate ester)s match the results reported earlier.¹²⁻¹⁷ The above results showed that some catalyst groups are still present in the polymer, probably as end groups.

The copolymer and terpolymer ratios for polymers VI-VIII were determined from ¹H-NMR spectroscopy. In these polymers, bisphenol A is present. The isopropyl group of bisphenol A shows a peak in the aliphatic region (a singlet at 1.6 δ). The H atoms of the bisphenols show a multiplet in the aromatic region (6.5-8 δ). In copolymer VI and terpolymer VIII, the aromatic groups are split into two groups due to the presence of the biphenol moiety in these two polymers, whereas, in copolymer VII, all the aromatic groups have merged together. From the integral ratios of the isopropyl group and the two aromatic multiplet groups, the copolymer and terpolymer ratios were calculated. The data are given in Table I.

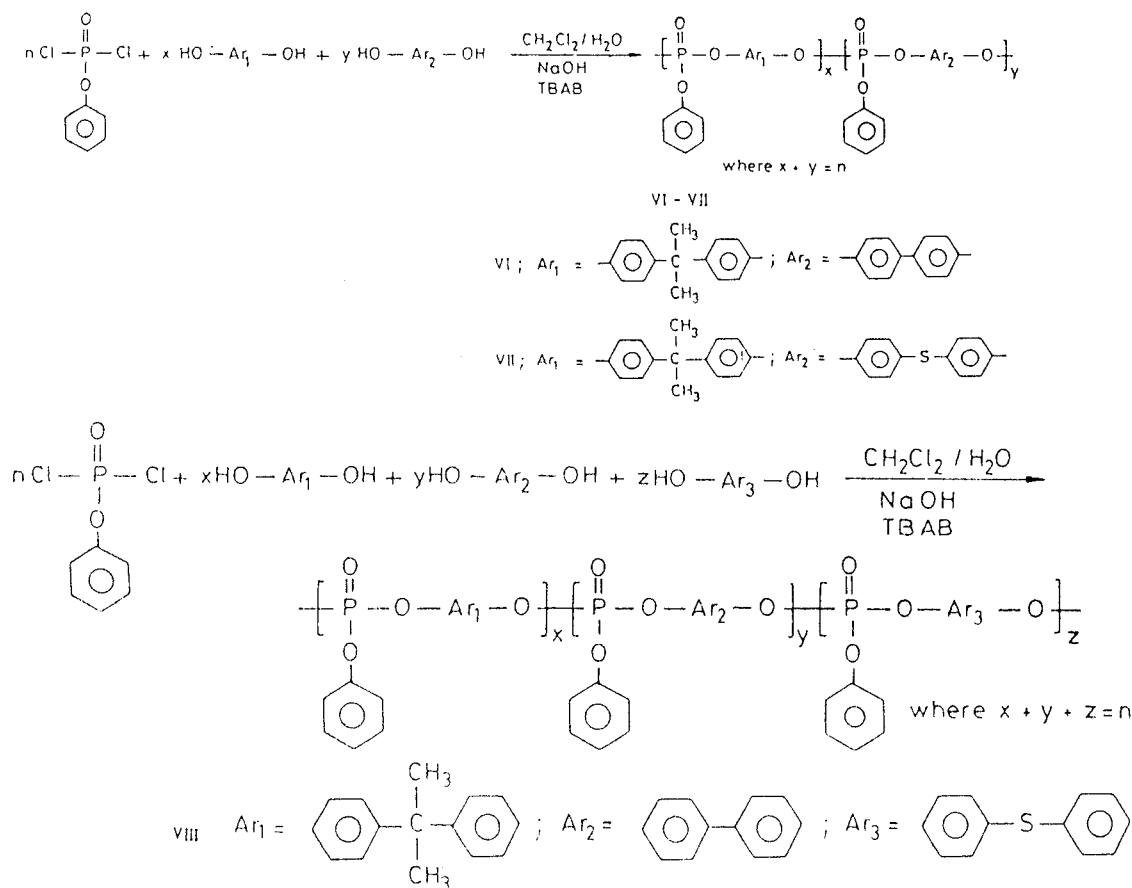
The molecular weights of the polymers were determined by end-group analysis using proton-decoupled ³¹P-NMR spectroscopy. The repeat unit of the P atom shows an intense peak around -18 ppm, while the P

atoms in the end show weakly intense peaks around -11 and -16 ppm. From the integral ratios of the peaks due to the repeat unit and peaks due to end groups, the degree of polymerization (DP) of the polymers was calculated, and from this, the molecular weights of the polymers were determined. The data are given in Table II.

Hydrolytic degradation studies

Accelerated hydrolytic degradation can be done at high concentrations of the catalyst. In the present study, we used alkali as the catalyst, since phosphate triester hydrolysis is catalyzed mainly by alkali.²¹ Pellets of the polymers were prepared and alkaline hydrolysis experiments carried out in a 6M sodium hydroxide solution for 6 h. The polymer from biphenol was not powdery and, hence, a film was used. The percentage weight loss at the end of 6 h was calculated and compared for all the polymers in Table III.

The polymer from bisphenol S (polymer II) and phenolphthalein (polymer III) showed 100 and 96.7% weight loss at the end of 2 and 3 h respectively. Further, the sodium hydroxide solution became turbid and small particles were seen in the solution in the experiment with these two polymers. In the case of the other polymers, the sodium hydroxide solution was clear after the experiment. It is quite possible that the degradation disintegration of the pellets also occurs in


Scheme 2 Synthesis of copolymers and terpolymer (VI-VIII).

polymers II and III. The DP of these two polymers is very low compared to those of the other polymers, that is, 4 for polymer II and 3 for polymer III. This also may be another reason for the disintegration of the pellets in these two polymers. Among the other homopolymers, the thiodiphenol polymer (polymer V) shows the highest weight loss. This polymer also softens to some extent at the experimental temperature. The polymer from biphenol (polymer IV) is the most stable. Thus, the hydrolytic stability follows the order.

Polymer IV > polymer I > polymer V

TABLE I
Copolymer and Terpolymer Ratios

Polymer	Ratio	Percentage of		
		Bisphenol A	Biphenol	Thiodiphenol
VI	Feed	50	50	
VI	Copolymer	59	41	
VII	Feed	50		50
VII	Copolymer	49		51
VIII	Feed	33.33	33.33	33.33
VIII	Terpolymer	49	37	14

The copolymer and terpolymer ratios were determined by $^1\text{H-NMR}$ spectroscopy.

The polymer from bisphenol A shows a 7.8% weight loss. On copolymerizing with biphenol (polymer VI), the weight loss decreases to 3.9%, since the homopolymer from biphenol (polymer IV) is the most stable. On the other hand, on copolymerizing with thiodiphenol (polymer VII), the weight loss increases to 12% since the homopolymer from thiodiphenol (polymer V) shows the highest amount of weight loss. For the same reason, the terpolymer (polymer VIII) from bisphenol A, biphenol, and thiodiphenol shows a 35.9% weight loss even though the thiodiphenol content is only 14% (Table I). Thus, the order of hydrolytic stability among the copolymers and terpolymer is as follows:

TABLE II
DP and Molecular Weights of the Polymers

Polymer	DP	Molecular weight
I	7	2928
II	4	1940
III	3	1824
IV	19	6156
V	11	4182
VI	11	4182 ^a
VII	6	2526 ^a
VIII	6	2443 ^a

^a Based on composition (determined by $^1\text{H-NMR}$) of copolymers and terpolymers.

TABLE III
Percentage Weight Loss of the Polymers

Polymer	Total Time (h)	Percentage of weight loss
I	6	7.8
II	2	100.0
III	3	96.7
IV ^a	6	6.1
V	6	43.8
VI	6	3.9
VII	6	12.0
VIII	6	35.9

^a Film conditions: 6M NaOH at 37°C.

Copolymer VI > copolymer VII > terpolymer VIII

Analysis of the degradation products and mechanism of alkaline hydrolysis

The products of hydrolytic degradation were analyzed to determine the mechanism of degradation. In a typical hydrolysis experiment on the polymer from bisphenol A (polymer I), after the experiment was over, the alkali solution was neutralized with an equivalent amount of HCl. A white solid precipitated out. The white solid and the filtrate were analyzed by NMR spectroscopy, TLC, and mass spectroscopy.

The ³¹P-NMR spectrum of the chloroform extract of the white solid showed an intense peak around -1.1 ppm, indicating the presence of a phosphate diester unit and also a peak of medium intensity around -18 ppm, indicating the presence of a phosphate triester unit (Fig. 2). The TLC and mass spectra of the white solid shows the presence of phenol and bisphenol A. Peaks corresponding to *m/z* 94 and 228 in the mass spectra of the white solid correspond to molecular ion peaks of phenol and bisphenol A (Fig. 3). Thus, the

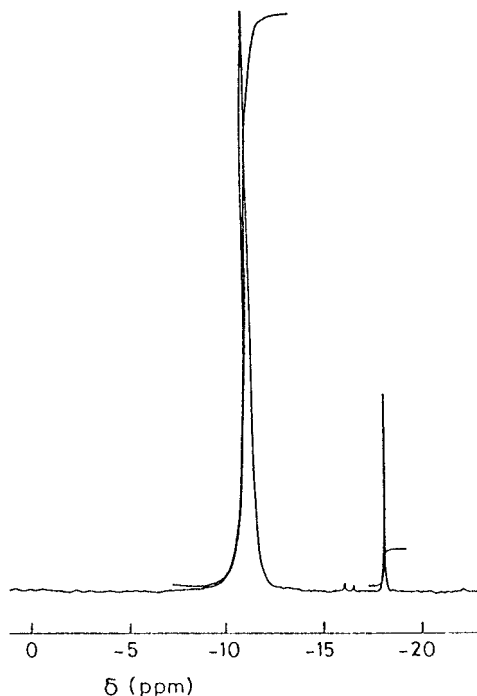


Figure 2 ³¹P-NMR spectra of white solid.

white solid is a mixture containing the phosphate diester compound, phosphate triester compound, phenol, and bisphenol A. The chloroform extract of the filtrate was found to contain some phosphate triester compound.

The phosphate triester polymer on hydrolysis can form a phosphate diester by the cleavage of main chain or side chain. Once a phosphate diester is formed, further hydrolysis of the diester to the monoester cannot occur easily, since the hydrolysis of the diester to the monoester is very slow.²² The presence

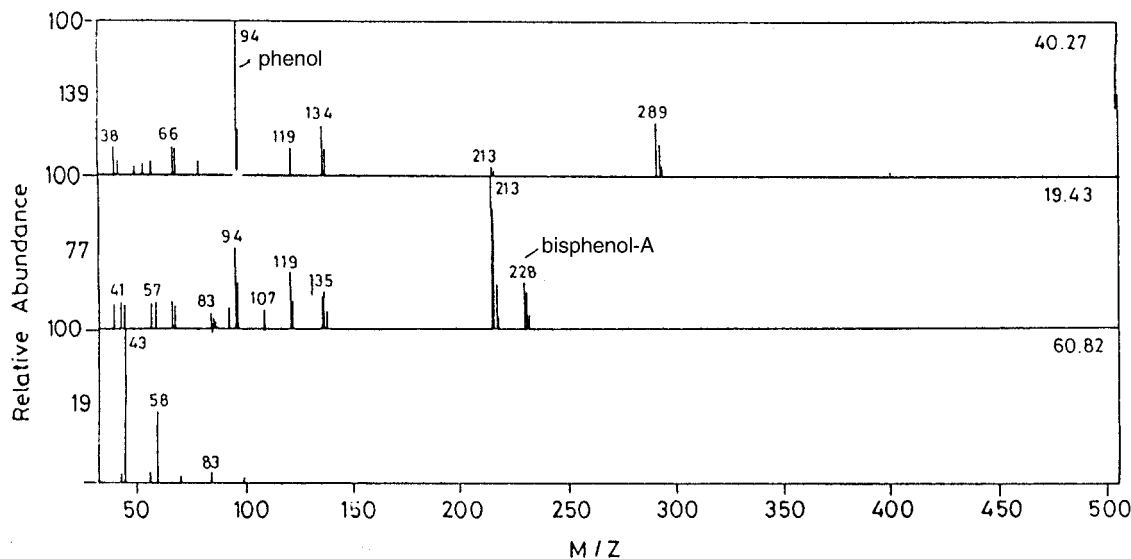
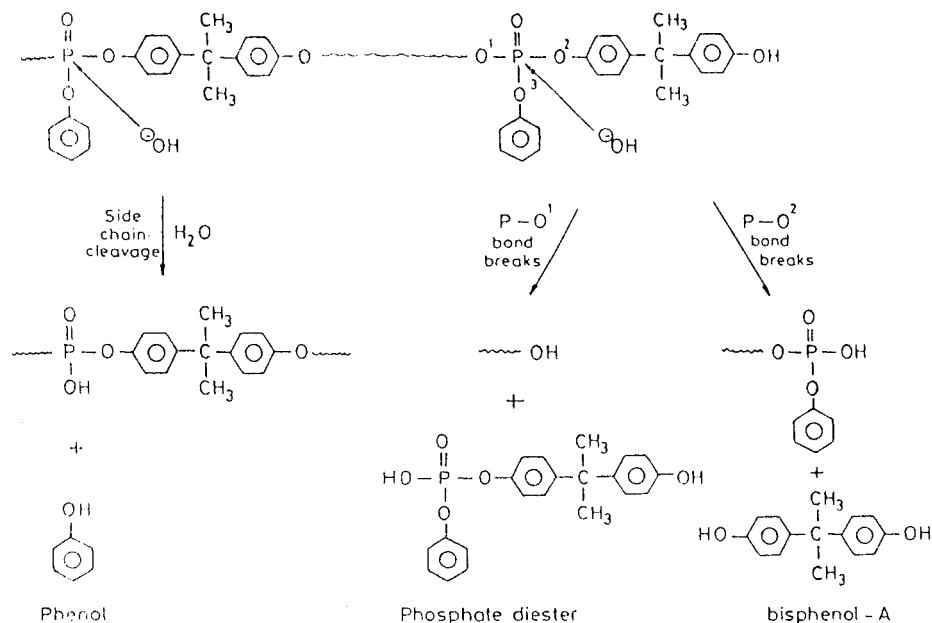


Figure 3 Mass spectrum of white solid.



Scheme 3 Mechanism of hydrolytic degradation of polymer I.

of phosphate diester groups clearly show evidence that hydrolysis had taken place. The mechanism of alkaline hydrolysis in simple phosphate triesters has already been established and it has been confirmed by isotope experiments that the P—O bond breaks, whereas in neutral or acidic conditions, the C—O bond breaks.²¹ We believe that in the phosphate polymer the same mechanism also should hold true. Based on the degradation products detected, the mechanism of hydrolytic degradation of the polymer from bisphenol A is proposed, which is shown in Scheme 3. Differences in the rate of degradation of the various poly(phosphate ester)s are due to the electronic effects of the bisphenol moieties which affect the P—O bond.

CONCLUSIONS

Eight poly(phosphate ester)s comprising five homopolymers, two copolymers, and one terpolymer were synthesized and characterized by spectroscopic techniques. A comparative study of the hydrolytic degradation under alkali-catalyzed conditions shows that the polymer from biphenol (polymer IV) is the most stable and the polymer from thiodiphenol (polymer V) is the least stable. The thiodiphenol moiety increases the rate of degradation whenever it is present in the copolymer and terpolymer, while the biphenol moiety decreases the rate of degradation. The products of hydrolytic degradation were analyzed and a suitable mechanism for the hydrolytic degradation was proposed.

We thank Dr. S. Ramakrishnan and Dr. K. Ganesh for useful discussions.

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