necessary that η be determined very accurately. An error of 5% in η produces an error of only about 1.5% in M_n.

Summary

1. The viscosities (η) of molten linear polyesters having average molecular weights in the range 200 to over 10,000 have been measured. Log η has been found to be precisely a linear function of the square root of the weight average chain length throughout this range.

2. The viscosities of mixtures of two polyesters, one of them having a low and the other a high average molecular weight, agree with the same relationship, when the weight average chain length of the mixture is used therein. Thus, the relationship between viscosity and weight average chain length does not seem to depend on the type of distribution of species in the polymer.

3. The viscosity–temperature coefficient ($d \ln \eta/dT$) is independent of the average molecular weight, and its magnitude is not many times greater than that found for similar monomeric substances. It has been concluded that the elementary process responsible for viscous flow must consist of displacement of only a small section of the chain, and that this elementary process is the same for polymers of all sizes.

4. The utility of the viscosity–chain length relationship as a simple and accurate means for determination of molecular weight has been discussed.

5. Densities and thermal expansion coefficients of polyesters have been measured.

6. An analysis of the errors incident to molecular weight determination by end-group titration has been presented.

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[CONTRIBUTION FROM THE GATES AND CRELLIN LABORATORIES OF CHEMISTRY, CALIFORNIA INSTITUTE OF TECHNOLOGY, No. 728]

Esters of Alginic Acid

BY H. J. LUCAS AND W. T. STEWART[1]

Since alginic acid is a polyuronide,[2] it would be expected to form two types of esters, *viz.*, alkyl esters and acyl esters, the former because of one carboxyl group per mannuronic residue, the latter because of one or two free hydroxyl groups per mannuronic residue. Of course, the terminal residue will have one additional hydroxyl group. If all of the carboxyl groups are free or are bound as in a salt or in an ester, there would then be two free hydroxyl groups per residue (except for the terminal ones), and dialkyl esters should be possible. However, if the carboxyl groups are bound in lactone formation, then only one hydroxyl group per residue would be free. Therefore the degree of esterification which can be attained presumably would depend, at least in part, upon the extent to which the mannuronic residues of the alginic acid molecule are in the acid or in the lactone form.

Alginic acid might be expected to undergo esterification and etherification of the hydroxyl groups, much as pectin does. The latter can be formylated, acetylated and nitrated without difficulty.[3,4] Methylation of pectin fragments or of pectin which has suffered partial degradation has been accomplished by heating the silver salt with methyl iodide under pressure,[5] by dimethyl sulfate[6] and by methyl iodide and thallium ethoxide.[7] Pectin acid has been exhaustively methylated.[8] Alkylation of the carboxyl group of alginic acid has been effected by heating with methanolic hydrogen chloride.[9,10]

Acetates of alginic acid have been prepared using acetic anhydride and aqueous hydriodic acid as the acetylating agent.[11] A dimethyl ether has been obtained from alginic acid methylglycoside methyl ester (from partially degraded alginic acid and methanolic hydrogen chloride) by the use of methyl iodide and thallium ethoxide.[10]

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[1] Kelco Company Fellow, 1938–39. Original manuscript received September 5, 1939.

[2] Nelson and Cretcher, THIS JOURNAL, **51**, 1914 (1929); **52**, 2130 (1930); Schoeffel and Link, *J. Biol. Chem.*, **95**, 213 (1932).

[3] Schneider and Ziervogel, *Ber.*, **69B**, 2530 (1936).

[4] Henglein and Schneider, *ibid.*, **69B**, 309 (1936).

[5] Buston and Nanji, *Biochem. J.*, **26**, 2090 (1932).

[6] F. Smith, *Chemistry and Industry*, **58**, 364 (1939).

[7] Beaven and Jones, *ibid.*, **58**, 363 (1939).

[8] Levene, Meyer and Kuna, *Science*, **89**, 370 (1939).

[9] Heen, *Tids. Kjemi Bergvesen*, **17**, 127 (1937).

[10] Hirst, Jones and Jones, *Nature*, **143**, 857 (1939); *J. Chem. Soc.*, 1880 (1939).

[11] Barry, Dillon and O'Muineachain, *Sci. Proc. Roy. Dublin Soc.*, **21**, 289 (1936).

Experimental

Alginic Acid.—This was supplied by the Kelco Company, of San Diego, who manufactured it from *Macrocystis pyrifera* by a process involving digestion of the kelp with hot aqueous sodium carbonate, precipitation of calcium alginate by the addition of aqueous calcium chloride and conversion of this to alginic acid by means of hydrochloric acid.[12] Alginic acid is a wet fibrous product of about 12% solids. The dried product leaves about 2.5% ash on ignition. For the nitration water was extracted by agitating with several portions of ethyl alcohol which were poured off. The alcohol left finally was allowed to evaporate. The alginic acid remained as a rather compact mass, water content 15%. Another portion was dissolved in aqueous sodium carbonate. The acid was precipitated from the solution by the addition of dilute hydrochloric acid. After filtration through cloth, washing twice with water and then with aqueous methanol until free of chloride, washing well with alcohol, finally with ether, and drying over sulfuric acid, the alginic acid was left as a light, fluffy mass. The ash was reduced to 2.1%. This product was used in methylation as well as in some of the nitration experiments. The presence of methanol (25%) in the water prevented peptization of alginic acid and yet allowed removal of chloride.

Nitration.—This was accomplished with a mixture of nitric acid (d. 1.47) and concentrated sulfuric acid (d. 1.84). The mixture was kept cold during the mixing of the acids and placed in a refrigerator at 3 to 5°. The product was recovered by adding ice and water and centrifuging. Mineral acid was removed by shaking the residue with ice and water and centrifuging. This was done eight times. At first, two or three preparations were worked up by filtering the nitration mixture through a sintered glass funnel, followed by washing with water. Centrifuging was found to be more satisfactory and convenient, however. Next, the nitrated product was taken up in acetone and precipitated by the addition of ether. After this was done five times, the product was placed in a vacuum desiccator over calcium chloride. The dried weight is the one recorded in Table I.

TABLE I

NITRATION OF ALGINIC ACID AT 3 TO 5°

Expt.	HNO_3, d. = 1.47, ml.	H_2SO_4, d. = 1.84, ml.	Alginic acid, g.	Moles HNO_3/moles $C_6H_8O_6$[c]	Time of standing, hr.	Product, g.	Nitrogen, %	$NO_2/C_6H_6O_5$[d]
1[a]	45	45	15	13	60	3.8	3.83	0.50[e]
2[a]	90	90	15	25	48	2.2	3.81	.49
3[b]	30	30	5	30	72	1.7	7.27	1.08
4[a]	67.5	22.5	15	19	1	12.0	5.09	0.69
5[a]	67.5	22.5	15	19	60	2.6	5.92	.83
6[a]	22.5	7.5	5	19	150	1.6	7.69	1.18
7[b]	67.5	22.5	15	23	12	9.8	5.23	0.71
8[b]	67.5	22.5	15	23	60	3.0	6.09	.85
9[a]	135	45	15	38	48	5.4	5.23	.71[f]
10[b]	45	15	5	45	48	1.8	6.94	1.01
11[b]	45	15	5	45	48	2.0	6.12	0.86

[a] Reprecipitated alginic acid, alcohol and ether washed, dried over sulfuric acid to a light, fluffy product, ash, 2.1%. [b] Alginic acid, alcohol washed, dried to a compact mass, ash, 2.5%, H_2O, 15%. [c] As free acid. [d] As lactone. [e] Ash, 0.6%. [f] Ash, 0.5%.

For analysis all samples were dried at 60° and 30 mm. over phosphorus pentoxide. Nitrogen was determined by the micro Dumas method. The analytical results are given in Table I.

Methylation.—Several attempts were made to methylate alginic acid with dimethyl sulfate and aqueous sodium hydroxide. It was found necessary to work at a temperature of 60° and to repeat the methylation twice with fresh reagents. An opalescent solution resulted. The product was recovered by acidifying with hydrochloric acid cold, centrifuging, and washing the precipitate four times with water, centrifuging each time. The product was dried by washing with ether, in which the methylated product was insoluble. Less than one methoxyl group per mannuronic residue was introduced. The methoxyl content of these and other preparations was determined by the method of Viebock and Schwappach[13] after drying at 60° and 30 mm. over phosphorus pentoxide (Table II).

TABLE II

METHYLATION OF ALGINIC ACID

Experiment		1	2	3	4
Alginic cpd.		Acid	Acid	Acid	Ag salt
Taken, g.		17.6	1.76	56.5	1.45
Reagent	Cpd.	Me_2SO_4 + NaOH	0.2 *M* CH_2N_2 in Et_2O		MeI
	g.	[a]	35.7[b]	2485	7.25
Methylated product (A)	g.	9.8	1.6	51	0.9
	MeO, %	9.78	18.2	22.4	2.44
Ammonolyzed product (B)	MeO, %	...	5.08	7.96[c]	..
MeO per C_6 unit	A	0.58	1.13	1.40	0.14
	B	...	0.29	0.48	..

[a] Me_2SO_4, 75.6 g.; NaOH, 30%, 80 g. Three treatments at 60°. [b] For eight hours. [c] After forty-eight hours; MeO was 8.16% after twenty-four hours.

Best results were obtained with diazomethane. The alginic acid used in the methylations with diazomethane was the fluffy reprecipitated product. It was not freed of ether but was treated directly with diazomethane. Seven portions of 500 ml. (355 g.) of 0.2 *M* diazomethane in ether were added over a period of two hundred and forty hours to the acid (56.5 g. of the original dry acid). The final volume was 3.5 liters. The yellow color after addition of the first and second portions largely disappeared in a few hours, but after subsequent additions diminished but little on standing. The methylated alginic acid was recovered by drawing off most of the ether through a filter stick. The rest was removed by suction filtration under a rubber dam and by vacuum drying over concd. sulfuric acid.

Silver alginate was prepared by adding aqueous silver nitrate to aqueous ammonium alginate. The precipitate, after filtering and washing with methanol, was shaken with a solution of methyl iodide in methanol for ten hours, and the mixture allowed to stand in the dark, with occasional shaking, for two months. The product was recovered by first removing the liquid through filtration, then adding aqueous sodium cyanide to the solid and precipitating

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(12) Thornley and Walsh, U. S. Patent 1,814,981 (July 14, 1931).

(13) Viebock and Schwappach, *Ber.*, **63B**, 2818 (1930); *J. Assoc. Official Agr. Chem.*, **15**, 136 (1932).

TABLE III

METHYLATION OF NITRATED ALGINIC ACID AT 25°

Experiment		1	2	3
Nitrated acid	Table I	3	5	10
	N, %	7.27	5.92	6.94
	$NO_3/C_6H_5O_5$	1.08	0.83	1.01
	Grams	0.50	2.0	0.50
Reagents		2.4 g. HCl in 15 ml. MeOH	1.25 g. Me_2SO_4 0.4 g. NaOH 2 g. H_2O	9.1 g. MeI 0.13 g. Ag_2O 5 ml. Me_2CO
Time, hours		48	0.5	72
Product	Grams	0.4	1.5	0.4
	N, %	7.20	5.50	6.32
	MeO, %	10.3	3.26	6.28
Per C_6 unit	NO_3	1.18	0.78	0.97
	MeO	0.79	.21	.44

the sodium salt of partially methylated alginic acid by the addition of ethyl alcohol to the cyanide solution. After centrifuging and washing the resulting gelatinous precipitate with small amounts of water, dilute hydrochloric acid was added. The gelatinous material was centrifuged, washed with a small amount of water, then with ether, and dried over concd. sulfuric acid at 30 mm.

Methylation of different specimens of nitrated alginic acid was carried out in three different ways as shown in Table III. The product from methanolic hydrogen chloride was precipitated by the addition of ether, thoroughly washed with ether and dried at 30 mm. over solid sodium hydroxide and concd. sulfuric acid. The aqueous solution from dimethyl sulfate treatment was acidified and the residue remaining after centrifuging was washed with 25% ethanol–water and dried at 30 mm. over sulfuric acid. The acetone solution from the treatment with silver oxide and methyl iodide was diluted with methanol, precipitated with ether and dried as above.

Ammonolysis.—Ammonolysis of methylated alginic acid was carried out by allowing the material to stand with concd. ammonium hydroxide for twenty-four hours. The resulting viscous liquid was acidified, the precipitated acid was washed several times with 50% ethanol–water, then with ether, and dried as usual. The recovery was approximately 60%. The methoxyl content was determined as before.[13] The results are shown in Table II. That the reaction was essentially complete is shown by the small drop in methoxyl content on a second twenty-four-hour treatment (8.16 to 7.96% OCH_3).

Other Derivatives.—Attempts to prepare products soluble in acetone by the action of benzoyl chloride, benzyl chloride and phenacyl bromide on sodium alginate were not successful.

Optical Rotations.—Optical rotations were observed on alginic acid, on two different specimens of nitrated alginic acid and on two specimens of methylated alginic acid (Table IV). The materials had been dried at 60° and 30 mm. over phosphorus pentoxide for twenty-four hours. The alginic acid, the nitrated alginic acid and the material methylated by means of dimethyl sulfate and sodium hydroxide were dissolved in aqueous sodium hydroxide, using just enough base to effect solution. The product obtained by the use of diazomethane was dispersed in water. Observations were limited to very dilute solutions, 0.3%, because at higher concentrations the Tyndall effect was so pronounced that satisfactory readings could not be made.

Titration.—The neutralization equivalent of nitrated alginic acid dried at 60° and 30 mm. over concd. sulfuric acid and solid caustic was determined by titrating a solution of the sample in acetone, obtained by shaking for about two hours, with standard base to a phenolphthalein end-point. The combined neutralization–saponification equivalent was obtained by heating the sample with an excess (10%) of aqueous standard base for four hours on a steam-bath, and back titrating. The equivalent weights are shown in Table V. The calculations were made thus:

Neutralization equivalent = $158 + (NO_3/C_6 \times 45)$

Combined neutralization–saponification equivalent = neut. equiv./$(1 + NO_3/C_6)$.

TABLE IV

Material	Description Table	Description No.	Solvent	Concn., %	Rotation α	$[\alpha]^{25}_D$	$[M]^{25}_D \times 10^{-3}$
Alginic acid			Aq. NaOH	0.300	−0.41	−137°	−22
Nitrated product	I	5	Aq. NaOH	.300	.34	−113	−22
Nitrated product	I	10	Aq. NaOH	.300	.33	−110	−22
Methylated product	II	1	Aq. NaOH	.300	.29	− 97	−16
Methylated product	II	3	H_2O	.300	.35	−117	−23
Methylated product	II	3	H_2O	.300	.35	−117	−23

TABLE V

TITRATION OF NITRATED ALGINIC ACID

From Table I		No. 8	No. 11
N, %		6.09	6.12
Neut. equiv.	Calcd.	197	198
	Found	198	200
Combined neut.–sapon. equiv.	Calcd.	107	107
	Found	104	109
Ash, %		0.3	0.1

Discussion

The various specimens of nitrated alginic acids are much alike in properties. They dissolve in aqueous sodium carbonate, from which they are precipitated on acidification. They are readily soluble in acetone, methanol and ethanol, less readily in 1-propanol, dioxane and methyl iodide, and but slightly soluble in acetic anhydride and glacial acetic acid. They are insoluble in ethyl ether, isopropyl ether and chloroform. These last serve to precipitate the nitrated alginic acids from their solutions in other solvents.

The extent to which nitration took place varied from 0.49 to 1.18 nitrate groups per mannuronic unit, calculated as the lactone (Table I). Additional purification by dissolving once more in acetone and precipitating with ether left the material essentially unchanged, as shown in experiments 3 and 10, for the nitrogen content in the first case changed from 7.27 to 7.02 and in the second case from 6.94 to 7.21%. The best yield was obtained in experiment 4, where the time was shortened to one hour. The extent of nitration, however, was low. When the time was lengthened the yield was less, and in a general way was lower the longer the period of standing. On the other hand, the degree of nitration usually increased as the time was lengthened.

The recovery of a small amount (2%) of material from the first acetone–ether liquor (Expt. 8, Table I) indicates that precipitation of a nitrated alginic acid from its acetone solution by the addition of ether is essentially quantitative. The recovered material analyzed 8.05% N (1.26 NO_3 per C_6 unit).

Since the maximum number of nitrate groups in the main products was essentially 1 per C_6 residue, the assumption is justified that the alginic acid while undergoing nitration was essentially in the lactone form unless the second free hydroxyl group would not nitrate under these conditions, even in the presence of a good excess of the nitrating mixture. This must be regarded as a possibility in view of the fact that with diazomethane less than one hydroxyl group was methylated (Table II). However, lactonization of alginic acid presumably would be as likely as that of nitrated alginic acid which was shown by titration to be lactonized when dried. Alginic acid being nitrated may have been lactonized during drying, or when put into the nitrating mixture.

The recovery of a small amount of higher nitrated product from the acetone–ether mother liquor (Expt. 8) would seem to indicate that higher nitration products are formed to some extent.

The various specimens of methylated alginic acid are alike in that they peptize in water but in solutions containing 25% methanol or ethanol they do not peptize. They are alike also in that they are slightly soluble in methanol and in acetone, insoluble in ethyl ether and in chloroform. They differ in that the diazomethane preparations are less soluble and do not reduce Fehling solution. The product obtained by the action of methyl sulfate and hot sodium hydroxide reduced Fehling solution. Thus the drastic conditions involved in methylating with dimethyl sulfate bring about degradation of the alginic acid molecule whereas this is not the case with diazomethane.

Ammonolysis of alginic acid methylated by diazomethane showed that in the two cases approximately 74 and 66%, respectively, of the total methylation had taken place on carboxyl groups, and 26 and 34%, respectively, on alcoholic hydroxyl groups (Table II). It showed also that in the first case 84% and in the second case 92% of the carboxyl groups had been methylated. These results are based on the assumption that only the carbomethoxy groups react with ammonia.

Methylation of specimens of nitrated alginic acid did not change the ratio of nitrate groups per C_6 unit. There is thus no replacement of these groups by methoxyl under the conditions employed (Table III). The calculation of nitrate and methoxyl content in the methylated product is made on the basis that the extent of lactone ring opening is equivalent to the degree of methylation.

From the optical data equivalent rotations $[M]^{25}\text{D}$ were calculated on the assumption that the dried samples of alginic acid, of nitrated alginic acid and of the alginic acid methylated by means of dimethyl sulfate were lactonized. However, in the solutions of these as examined the materials were lactone free since they were in the form of salts. The equivalent rotation of the product methylated with diazomethane agrees well with the rotations of the sodium salts of alginic acid and of nitrated alginic acid. Thus in the substances which essentially were lactone free (the data of Table II indicate that 92% of the carboxyl groups were methylated) and which had not suffered degradation, the equivalent rotations were in agreement.

The low equivalent rotation for the methylated product resulting from dimethyl sulfate treatment can be ascribed to degradation, for this was the only material which reduced Fehling solution. The drop in rotation may be the result of isomeric changes in the terminal mannuronic residues of the smaller degraded molecules. At one end the configuration about C-1 might change and at the other end a furanose structure might change over to a pyranose structure.[14]

From the data in Table V it is evident that when thoroughly dried, specimens of nitrated alginic acid go over to the lactone form.

[14] Levene, Meyer and Kuna[8] believe that in pectic acid some of the galacturonic units have the furanose structure.

This research was made possible by a grant from the Kelco Company of San Diego, California.

Summary

Alginic acid is converted into a nitrated alginic acid when in contact with nitric–sulfuric acid mixture. The ratio of nitrate groups per mannuronic unit, which varies from 0.49 to 1.2, largely depends upon the excess of nitric acid taken and upon the time of standing.

The failure to obtain higher nitration products is believed to be due to lactonization of the mannuronic units as the result either of drying the acid or of its coming in contact with concd. sulfuric acid.

When nitrated alginic acid is thoroughly dried lactonization of the carboxyl groups takes place.

Methylation of alginic acid by means of dimethyl sulfate and aqueous sodium hydroxide at 60° is not satisfactory since less than one methyl group per mannuronic unit is introduced, and degradation takes place.

Diazomethane is satisfactory as a methylating agent in that little or no degradation takes place. While the carboxyl group is undergoing methylation some methylation takes place on the hydroxyl group.

Nitrated alginic acid can be partially methylated but there is no replacement of nitrate by methoxyl groups.

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[CONTRIBUTION FROM THE AVERY LABORATORY OF CHEMISTRY OF THE UNIVERSITY OF NEBRASKA]

Some Fully Acetylated Sugar Acids and their Derivatives

BY GORDON B. ROBBINS AND F. W. UPSON

Interest in the fully acetylated aldonic acids has been stimulated by Major and Cook[1,2,3] through the preparation and application to synthesis of acid chlorides of these acids. A general method of preparing fully acetylated sugar acids has been reported by Hurd and Sowden,[4] who prepared fully acetylated *d*-gluconic, *d*-galactonic and *l*-arabonic acids by treating an acetic acid solution of the acetylated acid amide with nitrous anhydride. Direct acetylation of aldonic acid amides has been shown to be a simple and general method for preparing the fully acetylated amides.[5] Various acetylated amides which had been prepared by this method have been treated according to the method of Hurd and Sowden[4] to give new fully acetylated aldonic acids.

Direct acetylation of gluconic acid has been reported to be unsuccessful by Major and Cook.[3] We have found, however, that some aldonic acids can be acetylated directly. Several of these are described in the following investigation. In addition some other fully acetylated acids hitherto unknown were prepared by the method of Hurd and Sowden. Thus tetraacetyl-*d*-arabonic, pentaacetyl-*d*-gulonic, and hexaacetyl-*d*-α-glucoheptonic acids were prepared by this procedure. A modification of the method was employed in the preparation of pentaacetyl-*d*-talonic acid and pentaacetyl-*d*-mannonic acid monohydrate. These acids were prepared by treating the reaction mixture from the acetylation of the corresponding aldonic amide with nitrous anhydride.

It was impossible to prepare hexaacetyl-*d*-α-galaheptonic acid from the corresponding amide by this method. The acetylated amide proved too insoluble in any solvents at suitable temperatures.

The unusual stability of *d*-α-galaheptonic acid suggested the possibility of direct acetylation to give the fully acetylated acid. Direct acetylation yielded hexaacetyl-*d*-α-galaheptonic acid as was indicated by comparison of the product with the acetylated lactone, analysis of the product, and its conversion into the methyl ester. Direct acetylation of *d*-arabonic, *d*-galactonic, and *d*-talonic acids likewise yielded the corresponding fully acetylated acids which were identified by comparison with the product obtained from the acetylated amide. The yields were too low to be satisfactory for the preparation of the fully acetylated *d*-galactonic and *d*-talonic acids, but proved to be the most successful method for obtaining tetraacetyl-*d*-arabonic acid.

Attempts were made to prepare fully acetylated *d*-mannonic, *d*-gulonic and *d*-α-glucoheptonic acids

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[1] Major and Cook, THIS JOURNAL, **58**, 2477 (1936).

[2] Cook and Major, *ibid.*, **58**, 2410 (1936).

[3] Major and Cook, *ibid.*, **58**, 2474 (1936).

[4] Hurd and Sowden, *ibid.*, **60**, 235 (1938).

[5] Robbins and Upson, *ibid.*, **60**, 1788 (1938).