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(54) Title: PROCESS FOR MAKING A COUPLED BLOCK COPOLYMER COMPOSITION AND THE RESULTING COMPOSITION

(57) Abstract: This invention relates to a process far making a hydrogenated block copolymer, comprising the steps of: a) reacting a living lithium-terminated polymer having the formula P-Li, where P is a copolymer chain having at least one polymer block A composed of one or more mono alkenyl arenes having 8 to 18 carbon atoms and at least one polymer block B composed of one or more conjugated dienes having 4 to 12 carbon atoms, with an alkoxy silane coupling agent having the formula Si-$(OR)_4$, where R is selected from, linear and branched alkyl radicals, and where the molar ratio of Si to Li is between 0.4 and 0.55, thereby forming a coupled block copolymer composition; b) optionally hydrogenating the coupled block copolymer composition; and c) recovering the resulting block copolymer composition. It also relates to the resulting composition containing low levels of uncoupled polymer and having a substantial linear character.

PROCESS FOR MAKING A COUPLED BLOCK COPOLYMER COMPOSITION AND THE RESULTING COMPOSITION

BACKGROUND OF THE INVENTION

Field of the Invention

This invention relates to a process for making a coupled block copolymer composition and the resulting composition. More in particular, the invention relates to the coupling of anionic polymers and to the hydrogenation of such coupled polymers to make a polymer composition containing low levels of uncoupled polymer and having a substantial linear character.

Background of the Art

The coupling of lithium-terminated polymers is a process known in the art. In accordance with this known process, a lithium-terminated polymer is treated with a compound having two or more reactive sites capable of reacting with the carbon-lithium bonds of the lithium-terminated polymer. In many cases the multifunctional coupling agent thereby becomes a nucleus for the resulting structure. From this nucleus long chain polymeric branches radiate and such coupled polymers have specific properties that render them useful for particular applications.

Linear polymers are formed by employing coupling agents having two reactive sites. For example, one coupling agent employed in making linear polymers is methyl benzoate as disclosed in U. S. Pat. No. 3,766,301. Radial polymers are formed by employing coupling agents having more than two reactive sites. Examples of such coupling agents include among others silica compounds, including silicon tetrachloride and alkoxy silanes - U. S. Pat. Nos. 3, 244,664, 3,692,874, 4,076,915, 5,075,377, 5,272,214 and 5,681,895; polyepoxides, polyisocyanates, polyimines, polyaldehydes, polyketones, polyanhydrides, polyesters,

polyhalides - U. S. Pat. No. 3,281,383; diesters - U.S. Pat. No. 3,594,452; methoxy silanes - U.S. Pat. No. 3,880,954; divinyl benzene - U.S. 3,985,830; 1,3,5-benzenetricarboxylic acid trichloride - U.S. Pat. No. 4,104,332; glycidoxytrimethoxy silanes -U.S. Pat. No. 4,185,042; and oxydipropylbis(trimethoxy silane) - U.S. Pat. No. 4,379,891.

The production of styrenic block copolymers by coupling has a number of process advantages over sequential polymerization, such as better control over the styrene block size and lower viscosity during polymerization. However, the inevitable presence of un-coupled arms can limit product performance. Diblock contamination can greatly reduce tensile strength and related properties in a triblock copolymer or compound thereof. S-E/B-S polymers (hydrogenated poly(styrene-butadiene-styrene) block copolymers) for use in applications such as highly - oiled compounds cannot afford to sacrifice in this area. It is generally difficult to achieve coupling efficiencies of better than 90% whilst retaining the linear character of the product. While coupling efficiencies on the order of 90% can be achieved by reaction with m-divinylbenzene, the resulting products are high molecular weight "star" polymers. Although the melt viscosity of such a polymer is much lower than a linear product of the same total molecular weight, it is much higher than that of the corresponding triblock that would be prepared by coupling two of the diblock arms. Moreover, coupled copolymers are prone to decoupling during a subsequent hydrogenation step.

It would be highly desirable to identify a coupling agent that gives a substantially linear product, or, at least, a mixture of linear and radial polymers having substantial linear character. It would be particularly advantageous if coupling efficiencies approaching 95% could be obtained. More in particular, it would be advantageous if such coupling efficiencies could be obtained in systems that result in a butadiene microstructure suitable for hydrogenation to give a saturated rubber block. Such products

would be expected to have properties that are comparable to sequentially polymerized S-E/B-S polymers, which are often less economic to produce due to the viscosity increase of the polymer system towards the end of the polymerization step. It would also be highly advantageous if residual coupling agent or its by-products were found to have no adverse affect on the activity of the hydrogenation catalyst. Finally it would be highly advantageous if the coupled polymer composition does not suffer from decoupling during a subsequent hydrogenation step.

SUMMARY OF THE INVENTION

The present invention broadly encompasses a process for making a coupled block copolymer composition, comprising the steps of:

a. reacting a living lithium-terminated polymer having the formula P-Li, where P is a copolymer chain having at least one polymer block A composed of one or more mono alkenyl arenes having 8 to 18 carbon atoms and at least one polymer block B composed of one or more conjugated dienes having 4 to 12 carbon atoms, with an alkoxy silane coupling agent having the formula $Si-(OR)_4$, where R is selected from linear and branched alkyl radicals, and where the molar ratio of Si to Li is between 0.4 and 0.55, thereby forming a coupled block copolymer composition;

b. optionally hydrogenating the coupled block copolymer composition; and

c. recovering the resulting block copolymer composition.

The present invention also encompasses the resulting block copolymers made using the alkoxy silanes of the process. In particular, the present invention includes a block copolymer composition comprising:

a. a tetra-branched block copolymer (IV) represented by the general formula $(P)_4X$;

b. a tri-branched block copolymer (III) represented by the general formula $(P)_3X$;

c. a di-branched block copolymer (II) represented by the

general formula $(P)_2X$; and

d. a linear block copolymer (I) represented by the general formula P; where:

i) P represents a block copolymer having a number average molecular weight of 25,000 to 200,000 and having at least one polymer block A composed of one or more mono alkenyl arenes having 8 to 18 carbon atoms and at least one polymer block B composed of one or more conjugated dienes having 4 to 12 carbon atoms;

ii) X represents the residue of an alkoxy silane coupling agent having the formula $Si-(OR)_4$, where R is selected from linear and branched alkyl radicals; and

iii) the relative amounts of copolymers I, II, III and IV are 0 to 5 weight percent IV, 0 to 60 weight percent III, 40 to 95 weight percent II and 2 to 10 weight percent I, where the total of I, II, III and IV equals 100 weight percent. It also comprises the hydrogenated block copolymer composition.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

In one embodiment, the present invention is a process which includes a step of reacting a living lithium-terminated polymer having the formula P-Li where P is a copolymer chain of one or more conjugated dienes having 4 to 12 carbon atoms and one or more mono alkenyl arenes having 8 to 18 carbon atoms with the alkoxy silane coupling agent.

The preferred acyclic conjugated dienes that can be polymerized into the polymer chain P of the present invention are those containing 4 to 8 carbon atoms. Examples for such conjugated dienes are1,3-butadiene (termed "butadiene" in the claims and elsewhere in the specification), 2,3-dimethyl-1,3butadiene, piperylene, 3-butyl-1,3octadiene, isoprene, 2-phenyl-1,3-butadiene.

Mono alkenyl arenes that can be polymerized together with the dienes to form the polymer chain P are preferably those selected from the group of styrene, the methylstyrenes, particularly 3-methylstyrene, the propylstyrenes,

particularly 4-propylstyrene, the butyl styrenes, particularly p-t-butylstyrene, vinylnapthalene, particularly 1-vinylnapthalene, cyclohexylstyrenes, particularly 4-cyclohexylstyrene, p-tolylstyrene, and 1-vinyl-5-hexylnaphthalene.

The presently preferred monomers are isoprene, 1,3-butadiene and styrene. The presently preferred polymer chains P are those where the conjugated dienes are present in a major amount and the mono vinyl-substituted arenes are present in a minor amount. It is preferred that the mono alkenyl arene content be from about 5 to about 50 weight percent of the total block copolymer, more preferably from about 10 to about 35 weight percent.

Preferably, the polymer chain P has a structure A-B- or B-A-A- or A-B-B'- so that B or B' is attached to the coupling agent, and in which A represents a block of mono alkenyl arenes, preferably a polystyrene block, and B and B' represents a block that confers rubbery properties to the polymer chain, such as a poly conjugated diene block, a copolymer block of conjugated dienes, a copolymer block of a conjugated diene and a mono alkenyl-substituted arene (in which case the total content of mono alkenyl-substituted arene may be up to 70 weight percent), or a combination of such blocks. Such a polymer exhibits properties both of an elastomer and of a thermoplastic polymer. Therefore, such polymers can be formed into articles by standard procedures known for producing articles from thermoplastic polymers while the finished article exhibits elastomeric properties.

In an alternative embodiment, the mono alkenyl-substituted arenes are present in a major amount, thus resulting in a polymer that exhibits the properties of a toughened polystyrene.

It is generally important to control the molecular weight of the various blocks. For each A block the desired block weights are 3,000 to 60,000, preferably 5,000 to 50,000. For each B or B' block the desired block weights are

20,000 to 200,000, preferably 20,000 to 150,000. These molecular weights are most accurately determined by light scattering measurements, and are expressed as number average molecular weights.

It may also be important to control the microstructure or vinyl content of the conjugated diene in the B blocks. The term "vinyl" has been used to describe the polymer product that is made when 1,3-butadiene is polymerized via a 1,2-addition mechanism. The result is a monosubstituted olefin group pendant to the polymer backbone, a vinyl group. In the case of anionic polymerization of isoprene, insertion of the isoprene via a 3,4-addition mechanism affords a geminal dialkyl C=C moiety pendant to the polymer backbone. The effects of 3,4-addition polymerization of isoprene on the final properties of the block copolymer will be similar to those from 1,2-addition of butadiene. When referring to the use of butadiene as the conjugated diene monomer, it is preferred that 10 to 80 mol percent of the polymerized butadiene units in the polymer block have a 1,2-addition configuration. Preferably, from 30 to 80 mol percent of the polymerized butadiene units should have 1,2-addition configuration. When referring to the use of isoprene as the conjugated diene, it is preferred that 5 to 80 mol percent of the polymerized isoprene units in the block have 3,4-addition configuration. Polymer microstructure (mode of addition of the conjugated diene) is effectively controlled by addition of an ether, such as diethyl ether, a diether, such as 1,2-diethoxypropane, or an amine as a microstructure modifier to the diluent. Suitable ratios of microstructure modifier to lithium polymer chain end are disclosed and taught in US Re. 27,145.

Furthermore, specific polymers constituting preferred embodiments of this invention are those obtained by reactions and procedures disclosed in detail in the following description of a process to make these polymers.

The quantity of coupling agent employed with respect to the quantity of living polymers P-Li present depends largely upon the degree of coupling and the properties of the coupled polymers desired. Thus, the coupling agent defined above will be employed in a range of from 0.4 to 0.55 moles of coupling agent based upon the moles of lithium present in the polymer, P-Li, most preferably from 0.45 to 0.5 moles of coupling agent per mole of lithium, P-Li. At lower silicon coupling agent to lithium chain end molar ratios Si/Li (mol/mol), there is not enough coupling agent present to allow high levels of coupling; the coupling efficiency will start to decline if lower Si/Li molar ratios are employed. Lower levels of coupling will tend to lead to a block copolymer product having less strength; the unlinked arms tend to dilute out the strength forming network in the block copolymer A further problem with using lower Si/Li molar ratios is that at high conversion it will tend to advance the coupling reaction to make higher levels of 4-arm coupled product. The 4-arm coupled product is not preferred as it can contribute to excessive viscosity in the melt which makes melt processing of the product more difficult. Lower Si/Li (mol/mol) ratios are also not preferred because they can lead to weaker products that are more difficult to melt process.

On the other hand, Si/Li (mol/mol) ratios in excess of 0.55 are also not preferred. At Si/Li (mol/mol) = 0.5, there is sufficient coupling agent present to couple all of the chain ends into a linear, 2-arm product; this is the preferred result. Higher levels of Si/Li (mol/mol) only result in the addition of excess coupling agent. The addition of excess reagent contributes added cost to the process without an advantage in the quality of the coupled polymer. At ratios greater than 0.55, the excess coupling agent will tend to cap living chain ends without linking them together; this will contribute to a decline in coupling efficiency at higher Si/Li molar ratios. Lower coupling efficiency will afford block copolymer products having less strength. The use

of Si/Li (mol/mol) ratios in excess of 0.55 will unnecessarily increase the cost of the process and will afford lower quality coupled polymers.

As stated above, the coupling agent used in the present invention is an alkoxy silane of the general formula $Si(OR)_4$, where R is selected from linear and branched alkyl radicals. The alkyl radicals preferably have 1 to 12 carbon atoms, more preferably from 1 to 4 carbon atoms. Preferred tetra alkoxy silanes are tetramethoxy silane ("TMSi"), tetraethoxy silane ("TESi"), tetrabutoxy silane ("TBSi"), and tetrakis(2-ethylhexyloxy)silane ("TEHSi"). Of these the more preferred is tetraethoxy silane.

The temperature at which the coupling reaction is carried out can vary over a broad range and, for convenience, often is the same as the temperature of polymerization. Although the temperature can vary broadly from 0 to 150°C, it will preferably be within the range from 30 to 100°C, more preferably from 55 to 80°C.

The coupling reaction is normally carried out by simply mixing the coupling agent, neat or in solution, with the living polymer solution. The reaction period is usually quite short, and can be affected by the mixing rate in the reactor. The normal duration of the coupling reaction will be in the range of 1 minute to 1 hour. Longer coupling periods may be required at lower temperatures.

After the coupling reaction, the linked polymers may be recovered, or if desired they may be subjected to a selective hydrogenation of the diene portions of the polymer. Hydrogenation generally improves thermal stability, ultraviolet light stability, oxidative stability, and weatherability of the final polymer. It is important that the coupling agents not interfere with or otherwise "poison" the hydrogenation catalyst.

Hydrogenation can be carried out via any of the several hydrogenation or selective hydrogenation processes known in the prior art. For example, such hydrogenation has been

accomplished using methods such as those taught in, for example, U.S. Patents 3,494,942; 3,634,594; 3,670,054; 3,700,633; and Re. 27,145. These methods operate to hydrogenate polymers containing aromatic or ethylenic unsaturation, and are based upon operation of a suitable catalyst. Such catalyst, or catalyst precursor, preferably comprises a Group VIII metal such as nickel or cobalt which is combined with a suitable reducing agent such as an aluminum alkyl or hydride of a metal selected from Groups I-A, II-A and III-B of the Periodic Table of the Elements, particularly lithium, magnesium or aluminum. This hydrogenation can be accomplished in a suitable solvent or diluent at a temperature from 20 to 100°C, and a pressure of 2 to 50 bars. Other catalysts that are useful include titanium based catalyst systems and various heterogeneous catalysts.

Hydrogenation can be carried out under such conditions that at least about 90 percent of the conjugated diene double bonds have been reduced, and between zero and 10 percent of the arene double bonds have been reduced. Preferred ranges are at least about 95 percent of the conjugated diene double bonds have been reduced, and more preferably about 98 percent of the conjugated diene double bonds are reduced. Alternatively, it is possible to hydrogenate the polymer such that aromatic unsaturation is also reduced beyond the 10 percent level mentioned above. In that case, the double bonds of both the conjugated diene and arene may be reduced by 90 percent or more. Moreover, it is also possible to hydrogenate only a portion of the conjugated diene double bonds, corresponding (approximately) to the vinyl content of the conjugated diene polymer block.

It has been found, as shown in the comparative example (7774 H2, Table 4) in Example 1 below, that when employing tetramethoxy silane as the coupling agent without passivation by the addition of alcohol, the polymer tends to degrade on hydrogenation. The degradation appears to be by cleaving arms

off at the Si coupling center. This could be reduced or eliminated by contacting the coupled polymer with an alcohol, such as methanol, after coupling is complete and prior to hydrogenation. In that case it is preferred that the ratio of alcohol to P-Li is from 1 to 1.5 moles of alcohol per mole of P-Li (where the amount of P-Li in the calculation is based on the amount of living chain ends which were present prior to the addition of the coupling agent). However, it has been found that much less alcohol is needed when employing tetraethoxy silane or tetrabutoxy silane as the coupling agent. In that situation the ratio of alcohol to P-Li should be from 0.05 to 0.5 moles of alcohol per mole of P-Li.

After hydrogenation, the hydrogenated polymers may be cleaned up by standard techniques, such as addition of aqueous acid solutions to remove the residues of the polymerization initiator and hydrogenation catalyst. It is usually preferred to add an antioxidant to the reaction mixture before isolation of polymer.

The polymer may be separated from the reaction mixture by standard techniques, such as steam stripping or coagulation with a suitable non-solvent such as an alcohol or water. In the case of steam stripping, the polymer crumb may be separated from the volatile solvent by countercurrent flow through a cyclone. In a like manner, the coagulated polymer crumb may be separated from the liquid solvent phase by centrifugation or filtration. Alternatively, the polymer may be recovered by passing the cement through a devolatilizing extruder. Residual solvent and other volatiles can be removed from the isolated polymer by heating, optionally under reduced pressure or in a forced airflow.

As far as the synthesis of the living polymer chain P-Li is concerned, this may be obtained by reacting a mono-functional lithium initiator system with the respective monomer or monomers. This polymerization step can be carried out in one step or in a sequence of steps. In the case where the polymer chain P comprises a random or tapered copolymer

block of two or more monomers, the monomers may be simultaneously polymerized with the lithium initiator. In the case where the polymer chain P is a block copolymer comprising two or more homo- or copolymer blocks, these individual blocks can be generated by incremental or sequential monomer addition.

The monomers that are generally employed, as well as the monomers that are preferably used have been defined above in connection with the novel polymers of this invention.

The lithium-based initiator systems used to make the living polymer chain generally have the general formula R" Li wherein R" is a hydrocarbyl radical of 1 to about 20 carbon atoms. Examples of such lithium initiators are methyllithium, isopropyllithium, n-butyllithium, sec-butyllithium, t-octyllithium, n-dodecyllithium, n-eicosyllithium, phenyllithium, naphthyllithium, p-tolyllithium, 4-phenylbutyllithium, cyclohexyllithium, and 4-cyclohexyllithium. The amount of the lithium initiator employed depends upon the desired properties of the polymer, particularly the desired molecular weight. Normally, the organomonolithium initiator is employed in the range of from 0.1 to 100 gram millimoles per 100 grams of total monomers.

The polymerization reaction is preferably carried out in the presence of a hydrocarbon diluent. Preferably the hydrocarbon diluent is a paraffinic, cycloparaffinic or aromatic hydrocarbon having from 4 to10 carbon atoms or a mixture of such diluents. Examples for the diluent are n-hexane, hexanes, n-heptane, heptanes, 2,2,4-trimethylpentane, cyclohexane, cyclopentane, isopentane, benzene and toluene. The reaction is generally carried out with a weight ratio of diluent to monomers exceeding 1. Preferably the diluent is employed in a quantity of from 200 to 1000 parts by weight per 100 parts by weight of total monomers.

The polymerization reaction in step 1 usually occurs within a period of time ranging from a few minutes up to about 6 hours. Preferably, the reaction is carried out within

a time period of from 10 minutes to 2 hours. The polymerization temperature is not critical and will generally be in the range of from 30 to 100°C, preferably in the range of 55 to 85° C.

The other object of the present invention comprises coupled block copolymer compositions having substantial linear character.

The relative amounts of the tetra-branched (IV), tri-branched (II), di-branched (II) and linear diblock (I) species are: 0 to 5 weight percent tetra-branched IV, 0 to 60 weight percent tri-branched III, 40 to 95 weight percent di-branched II and 2 to 10 weight percent linear diblock I. Preferred amounts are: 0 to 5 weight percent IV, 0 to 36 weight percent III, 60 to 95 weight percent II and 4 to 8 weight percent I.

The block copolymer composition has a Coupling Efficiency ("CE") of about 90 to 98 weight percent, preferably about 92 to about 98 weight percent. Coupling Efficiency is defined as the proportion of polymer chain ends which were living, P-Li, at the time the coupling agent was added that are linked via the residue of the coupling agent at the completion of the coupling reaction. In practice, Gel Permeation Chromatography (GPC) data is used to calculate the coupling efficiency for a polymer product. The sum of the areas under the GPC curve for all of the coupled species (II+III+IV) is divided by the sum of the areas under the GPC curve for all of the coupled moieties plus the area under the curve for the starting, uncoupled polymer species (I+II+III+IV). This ratio is multiplied by 100 to convert the coupling efficiency to a percentage value.

Various materials are known to be detrimental to the lithium alkyl initiated polymerization. Particularly, the presence of carbon dioxide, oxygen, water and alcohols should be avoided during an organomonolithium-initiated polymerization reaction of step 1 of this combined process for making the coupled polymers. Therefore, it is generally

preferred that the reactants, initiators, and the equipment be free of these materials and that the reaction is carried out under an inert gas such as nitrogen.

In one embodiment of the present invention, one may polymerize first styrene, then butadiene and finally isoprene, therein producing an S-B-I- triblock arm. As shown below in Example 5, use of isoprene to cap the arm results in high coupling efficiencies and increased linearity of the polymer.

EXAMPLES

The following examples are provided to illustrate the present invention. The examples are not intended to limit the scope of the present invention and they should not be so interpreted. Amounts are in weight parts or weight percentages unless otherwise indicated.

Example 1

A diblock polymer anion, S-B-Li, was prepared as follows (Experiment 7774): 96 kg cyclohexane and 24 kg styrene were charged to a reactor, followed by 590 milliliters of a sec-butyl lithium solution (12%wt BuLi, 0.86 mol). A second reactor was charged with 264 kg cyclohexane, 25 kg diethyl ether and 20.2 kg butadiene. Following titration to remove impurities, 95 kg of polystyryllithium solution prepared in the first reactor was transferred to the second reactor. After polymerization had commenced, an additional 20.3 kg of butadiene was added, at a rate sufficient to keep the temperature around 55°C. After about 98% conversion of the butadiene, 45 grams of tetramethoxy silane ("TMSi") was added (TMSi:PLi about 0.45). The final product consisted of a mixture of 46% 2-arm (linear), 49% 3-arm polymer, traces of 4-arm polymer and 5% of diblock polymer, with an overall coupling efficiency (all coupled products/coupled products + un-coupled diblock) of 95.3% as measured by a Gel Permeation Chromatography (GPC) method. Before coupling, the styrene block had a molecular weight of 29,000 and the butadiene

block has a molecular weight of 62,000. The vinyl content in the butadiene block was 38%.

Example 2a

An aliquot of this polymer was passivated prior to hydrogenation by the addition of MeOH. An equivalent of MeOH was added for every equivalent of P-Li chain ends present prior to the coupling reaction. The MeOH passivated cement was hydrogenated using a standard Co/Al technique. The hydrogenation catalyst was prepared by adding triethylaluminum to cobalt (II) neodecanoate (Al/Co = 2.0 (mol/mol)) in a hydrocarbon solvent. The catalyst was added to the cement under hydrogen pressure at a level that affords a concentration of 6ppm of Co in the cement. Hydrogenation at 78°C for 18 hours resulted in the saturation of 98.5% of the C=C bonds in the rubber segment of the polymer (Experiment 7774H3). Importantly, after complete hydrogenation, the coupling efficiency of the polymer was unchanged; the coupling efficiency of the hydrogenated polymer was assayed at 95.7% by the GPC method. The catalyst was removed by washing with aqueous phosphoric acid and water, and the polymer is recovered via steam stripping, under conditions typical for hydrogenated polymers.

Example 2b (comparative)

In a comparative example, a sample of the same polymer (7774) was hydrogenated without methanol addition (Experiment 7774H2) using the Co/Al technique ([Co]=16ppm, 60°C, 6hr). At 99.5% hydrogenation of the C=C centers, the cement which has not been passivated with MeOH had undergone severe degradation by a chain cleavage mechanism; only 90.6% of the polymer remains coupled as assayed by GPC. Nearly 5% of the coupled polymer in the starting material had been degraded to the strength reducing uncoupled diblock arm during hydrogenation. Similar results were obtained using a hydrogenation catalyst prepared by adding triethylaluminum to nickel(II) octoate (Al/Ni = 2.16 (mol/mol)). Hydrogenation

without passivation with MeOH results in degradation of the coupled polymer.

Conclusion

The average mechanical properties of oiled compounds prepared from the polymer hydrogenated in the presence of methanol (CE = 95.7% after hydrogenation) are compared to those of the same compounds, but prepared with an S-EB-S sequentially polymerized triblock copolymer, listed as CP-1 in Table 1 below. The properties of the compounds made with the coupled product of the present invention are quite comparable to those of the compounds made with the sequential triblock. When TMSi is used as the coupling agent, passivation of the cement by the addition of an equivalent of MeOH prior to hydrogenation is an effective way to prepare highly coupled and as a result very strong block copolymers.

Table 1

Average mechanical properties of oiled compounds prepared from the polymer hydrogenated in the presence of methanol

		Tensile Strength	Elongation	100% Modulus	500% Modulus	1000% Modulus	1500% Modulus
polymer	phr oil	(PSI)	(%)	(PSI)	(PSI)	(PSI)	(PSI)
CP-1	200	954	1845	16	4	134	391
CP-1	300	469	1973	8	23	74	172
CP-1	500	237	2176	3	9	25	76
7774H3	200	812	1788	14	43	132	412
7774H3	300	424	2026	-	13	5	153
7774H3	500	190	2011	2	6	26	98

Example 3

Using the polymer synthesis procedure outlined above in Example 1, a living triblock copolymer, Bd-S-Bd-Li, was prepared (Experiment 7768), having block molecular weights of respectively 5,900-8,900-26,500 and vinyl contents of 30, respectively 38% (an aliquot of the living polymer is terminated at each step in the polymerization by the addition of MeOH and the individual aliquots are analyzed by GPC affording the step block molecular weight results). The living cement was coupled using TMSi as the coupling agent (TMSi/Living Chain End = 0.45 (mol/mol)). The efficiency of the coupling reaction was excellent, 96%. The coupled polymer consists of mostly a linear two arm (51%) and a three arm polymer (40) with 4% tetra arm material and 5% uncoupled material. The new polymer has the pentablock configuration Bd-S-Bd-S-Bd.

The tetramethoxysilane coupled, pentablock copolymer cement from Experiment 7768 was passivated by the addition of one mole of MeOH for every mole of living chain ends present in the cement prior to the coupling reaction. Hydrogenation, after passivation with MeOH, using the Ni/Al technique described before, afforded a selectively hydrogenated pentablock copolymer with essentially no loss of coupling efficiency in the saturated polymer (coupling efficiency of 95 %wt). The hydrogenation catalyst was extracted from the polymer cement by contacting the cement with aqueous acid in the presence of air. The polymer was recovered from the washed cement by a steam stripping process. A solvent cast film of the product polymer had remarkable strength.

Example 4

A diblock polymer anion, S-B-Li, is prepared as follows (run 7852D): 60 kg cyclohexane and 15 kg styrene are charged to a reactor, followed by 400 milliliters of sec-butyl lithium. A second reactor is charged with 155.4 kg cyclohexane, 15 kg diethyl ether and 23.8 kg butadiene.

Following titration to remove impurities, 56 kg of polystyryllithium solution prepared in the first reactor is transferred to the second reactor. After about 98% conversion of the butadiene, 26.3 grams of tetramethoxy silane ("TMSi") is added (TMSi:PLi about 0.45). The final product consists of 41 % 2-arm (linear) and 53% 3-arm polymer, with an overall coupling efficiency (all coupled products/coupled products + un-coupled diblock) of about 96%. The styrene block has a molecular weight of 29,300 and the butadiene block has a molecular weight of 62,000.

Samples of the polymer were hydrogenated with respectively 100% methanol/Li addition (run 7852D - H4); 50% methanol/Li addition (run 7852D - H2) and 10% methanol/Li addition (run 7852D - H1) to a residual olefin concentration of about 0.10 meq./g. in the presence of about 10 ppm Co/solution of a cobalt neodecanoate-aluminum triethyl catalyst (Al/Co = 1.6 mol/mol). After hydrogenation under these conditions, the polymer remained respectively 95.7%; 94.7% and 92% coupled. The catalyst is removed by washing with aqueous phosphoric acid, and the polymer is recovered via steam stripping, under conditions typical for hydrogenated polymers. This experiment shows the coupling efficiency after hydrogenation of polymers made with tetramethoxy silane as a function of methanol addition prior to hydrogenation.

Example 5

A diblock polymer anion, S-B-Li, was prepared as follows (run 7919D): 80 kg cyclohexane and 20 kg styrene were charged to a reactor, followed by 510 milliliters of sec-butyl lithium. A second reactor was charged with 188 kg cyclohexane, 18 kg diethyl ether, and 28.5 kg butadiene. Following titration to remove impurities, 67 kg of polystyryllithium solution prepared in the first reactor was transferred to the second reactor. After about 98% conversion of the butadiene, 43.3 grams of tetraethoxy silane ("TESi") is added (TESi:PLi about 0.45). The final product consisted

of 54.5 % 2-arm (linear) and 38.6% 3-arm polymer, with an overall coupling efficiency (all coupled products/coupled products + un-coupled diblock) of about 96%. The styrene block had a molecular weight of 28,730 and the butadiene block had a molecular weight of 62,000.

A sample of the polymer was hydrogenated with 10% methanol/Li addition (run 7919D - H1) to a residual olefin concentration of 0.21 meq/g in the presence of 5 ppm Co/solution of a cobalt neodecanoate-aluminum triethyl catalyst (Al/Co = 1.6 mol/mol). After hydrogenation under these conditions, the polymer remained 94.4% coupled. The catalyst is removed by washing with aqueous phosphoric acid, and the polymer is recovered via steam stripping, under conditions typical for hydrogenated polymers. This experiment shows the coupling efficiency after hydrogenation of polymers made with tetraethoxy silane as a function of methanol addition prior to hydrogenation, which is a more robust system than in case of tetramethoxy silane coupling.

Comparative Example 6 (Experiments 167 and 155)

When a trialkoxysilane hydride is used as a coupling agent, rather than the tetraalkoxysilanes of the present invention, the coupled polymer suffers extreme degradation during hydrogenation. A solution of a living, anionic polybutadienyl-lithium reagent was prepared by adding 24.52g of a 10%wt solution of s-BuLi (0.038 mol) to a mixture containing 200g of butadiene, 121g of diethyl ether, and 1655g of cyclohexane. Polymerization was allowed to proceed for 32 minutes at temperatures below 55°C (10 half-lives). An aliquot of the polymer was quenched and analyzed by GPC. The molecular weight of the polybutadiene is 4,802. The remainder of the living polybutadienyl-lithium cement was treated with 1.69g of trimethoxysiliconhydride, $(MeO)_3SiH$, TMSiH (0.0138 mol) (Si/Li=0.36 (mol/mol). The coupling reaction was allowed to proceed at 40°C for 30 minutes. An aliquot of the coupled cement was analyzed by GPC and found to contain only three arm branched polymer and uncoupled homopolymer. The coupling

efficiency was 84%. The cement was treated with 1.4g of MeOH (0.04 mol); this is one mole of MeOH per P-Li chain end in the living polymer prior to coupling. When tetramethoxysilane is used as a coupling agent, this is enough MeOH to passivate the polymer cement against degradation during hydrogenation of the polybutadiene. Hydrogenation, using the Ni/Al catalyst (101ppm of Ni in the cement) described in Example 2, at 700 psi of hydrogen pressure, at temperatures below 70°C for 3hr, resulted in complete saturation of the butadiene polymer (99.5% of the C=C centers is reduced). Unfortunately, degradation of the coupled polymer was extreme. The GPC analysis of the hydrogenated polymer was so complex due to the fragmentation of the polymer that quantitative analysis was not possible. It is clear that most of the coupled polymer degraded during hydrogenation. In this case, using the MeOH passivation technique that has worked to protect tetramethoxysilane coupled polymers from degradation during hydrogenation and using the same Ni/Al hydrogenation technique does not work when the polymer is coupled with TMSiH.

The procedure was repeated with the significant exception that triethoxysiliconhydride, $(EtO)_3SiH$, TESiH, was used as the coupling agent rather than TMSiH. Hydrogenation with a Ni/Al technique gave extreme degradation, which had not been observed when tetraethoxysilane, TESi, was used as the coupling agent. Addition of an equivalent of MeOH before hydrogenation did not passivate the polymer against degradation: when TESiH was used to couple a polybutadienyl-lithium reagent and an equivalent of MeOH was added before hydrogenation extreme degradation of the coupled polymer during hydrogenation was still observed.

Albeit that the above experiments have been carried out with a polybutadienyl-lithium living polymer, rather than a living block copolymer, similar degradation may be expected when a living block copolymer is used.

Comparative Example 7

A living, anionic, polystyrene-polybutadienyl-lithium reagent is coupled with methyldichlorosiliconhydride, MeCl2SiH, and MDSiH. Hydrogenation of the coupled polymer cement using the Ni/Al technique described before results in degradation of the coupled polymer ranging from 10 to 90%. From severe to extreme degradation during hydrogenation is observed when MDSiH is used as the coupling agent. This coupling agent is not part of the present invention.

Example 8

The addition of a small amount of isoprene at the end of the diene polymerization allows the production of a highly coupled, primarily linear polymer comprised essentially of butadiene and styrene, as demonstrated by the following example.

A 2-gallon stainless steel reactor was charged with 3.2 kg of cyclohexane, 240 g of diethyl ether, and 107 g, of styrene. The reactor temperature was increased to about 50°C. Impurities were removed by adding small aliquots of s-butyllithium until the first evidence of color. 25.3 milliliters of a solution of an approximately 6%wt solution of s-butyllithium in cyclohexane was added, and the styrene was allowed to complete polymerization at 50°C - 60°C. The molecular weight of the polystyrene produced in this reaction was determined to be 6,300 by GPC. The temperature was adjusted to 50°C and 710 g of butadiene were added at such a rate as to allow the temperature to remain about 50°C. When the butadiene polymerization was complete, 10 g of isoprene was added. A sample collected at this point had a styrene content of 13.8%wt and a vinyl content of 39% basis ^{1}H NMR and an overall molecular weight of 50,800 as determined by GPC. After the isoprene had reacted for about 10 minutes, 1.88 g of TESi were added, and the coupling reaction was allowed to proceed for 60 minutes at 50°C. Methanol (0.6 g as a 10%wt solution in CH, one mole per mole of Li) was added to terminate any uncoupled chains the following morning. The

final product had a coupling efficiency of 90%, and 87% of the coupled species were linear, the remaining being 3-arm radial.

The polymer prepared above was hydrogenated using a standard Ni/Al technique. The hydrogenation catalyst was prepared by adding triethylaluminum to nickel(II) octoate in a 2.16 to 1 molar ratio (Al/Ni = 2.16 (mol/mol)) in a hydrocarbon solvent. The catalyst was added to the cement under hydrogen pressure (700 - 800 PSI) in three 20 milliliter aliquots, affording a final concentration of about 75ppm of Ni in the cement. The initial aliquot was charged at a temperature of about 50°C and the temperature was allowed to increase to about 60°C. The second aliquot was added after about 2 hours. About 5 hours later, the temperature was increased to 80°C and the third aliquot was added. The hydrogenation reaction was allowed to proceed overnight, resulting in the saturation of about 99% of the C=C bonds in the rubber segment of the polymer. The catalyst was removed by washing with aqueous phosphoric acid and water, antioxidant (Ethanox 330, 0.1 PHR) was added, and the polymer was recovered via steam stripping, under conditions typical for hydrogenated polymers. The final product maintained a coupling efficiency of 90% with 87% of the coupled product being linear.

Example 9

Using the polymerization method described for the preparation of 7774 in Example 1, a series of S-Bd-Li polymers were coupled using tetraethoxysilane, TESi, as the coupling agent. The TESi/P-Li ratio (mol/mol) was varied over a narrow range to assess the optimum ratio of Si/Li (mol/mol) for good coupling efficiency in combination with high levels of linearity (minimal levels of branched polymer ("Coupled Polymer 3-arm (III) (%)") in the product) in the coupled polymer product. From the data in Table 2, it is clear that coupling efficiency is high at Si/Li molar ratios between 0.54 and 0.36. Over this range, the proportion of 2-arm

polymer (II) in the coupled product ("Coupled Polymer 2-arm (II) (%)") increased with increasing molar ratios of Si/Li. The highest levels of linear coupled polymer were realized at TESi/P-Li (mol/mol) > 0.5; at these ratios, over 80% of the coupled polymer was linear. At TESi/Li (mol/mol) > 0.4, over 40% of the coupled polymer was the linear triblock copolymer, (II). A well coupled linear block copolymer was prepared over a range of Si/Li molar ratios.

Each of these products was passivated by treatment with 0.1 moles of MeOH per mole of P-Li moieties which were present prior to the addition of the coupling agent, TESi (The alcohol was actually added to the reactor after the coupling reaction was complete). Hydrogenation of each of these block copolymer products using the Co/Al technique described above for polymer 7919D-H1 gave fully hydrogenated rubber segments (over 98% of the C=C centers were saturated), S-E/B-S polymers, with no significant loss in coupled polymer content.

Table 2. Affect of TESi/P-Li Ratio on CE and Linearity for Coupled S-Bd-Li.

Exp. No.	TESi/P-Li (mol/mol)	CE (%)	(II) (%)	(III) (%)
1	0.58	89.2	85.8	13.6
2	0.54	92.8	81.7	16.7
3	0.54	94.6	79.8	17.9
4	0.54	90.7	81.6	16.5
5	0.52	94.4	80.8	18.4
6	0.52	93.5	80.9	17.5
7	0.50	95.6	75.0	24.0
8	0.50	95.6	73.7	25.2
9	0.49	96.3	74.4	24.3
10	0.48	97.1	71.0	28.1
11	0.47	96.4	68.1	30.6
12	0.46	97.0	63.6	36.4
13	0.45	97.2	66.3	33.7
14	0.44	96.5	61.0	37.8
15	0.44	96.6	59.5	39.3
16	0.44	97.0	60.0	38.8
17	0.43	96.4	65.4	32.9
18	0.43	96.8	53.3	46.7
19	0.43	96.7	52.5	46.6
20	0.42	96.3	42.6	56.1
21	0.42	96.4	46.3	52.6
22	0.41	96.7	54.2	44.1
23	0.41	96.1	45.7	54.3
24	0.4	97.0	50.9	48.3
25	0.4	96.5	41.1	57.6
26	0.39	96.6	32.4	66.3
27	0.39	96.6	31.1	67.6
28	0.39	97.3	38.4	61.6
29	0.39	97.4	33.8	66.2
30	0.36	93.2	5.0	90.8
31	0.33	87.6	8.9	87.0

CE = Coupling Efficiency; (II) = coupled product 2-arm; (III) = coupled product 3-arm

C L A I M S

1. A process for making a hydrogenated block copolymer, comprising the steps of:

a. reacting a living lithium-terminated polymer having the formula P-Li, where P is a copolymer chain having at least one polymer block A composed of one or more mono alkenyl arenes having 8 to 18 carbon atoms and at least one polymer block B composed of one or more conjugated dienes having 4 to 12 carbon atoms, with an alkoxy silane coupling agent having the formula $Si-(OR)_4$, where R is selected from linear and branched alkyl radicals, and where the molar ratio of Si to Li is between 0.4 and 0.55, thereby forming a coupled block copolymer composition;

b. optionally hydrogenating the coupled block copolymer composition; and

c. recovering the resulting block copolymer composition.

2. The process according to claim 1 wherein said alkoxy silane coupling agent is a tetra alkoxy silane and R is a linear or branched alkyl hydrocarbon radical having 1 to 12 carbon atoms.

3. The process according to any one of claims 1 or 2 wherein the coupled polymer is contacted with an alcohol prior to hydrogenation.

4. The process according to claim 3 wherein said alkoxy silane coupling agent is tetramethoxy silane and wherein the coupled polymer is contacted with methanol in a molar ratio of from 1 to 1.5 moles of methanol per mole of Li.

5. The process according to claim 3 wherein said alkoxy silane coupling agent is tetraethoxy silane and wherein the coupled polymer is contacted with methanol in a molar ratio of from 0.05 to 0.5 moles of methanol per mole of Li.

6. A block copolymer composition comprising:

a. a tetra-branched block copolymer (IV) represented by the general formula $(P)_4X$;

b. a tri-branched block copolymer (III) represented by the general formula $(P)_3X$;

c. a di-branched block copolymer (II) represented by the general formula $(P)_2X$; and

d. a linear block copolymer (I) represented by the general formula P; where:

i) P represents a block copolymer having a number average molecular weight of 25,000 to 200,000 and having at least one polymer block A composed of one or more mono alkenyl arenes having 8 to 18 carbon atoms and at least one polymer block B composed of one or more conjugated dienes having 4 to 12 carbon atoms;

ii) X represents the residue of an alkoxy silane coupling agent having the formula $Si-(OR)_4$, where R is selected from linear and branched alkyl radicals; and

iii) the relative amounts of copolymers I, II, III and IV are 0 to 5 weight percent IV, 0 to 60 weight percent III, 40 to 95 weight percent II and 2 to 10 weight percent I, where the total of I, II, III and IV equals 100 weight percent. It also comprises the hydrogenated block copolymer composition.

7. The block copolymer composition of claim 6 wherein said one or more conjugated dienes is or are selected from butadiene and isoprene and said mono alkenyl arene is styrene.

8. The block copolymer composition of claim 7 wherein said block copolymer is selectively hydrogenated such that greater than 95% of the olefinic unsaturation in the B blocks have been reduced.