Investigation of Macromolecules Exhibiting the Structure of a Once-Broken Rod by Molecular Optics. 2. Synthesis and Investigation of Three-Block Copolymers: Poly(γ-benzyl L-glutamate)–Poly(methyl methacrylate)–Poly(γ-benzyl L-glutamate)

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Received December 4, 1989; Revised Manuscript Received June 18, 1990

ABSTRACT: Samples of an ABA-type three-block copolymer (where A is poly(γ-benzyl L-glutamate) (PBG) and B is poly(methyl methacrylate) (PMMA)) were synthesized on a polymer initiator, PMMA, with the aim of elucidating the effect of a flexible polymer joint of different lengths on the conformational characteristics of rigid PBG molecules. The copolymer is considered to be a flexible polymer coil bonded at its ends to helical sequences of PBG exhibiting high equilibrium rigidity. The molecular weight and fraction of each copolymer component were varied. Solutions of copolymer samples were investigated in DMF at 25 °C by light scattering, flow birefringence, and viscometry. Their compositions, molecular weights, intrinsic viscosities, radii of gyration, second virial coefficients, and optical anisotropy were investigated. The molecular weights and optical anisotropy of the copolymer components were calculated. A comparative analysis of the molecular weight dependence of intrinsic viscosity and optical anisotropy was carried out for the investigated copolymers and the PBG homopolymer. It was shown that the introduction of a long flexible PMMA joint into the rigid PBG molecule does not change the equilibrium rigidity of PBG. A model for the structure of a three-block PBG–PMMA–PBG copolymer making it possible to explain all the experimental data was considered.

Introduction

The aim of the present paper is to establish the effect of the introduction of a flexible polymer joint of various length on the conformational characteristics of rigid poly(γ-benzyl L-glutamate) (PBG) molecules. The effect of a long flexible joint on the thermodynamic flexibility of rigid-chain polymers has been considered by the authors of an experimental paper.[1]

The investigation of these polymers is not only of theoretical interest because the block copolymers containing a carbon chain and polypeptide blocks can form liquid-crystalline polymer structures and are widely used as models for membrane studies. In addition, under the influence of the enzymatic systems of the organism they can undergo controlled biodegradation and are used as carriers of biologically active compounds. Samples of a three-block copolymer of the ABA type where A is PBG and B is poly(methyl methacrylate) (PMMA) were synthesized (Figure 1).

The molecule of this copolymer in a helix-forming solvent consists of two PBG helices bonded to the ends of the Gaussian coil. It was of interest to establish whether correlation exists in the mutual orientation of rigid PBG helices. Solutions of the samples obtained in DMF at 25 °C were investigated by light scattering, flow birefringence (FB), and viscometry.

Experimental Section

Polymer Carbon-Chain Initiators. NH_2–PMMA–NH_2 were obtained by free-radical polymerization according to refs 2 and 3 by using bis(*o*-(glycylamino)phenyl) disulfide as an "iniferter" (simultaneously chain *ini*tiator–trans*fer*–*ter*mination agent). A part of the NH_2–PMMA–NH_2 samples was fractionated in a benzene–petroleum ether system. For comparative investigations carried out under the same conditions but without the iniferter, PMMA was obtained without end groups. The molecular characteristics of the PMMA and NH_2–PMMA–NH_2 samples are given in Table I.

Synthesis of Block Copolymers. The polymer initiators of various molecular weights obtained here were used in the synthesis of block copolymers. Three-block PBG–PMMA–PBG copolymers were obtained by polymerizing the *N*-carboxyanhydride of γ-benzyl L-glutamate (NCA-BG) (synthesized by Fuller's method[4]) on the corresponding NH_2–PMMA–NH_2 in dioxane at a total solution concentration of 3–7% at room temperature. After the completion of polymerization (2–7 days) the product was precipitated into methanol and treated with selective solvents. The unreacted PMMA was extracted with ethyl acetate. According to elemental analysis for nitrogen and IR spectroscopy, the amount of this fraction was 30–40% of the initial PMMA. In the case of PMMA with molecular weight exceeding 120×10^3, this fraction contained 50–60% of the initial PMMA. The PBG content in this fraction did not exceed 2–4%. The copolymer greatly enriched with PMMA was washed with methyl ethyl ketone (MEK). This fraction was usually present in the amount of 8–15% from the total yield. The main fraction of the copolymer was washed with hot MEK (T = 40–60 °C). The copolymer yield with respect to the total polymer yield is given in Table II. The amount of the polymer that was not dissolved in hot MEK was <5%. According to the elemental analysis data, this fraction is greatly enriched with PBG. This treatment of the samples makes it possible to obtain copolymers that virtually do not contain homopolymers.

Light scattering, FB, and intrinsic viscosity were measured by standard procedures taking into account the main features of the investigated systems (see part 1). All copolymers in DMF formed molecular-disperse solutions. The copolymer composition was determined from the refractive index increment, dn/dc, and monitored by IR spectroscopy. For most samples these data are in satisfactory agreement with the results of elemental analysis (Table II) with the exception of sample II. The IR spectroscopic data suggest that in this sample PBG exhibits the β structure. Taking into account the possible effect of compositional inhomogeneity of the samples on the values of M_w and $\langle R^2 \rangle$ we estimated the value $[(dn/dc)_A - (dn/dc)_B]/(dn/dc)_{cop}$, in which the subscripts A and B refer to the components of the copolymer. This value was found to vary from 0.50 to 0.64. In this case the corrections for M_w and $\langle R^2 \rangle$ are within a standard experimental error.[5-7]

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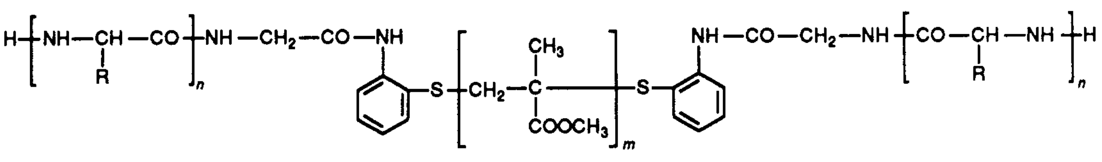

Figure 1. Structure of a three-block copolymer of the ABA type, R = $(CH_2)_2COOCH_2C_6H_5$.

Table I
Molecular Characteristics of PMMA Fractions at 25 °C

			DMF			acetone		
sample type	fraction no.	iniferter wt %	$M_w \times 10^{-3}$	$[\eta] \times 10^{-2}$, cm^3/g	$A_2 \times 10^4$, $cm^3/(g^2\ mol)$	$M_w \times 10^{-3}$	$[\eta] \times 10^{-2}$, cm^3/g	$A_2 \times 10^4$, $cm^3/(g^2\ mol)$
PMMA	1	0	130	0.28	3.6			
	2	0	160	0.34	3.5			
	3	0	230	0.40	3.3			
	4	0	250	0.50	2.6			
	5	0	290	0.63	1.9			
	6	0	400	0.79	1.8			
NH_2-PMMA-NH_2	7	0.16	190	0.43	2.7	190	0.41	2.4
	8	0.16	360	0.64	2.8			
	9	0.50		0.21		55	0.20	3.3
	10	1.00	70	0.23	2.6	60	0.21	3.0
	11	1.00	130	0.34	2.3	130	0.31	3.4
	12	1.00	150	0.34	2.8	120	0.37	2.8
	13	1.00	180	0.44	0.7	170	0.43	1.7
	14	1.00	250	0.54	2.5			
	15	1.50		0.17		30	0.15	3.6
	16[a]	1.50	45	0.17	2.9			

[a] Unfractionated sample.

Table II
Molecular Characteristics of Samples of Three-Block PBG–PMMA–PBG Copolymers in DMF at 25 °C

					wt % of PBG in the copolym determined from									
sample no.	no. of polym init[a]	[A]/[I]	$100(Y_{tot}/Y_{theor})$,[b] %	$100(Y_{cop}/Y_{tot})$,[c] %	dn/dc	IR spectrosc	nitrogen anal.	$[\eta] \times 10^{-2}$, cm^3/g	$M_{w,cop} \times 10^{-3}$	$M^{cop}_{PMMA} \times 10^{-3}$	$M^{cop}_{PBG} \times 10^{-3}$	$A_2 \times 10^4$, $cm^3/(g\ mol)$	$(\Delta n/\Delta\tau)_{cop} \times 10^{10}$, $(cm\ s^2)/g$	$(1/\gamma)(\Delta n/\Delta\tau)_{cop} \times 10^{10}$, $(cm\ s^2)/g$
I	9	50	99	35	36	26	33	0.37	100	64	36	4.0	100	290
II	9	700	57	28	40	71	56	0.19	60	36	24	3.7	60	140
III[d]		200	78	49	44	54	45	0.52	160	90	70	3.1	160	360
IV	15	50	75	55	52	52	56	0.32	80	38	42	2.9	240	460
V	7	530	74	20	56		57	0.20	55	24	31	3.2	30	50
VI	9	300	94	77	56	63	62	0.37	95	42	53	3.2	180	320
VII[d]		300	90	65	56	62	60	0.66	170	75	95	3.2	240	430
VIII[d]	2	200	78	49	60	65	65	1.90	320	128	192	2.1	660	1100
IX	15	300	90	88	64	76	76	0.41	85	31	54	3.1	210	330
X[d]		300	90	77	64	78	76	0.62	140	50	90	3.7	270	420
XI[d]		300	97	24	66	76	78	0.69	140	48	92	1.7	510	770
XII[d]					74		83	2.40	320	83	237	2.2	650	810
XIII		300	97	40	80	86	86	0.92	150	30	120	2.3	580	720

[a] The numbers of polymer initiators correspond to fraction numbers in Table I. [b] Ratio of total yield to theoretical yield. [c] Ratio of copolymer yield to total yield. [d] The molecular weight M_w was not measured for polymer initiators of these samples.

The solutions of these copolymers in DMF exhibit FB, Δn, positive in sign. The dependence of Δn on the velocity gradient g is linear. The value of the shear optical coefficient $\Delta n/\Delta\tau = \Delta n/g(\eta - \eta_0)$ (η_0 and η are the viscosities of the solvent and the solution, respectively) does not depend on polymer concentration. The obtained values of $(\Delta n/\Delta\tau)_{c\to 0, g\to 0}$, are listed in Table II.

Results and Discussion

A. Investigation of Polymer Initiator, NH_2–PMMA-NH_2. An indispensable stage in the study of the copolymers was the investigation of the molecular parameters and properties in a solution of the polymer initiator, NH_2-PMMA-NH_2. Table I gives the values of M_w and $[\eta]$ of the investigated PMMA fractions in DMF. In order to compare the thermodynamic behavior of NH_2–PMMA-NH_2 in DMF with that of PMMA, fractions 1–6 were investigated. For control, the molecular parameters of NH_2-PMMA-NH_2 in acetone were measured simultaneously (Table I) since PMMA in acetone has been studied in sufficient detail.[8] For PMMA and NH_2–PMMA-NH_2 in DMF and acetone, the dependence of $[\eta]$ on M_w (Figure 2) processed by the least-squares method corresponds to the Mark–Kuhn–Houwink equation: $[\eta] = 2.16 \times 10^{-2} M^{0.62}$. The parameters of this equation, K_η and α, are in good agreement with the literature data.[8,9]

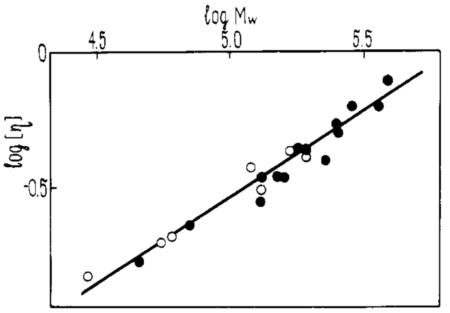

Figure 2. Intrinsic viscosity $[\eta]$ vs molecular weight M_w for PMMA in DMF (●) and in acetone (○).

For fractions 11–14, scattering asymmetry was observed ($[Z] = I_{45°}/I_{135°} \leq 2.0$). Its value decreased with the dilution of the solution ($[Z] \to 1$ as $C \to 0$). Solutions of fractions

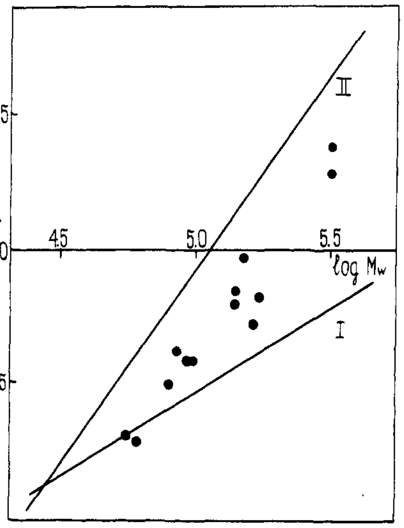

Figure 3. Intrinsic viscosity $[\eta]$ vs molecular weight M_w in DMF: for PBG (curve I), see part 1; for PMMA (curve II), the points are the experimental data for PBG-PMMA-PBG copolymers.

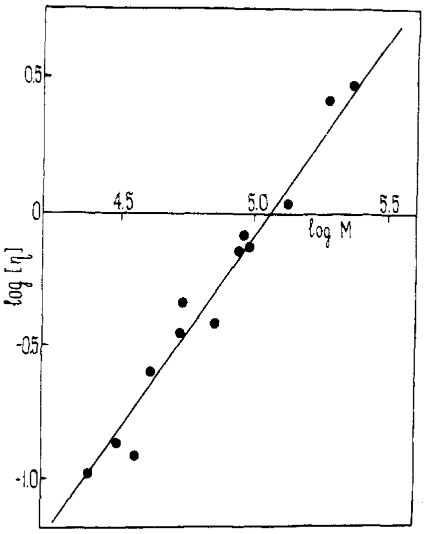

Figure 4. Intrinsic viscosity $[\eta]$ vs molecular weight M in DMF. The points refer to the values of $[\eta]^{cop}_{PBG}$ calculated from eq 1 with respect to M^{cop}_{PBG}. The straight line is the Mark-Kuhn-Houwink dependence for the PBG homopolymer (see part 1).

with a higher M_w value also exhibited a higher asymmetry in the range of C 0.7-2.5%. This fact indicates that associates are formed in DMF and are dissociated at $C \rightarrow 0$. This is confirmed by the presence of glycyl end groups in the polymer initiator. Scattering asymmetry was observed only for fractions obtained at an iniferter concentration of 1% and having a molecular weight not lower than $M_w = 130 \times 10^3$. Hence, it was assumed that it is these fractions that have the highest number of macromolecules with glycyl end groups. Since the molecular weight M_w of PMMA with amino end groups, NH_2-PMMA-NH_2, was experimentally determined before PMMA became a part of the copolymer (Table I) and the molecular weight of PMMA in the copolymer (M^{cop}_{PMMA}) was calculated (Table II), it was of interest to compare these data. It was found that for copolymer samples obtained at a large iniferter content (samples I, II, IV, VI, and IX in Table II) these values are in good agreement to within experimental error. For a sample obtained at a low iniferter content (sample V in Table II) the value of M^{cop}_{PMMA} is 8 times lower than that of M_w for the initial NH_2-PMMA-NH_2. This fact indicates that the copolymer contains mainly low molecular weight fractions of the polymer initiator enriched with amino end groups. Hence, the fraction and molecular weight of NH_2-PMMA-NH_2 molecules capable of polymerizing NCA-BG are directly dependent on the amount of iniferter in the synthesis of the polymer initiator. At a low iniferter content, conventional polymerization of the monomer dominates over the formation of NH_2-PMMA-NH_2. This polymerization leads to the formation of PMMA without end groups.

B. Investigation of a Three-Block PBG-PMMA-PBG Copolymer. Light Scattering and Viscosity. For the investigated copolymers Table II gives the values of molecular weights M_w, intrinsic viscosities $[\eta]$, and second virial coefficients A_2. Figure 3 shows the dependence of $[\eta]$ on M_w for the copolymers. For comparison, similar dependences are given for PMMA (curve I, obtained in this work) and for PBG (curve II, obtained in part 1). It is clear that almost all experimental points for the copolymers fall between straight lines I and II. It should be taken into account that the lower the molecular weight of PMMA in the copolymer, the closer the viscosity of the copolymer ($[\eta]_{cop}$) should approach that of the PBG homopolymer ($[\eta]_{PBG}$) at any composition. Since we are interested in the effect of the flexible joint on the PBG viscosity in the copolymer ($[\eta]^{cop}_{PBG}$), the values of $[\eta]^{cop}_{PBG}$ were calculated with the following assumptions: the components of the copolymer behave in solution as independent chains, and the polydispersity of these components is constant in all samples. Then the following expression may be used:

$$[\eta]_{cop} = \gamma[\eta]^{cop}_{PBG} + (1-\gamma)[\eta]^{cop}_{PMMA} = \gamma C_1[\eta]_{PBG} + (1-\gamma)C_2[\eta]_{PMMA} \quad (1)$$

The values of coefficients C_1 and C_2 were obtained by the method of successive approximations at the lowest quadratic deviations of $[\eta]_{cop}$ calculated according to eq 1 from its experimental value. The following values were obtained: $C_1 = 1.05$ and $C_2 = 2.47$. Since the coefficient C_1 is virtually equal to unity, the values of $[\eta]^{cop}_{PBG}$ obtained from eq 1 fall closely to the straight line for PBG (Figure 4). Hence, $[\eta]^{cop}_{PBG}$ corresponds to the viscosity of the PBG homopolymer ($[\eta]_{PBG}$) of length $L = l_1 + l_2$ (l is the length of one PBG block in the copolymer) assuming that $l_1 \simeq l_2$.

Flow Birefringence. The FB of solutions of the PBG homopolymer in helix-forming solvents has already been investigated in detail.[10] Figure 5 shows the experimental values of the shear optical coefficient $\Delta n/\Delta\tau = f(M_w)$ for the PBG homopolymer (see part 1). The same figure shows the theoretical dependence $(\Delta n/\Delta\tau)/\beta BA = \varphi(x)$ for the model of a kinetically rigid wormlike chain.[11,12] Here, $\varphi(x) = x/(x+2)$, β is the anisotropy of unit length, $B = (4\pi/45kT)[(n^2+2)^2/n]$, and $x = L/a$. It is clear that the experimental points for the PBG homopolymer coincide with the theoretical curve $\varphi(x)$ over the entire range of M_w ($55 \times 10^3 \leq M_w \leq 800 \times 10^3$) at the value of the persistence length $a = 1000$ Å and $\beta = 1 \times 10^{-16}$ cm^2.

It was of interest to establish the effect of introduction of a long flexible joint into the PBG chain on the optical anisotropy of the molecules, which is very sensitive to any conformational changes. The comparison of data for $(\Delta n/\Delta\tau)_{cop}$ and $M_{w,cop}$ (Table II) does not make it possible to solve this problem because there is no unique correlation between these values since both the composition of copolymers and the M_w of the components are varied. Consequently, the value of $(\Delta n/\Delta\tau)^{cop}_{PBG}$, the shear optical coefficient of two PBG blocks contained in the investigated copolymer, was calculated from the experimental values

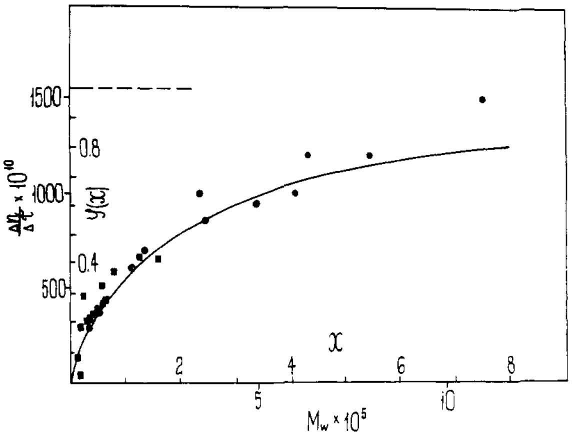

Figure 5. Shear optical coefficient $\Delta n/\Delta\tau$ vs molecular weight M_w. The points refer to the experimental data for the PBG homopolymer (see part 1) (⊙) and $(\Delta n/\Delta\tau)^{cop}_{PBG}$ with respect to M^{cop}_{PBG} (■). The theoretical curve is plotted according to the equation[11,12] $\varphi(x) = (\Delta n/\Delta\tau)/\beta BA = x/(x+2)$ at $A = 2000$ Å and $\beta = 1 \times 10^{-16}$ cm^2. The broken line is the limit of the function $\varphi(x) = 1$ at $x \to \infty$.

of $(\Delta n/\Delta\tau)_{cop}$. It should be borne in mind that in this case the PMMA molecules may be considered to be "invisible" because their optical anisotropy is low[13] and virtually does not contribute to the value of Δn of the copolymer solution. However, the contribution of the viscosity of the PMMA coil contained in the copolymer $[\eta]^{cop}_{PMMA}$ to the copolymer viscosity $[\eta]_{cop}$ should be taken into account. Calculations show that only for some copolymers (VIII, XI, XII, and XIII) the $[\eta]^{cop}_{PMMA}/[\eta]_{cop}$ ratio is 10–15%, and it is possible to assume to a first approximation for these polymers that $(\Delta n/\Delta\tau)^{cop}_{PBG} = (\Delta n/\Delta\tau)_{cop}$. For most investigated polymers the $[\eta]^{cop}_{PMMA}/[\eta]_{cop}$ ratio is 30–80%. Hence, the presence of PMMA coil increases the viscosity of the copolymer solution $[\eta]_{cop}$ as compared to that of two PBG blocks and thus affects the shear optical coefficient of the copolymer $(\Delta n/\Delta\tau)_{cop}$. It can easily be shown that in this case we have $(\Delta n/\Delta\tau)^{cop}_{PBG} = (1/\gamma)(\Delta n/\Delta\tau)$ (γ is the weight percentage of PBG in the copolymer). The values of $(\Delta n/\Delta\tau)^{cop}_{PBG} = f(M)$ are shown in Figure 5. It is clear that these values fall close to the same theoretical curve as those of $(\Delta n/\Delta\tau)_{PBG}$, taking into account the experimental error. Since the introduction of a long flexible joint into the PBG chain did not change its optical anisotropy, this implies that the PBG blocks touch each other and are oriented in the copolymer at an angle $\theta = 180°$ to each other.

The same arrangement is indicated by coincidence in the values of the radii of gyration $\langle R^2\rangle^{1/2}$ obtained from scattering asymmetry for samples VIII ($\langle R^2\rangle^{1/2} = 500$ Å) and XII ($\langle R^2\rangle^{1/2} = 600$ Å) with the corresponding values for the PBG homopolymer with molecular weight equal to that of M^{cop}_{PBG} (see part 1).

A priori it could be assumed that when a long flexible joint is present, there will be no correlation in the mutual orientation in two rigid copolymer parts. However, the experimental data obtained in this paper and the literature data[1] indicate that PBG blocks in the copolymer are oriented at an angle $\theta = 180°$ to each other. Taking into account the above considerations, it is possible to describe the molecular structure of the PBG–PMMA–PBG copolymer by a model consisting of two antiparallel rods partly overlapping in the volume of the PMMA coil (Figure 6). This model has been proposed in ref 1. In this hypothetical model, PBG parts are shown for clarity as rigid rods although, strictly speaking, a slightly bent rod exists at $0.2 < x < 2.2$.

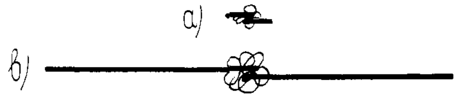

Figure 6. Model for the molecule of a three-block PBG–PMMA–PBG copolymer: (a) low molecular weight sample (V in Table II); (b) high molecular weight sample (XII in Table II).

This type of model is based on the following concepts: (1) the angle between PBG sequences θ is 180° and the length of two PBG sequences is $L \simeq l_1 + l_2$ and (2) the stabilization of this structure is probably due to the partial overlapping of PBG blocks having a tendency to associate. The presence of PMMA sequences incompatible with PBG increases the interaction between the PBG blocks.

This model assumes the existence of a part in which PBG blocks surrounded by the PMMA coil partly overlap. Therefore it may be suggested that the complex thermodynamic interaction in this part can affect the size of the PMMA coil in the copolymer. The assumption of the partial overlapping of rods inside the coil is used for the explanation of the stability of this structure. However, it cannot be completely ruled out that rigid blocks are arranged according to the "head-to-head" type. The solution of this problem is beyond the experimental precision.

This model for the molecular structure of a three-block PBG–PMMA–PBG copolymer shows that the length of the overlapping of two helical PBG sequences and their mutual orientation are directly related to the length of the flexible joint linking the ends of rigid rods. A short flexible joint prevents rigid helical PBG sequences from approaching each other and serves as a break. It is this case that was considered by the authors in part 1 of this work where it was shown that when a decamethylene joint, $-(CH_2)_{10}-$, is introduced into the chain, the equilibrium rigidity in the investigated range is lower by 25–30% than that of PBG molecules.

Hence, the comparative investigation of the molecular weight, the radius of gyration, the intrinsic viscosity, and the optical anisotropy of the molecules of PBG and a three-block PBG–PMMA–PBG copolymer showed that the presence of a joint consisting of thermodynamically flexible PMMA molecules does not affect the thermodynamic rigidity of PBG in the range of M_w ($24 \times 10^3 \leq M_w \leq 128 \times 10^3$).

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Registry No. (PBG)(MMA) (block copolymer), 107241-15-6.