Supporting Information

A ketene-based route to rigid cyclobutanediol monomers for the replacement of BPA in high performance polyesters

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General Methods:

Compounds **1** and **4** were prepared as previously reported.[1] Meldrum's acid, 2,2,5-trimethyl-1,3-dioxane-4,6-dione, formaldehyde (37% in water), butadiene, isoprene, cyclopentadiene, lithium aluminum hydride, benzyl bromide, *o*-dichloroxylene, tetraethylene glycol monomethyl ether, and terephthaloyl chloride were purchased from Aldrich and used as received. Acetonitrile, ethyl acetate, pyridine, acetic acid, and potassium carbonation (anhydrous) were purchased from Fischer and used as received. Anhydrous *o*-dichlorobenzene was purchased from Aldrich, and distilled over calcium hydride before use. Tetrahydrofuran and *N,N*-dimethylformamide were purchased from Fischer and dried before use. ^{1}H NMR (500MHz) and ^{13}C NMR (125 MHz) were performed on a Bruker AVANCE500 spectrometer at room temperature. Proton chemical shifts are reported in ppm downfield from tetramethylsilane (TMS). The following splitting patterns are designated as s, singlet; d, doublet; t, triplet; q, quartet; b, broad; m, multiplet; and dd, doublet of doublets. Carbon chemical shifts are reported downfield from TMS using the resonance of the deuterated solvent as the internal standard. Size exclusion chromatography was carried out at room temperature on a Waters chromatograph connected to a Waters 410 differential refractometer and six Waters Styragel columns (five HR-5 μmand one HWM-20 μm) using chloroform as eluent (flowrate: 1 mL/min). A Waters 410 differential refractometer and a 996 photodiode array detector were employed. The molecular weights of the polymers were calculated relative to linear polystyrene standards. Fourier transformed infrared spectroscopy was performed using a PerkinElmer Spectrum One spectrometer equipped with a Universal ATR accessory. Spectra are the sum of 16 scans acquired at a resolution of 4 cm^{-1}. Electrospray ionization time-of-flight (ESI-TOF) data were obtained on a Micromass QTOF2 quadrupole/time-of-flight tandem mass spectrometer. Differential scanning calorimetry data were acquired on a TA Instruments Q2000 modulated DSC at a heating rate of 10 °C. Data presented are from the second heating after a single cycle from 0 to 250 °C.

General Procedure for Diels-Alder Synthesis of Spirocyclic MA Derivatives

3 was prepared according to the general procedure: A solution of **1** (2.15g, 9.1mmol) in acetonitrile (50mL) in a 100-mL round bottom flask was cooled in an ice bath and acetic acid (0.5mL) was added with stirring. Isoprene (5.00g, 73mmol) was added and the flask was sealed with a septum. The flask was removed from the ice bath and allowed to warm to room temperature. The bright yellow color of **1** fades as the reaction proceeds, and after 4-6 hours only a very faint pale yellow color remains. Excess isoprene was removed by rotary evaporation. The solution was added to a separatory funnel containing 100mL ethyl acetate, which was washed with 150mL 1M HCl, 150mL saturated sodium bicarbonate, and 150mL brine. After drying over sodium sulfate, the solution was concentrated to provide **3** (1.88g, 91%) as a white solid of sufficient purity (>95% by GC) to be used without further purification. ^{1}H-NMR (500 MHz, $CDCl_3$) δ 5.58 (m,0.07 H), 5.41 (m, 0.93H), 2.63 (m, 1.86H), 2.51 (m, 0.14H), 2.15-2.20 (m, 4H), 1.74-1.52 (m, 9H). ^{13}C NMR (126 MHz, $CDCl_3$), δ 169.8, 133.1, 116.0, 104.7, 47.0, 31.5, 31.0, 29.5, 28.5, 26.4, 23.4. [M+Na]: 247.23 Found: 247.23.

2 was synthesized by the general procedure with the only modification being that the reaction was initially cooled in dry ice/acetone in order to condense the butadiene. The reaction mixture was added to ethyl acetate and washed with 1M HCl, then saturated potassium carbonate, then brine. Concentrating the organic layer provided **2** in 87% yield. ^{1}H-NMR (500 MHz, $CDCl_3$) δ 5.59 (dt, J=11Hz, J=5.5 Hz, 1H), 5.62 (dt, J=11Hz, J=5.5, 1H), 2.63 (d, J=5.5 Hz, 2H) 2.15-2.20 (m, 4H), 1.75 (s, 6H). ^{13}C NMR (126 MHz, $CDCl_3$), δ 169.8, 128.1, 127.0, 104.7, 47.0, 31.5, 29.5, 26.4, 23.4. [M+Na]: 233.08; Found: 233.08

11 was synthesized by the general procedure and isolated as a mixture of isomers in 76% yield by column chromatography (5:1 Hexanes:Ethyl Acetate). ^{1}H NMR (600 MHz, $CDCl_3$) δ 5.43 – 5.35 (s, 1H), 5.11 (s, 1H), 2.68 – 2.57 (m, 2H), 2.23 – 2.13 (m, 4H), 2.11 (m, 2H), 2.07 – 2.00 (m, 2H), 1.74 (d, *J* = 18.9 Hz, 6H), 1.65 (d, *J* = 49.0 Hz, 6H). ^{13}C NMR (151 MHz, $CDCl_3$) δ 171.52, 169.70, 168.39, 166.15, 137.77, 136.99, 136.62, 135.08, 122.94, 122.47, 122.10, 120.85, 104.99, 104.77, 104.65, 77.20, 76.99, 76.77, 53.46, 52.77, 41.68, 41.25, 40.84, 36.67, 31.23, 30.49, 29.76, 29.17, 29.15, 29.09, 28.49, 25.92, 25.81, 21.02, 20.91, 18.77, 18.46, 18.06, 18.02. [M+Na]: 315.1562; Found 315.1570

12 was synthesized by the general procedure and isolated as a mixture of isomers in 61% yield by column chromatography (5:1 Hexanes:Ethyl Acetate). Proton coupling and the mixture of isomers complicated the NMR spectrum, but the identity of the compound was confirmed by high-res mass spectrometry. [M+Na]: 315.1562; Found 315.1572. Hydrogenation of this product also provided the fully saturated derivative, again the identity was confirmed by high-res mass spectrometry: [M+Na]: 319.1885; Found 319.1885

General Procedure for Hydrogenation of Spirocyclic MA Derivatives

6 was prepared according to the general procedure: **3** (1.5g, 6.69mmol) was dissolved in tetrahydrofuran (50mL) in a 100mL round bottom flask. 10% w/w palladium on carbon (200mg) was added and the flask was sealed with a septum, evacuated and backfilled with a hydrogen gas-filled balloon 3 times. After stirring overnight, the reaction was filtered through celite which was washed with ethyl acetate. The solution was concentrated and passed through a short plug of silica (80:20 vol/vol dichloromethane:ethyl acetate) to provide **6** (1.45g, 96%) as a white solid. ^{1}H-NMR (500 MHz, $CDCl_3$) δ 2.06-2.09 (m, 4H), 1.71 (s, 6H), 1,39-1,60 (m, 4H), 0.97 (dd, 3H).^{13}C NMR (125 MHz, $CDCl_3$), δ 169.8, 104.7, 47.0, 31.5, 31.0, 29.5, 29.1, 28.5, 27.2, 26.4, 23.4. [M+Na]: 249.26 Found: 249.26.

5 was synthesized according to the general procedure and isolated in 94% yield. ^{1}H-NMR (500 MHz, $CDCl_3$) δ 2.02-2.05 (m, 4H), 1.70 (s, 6H), 1.35-1.58 (m, 6H). ^{13}C NMR (125 MHz, $CDCl_3$), δ 169.8, 104.7, 47.0, 31.5, 31.0, 29.5, 29.1, 28.5, 27.2, 23.4. [M+Na]: 235.23; Found: 235.23

7 was synthesized according to the general procedure and isolated in 95% yield. ^{1}H-NMR (500 MHz, $CDCl_3$) δ 2.77 (m, 1H), 2.45 (m, 1H), 2.37 (ddd, J = 3, 4.5, and 12.5, 1H), 2.36 (dq, J = 2 and 10.5, 1H), 2.0 (dd, J = 2.5 and 12, 1H), 1.82 (s, 3H), 1.71 (s, 3H),

1.65-1.45 (m, 4H), 1.38 (dq, J = 1.5 and 10, 1H). ^{13}C-NMR (125 MHz, $CDCl_3$) δ 169.21, 168.50, 104.83, 56.51, 50.25, 39.05, 38.56, 36.69, 29.95, 28.78, 27.44, 25.93; IR (neat, ATR) 2966 (w), 1770 (m), 1734 (vs), 1292 (m), 1278 (m), 1050 (w), 904 (s) cm-1; TOF-MS (ESI) calcd for C12H16O4 [M+Na]: 270.09; Found: 270.10

General Procedure for Alkylation of MA and Methyl-MA

14 was prepared according to the general procedure: To a solution of Meldrum's acid (2.35g, 16.3mmol) in DMF (100mL), potassium carbonate (3.00g, 21.7mmol) and benzyl bromide (6mL, 50mmol) were added with stirring, and the solution was heated to 60C overnight. The reaction was cooled to room temperature and then added into a separatory funnel containing 200mL chloroform and washed with brine (2 x 200mL). The organic layer was collected and dried over sodium sulfate, and then concentrated. The crude product **14** could be recovered by recrystallization from chloroform/hexanes as colorless, thick needles (2.7g, 51%). Concentration of the mother liquor and column chromatography with chloroform:ethyl acetate provided an additional 1.5g, 28% of the product. ^{1}H NMR (600 MHz, CDCl3) δ7.35 – 7.23 (m, 10H), 3.50 (s, 4H), 0.68 (s, 6H).. ^{13}C NMR (151 MHz, $CDCl_3$) δ 168.17 (s), 134.87 (s), 130.15 (s), 128.80 (s), 127.77 (s), 105.86 (s), 77.22 (s), 77.01 (s), 76.80 (s), 60.09 (s), 44.94 (s), 28.58 (s). [M+Na]: 347.13; Found 347.13

13 was synthesized according to the general procedure and isolated by column chromatography using a gradient of hexanes to 3:7 ethyl acetate:hexanes as the eluent in 72% yield. ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.22 (d, *J*=8.4 Hz, 2H), 7.13 (d, *J*=8.4 Hz, 2H), 4.67 (s, 2H), 3.32 (s, 2H), 1.75 (s, 3H), 1.60 (s, 3H), 0.92 (s, 3H), 0.91 (s, 9H), 0.057 (s, 6H); ^{13}C NMR (150 MHz, $CDCl_3$) δ 170.1, 141.34, 134.1, 130.2, 126.6, 105.5, 64.8, 52.5, 44.8, 29.6, 28.6, 26.1, 26.1, 18.6, -5.0; HR-MS (TOF-ESI) calcd for $C_{21}H_{32}O_5SiNa$ [M+Na]: 415.1917, Found: [M+Na]: 415.1921.

15 was synthesized according to the general procedure and isolated in 65% yield by recrystallization from Hexanes. ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.32 – 7.19 (m, 5H), 3.32 (s, 2H), 1.75 (s, 3H), 1.59 (s, 3H), 0.89 (s, 3H). ^{13}C NMR (151 MHz, $CDCl_3$) δ 169.76 (s), 135.32 (s), 130.05 (s), 128.71 (s), 127.72 (s), 105.21 (s), 52.20 (s), 44.86 (s), 29.36 (s), 28.26 (s), 25.83 (s). [M+Na]: 271.09; Found 271.09

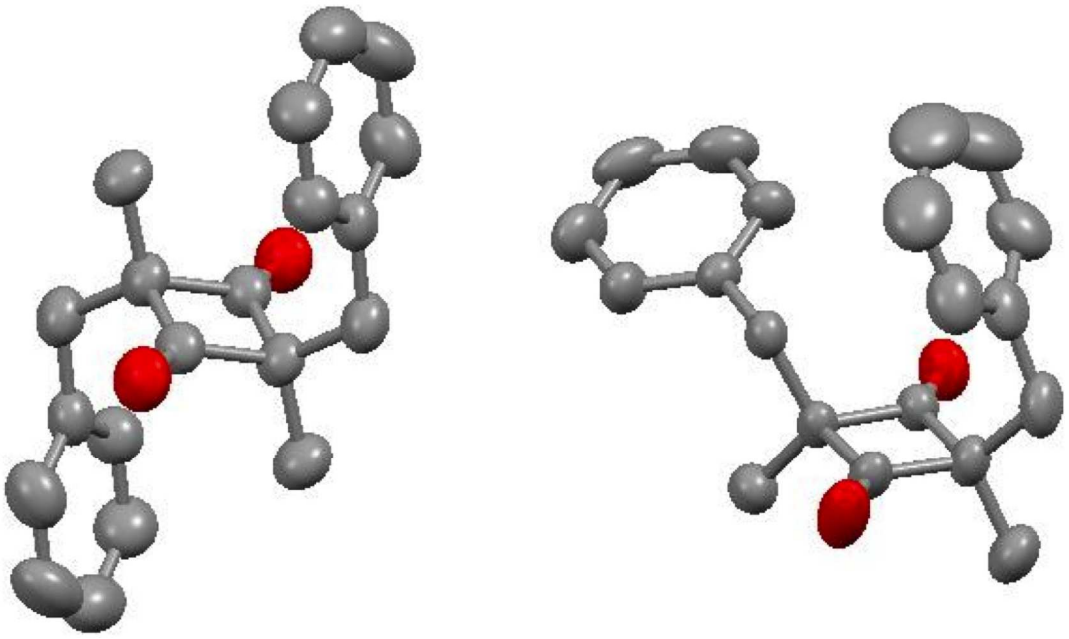
16 was synthesized according to the general procedure and was isolated in 56% yield by column chromatography (95:5 dichloromethane:methanol). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.24 (d, J = 8.0 Hz, 2H), 7.14 (d, J = 8.0 Hz, 2H), 4.50 (s, 2H), 3.72 – 3.60 (m, 12H), 3.54 (ddd, J = 20.4, 10.4, 7.3 Hz, 4H), 3.36 (s, 3H), 3.31 (s, 2H), 1.74 (s, 3H), 1.59 (s, 3H), 0.93 (d, J = 5.7 Hz, 3H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 169.77, 137.85, 134.49, 129.99, 127.89, 105.07, 72.57, 71.83, 70.62, 69.26, 60.24, 58.91, 52.05, 44.50, 29.29, 28.27, 25.69, 14.08. [M+Na] = 491.23; Found: 491.24

General Procedure for Cyclobutanedione Synthesis via Ketene Dimerization

17 was provided according to this general procedure: **14** (530mg, 1.63mmol) was loaded into a reaction ampoule as a neat solid. The ampoule neck was heated with a butane torch and bent to an angle while preserving the opening to allow venting. A silicone oil bath was heated to 220 °C, and the ampoule was submerged in the bath, quickly melting **14**

and evolving gas within minutes. Heating was continued until the visible evolution of gas ceased, and then continued for 2 more minutes. Typical total time is 10-15 minutes of heating, and reaction completion can be confirmed by GC. The ampoule is removed from the oil bath and cooled to room temperature, and the crude productpurified by recrystallization from chloroform with a small amount of hexanes to give **17** as a white solid (320mg, 88%). ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.27 – 7.05 (m, 20H), 3.39 (s, 8H). ^{13}C NMR (151 MHz, $CDCl_3$) δ 212.15 (s), 135.87 (s), 130.31 (s), 128.42 (s), 127.16 (s), 82.19 (s), 35.39 (s). [M+Na]: 467.20; Found 467.20

19 was prepared according to the general procedure and isolated by column chromatography with 20% ethyl acetate in dichloromethane as the solvent. The mixture of isomers was obtained as a colorless waxy solid, isolated in 95% yield. From this mixture, the individual isomers could be isolated by repeated chromatography and recrystallization. *cis*-**19**: ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.30 – 7.23 (m, 4), 7.23 – 7.16 (m, 2), 7.13 – 7.04 (m, 4), 2.34 (s, 4), 1.27 (s, 6). ^{13}C NMR (151 MHz, $CDCl_3$) δ 214.31, 135.73, 130.16, 128.40, 127.12, 76.28, 36.09, 18.60. *trans*-**19**: ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.29 – 7.20 (m, 6H), 7.14 – 7.08 (m, 4H), 2.85 (s, 4H), 0.46 (s, 6H). ^{13}C NMR (151 MHz, $CDCl_3$) δ 214.09, 136.27, 130.02, 128.56, 127.22, 78.19, 40.24, 14.40. [M+Na]: 315.14; Found 315.14

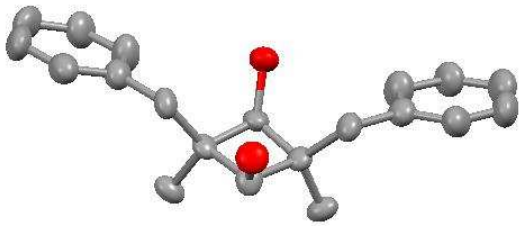


SI Figure 1

Crystallographic information files (CIF) for compounds **19** are available for download on the World Wide Web at http://pubs.acs.org.

General Procedure for Reduction of Cyclobutanediones to Diol Monomers

20 was synthesized according to the general procedure: In a 250mL, 2-neck round bottom flask fitted with a reflux condenser, **19** (2.5g, 10mmol) was dissolved in anhydrous THF (100mL). Lithium aluminum hydride (1.55g, 40mmol) was added in one portion with stirring and the reaction mixture was refluxed overnight. The flask was allowed to cool to room temperature, and then cooled in an ice bath before the excess lithium aluminum hydride was quenched by addition of water (1.5mL), 10% aqueous NaOH (3mL), and finally a second portion of water (4.5mL). After quenching, the reaction mixture was filtered through celite, concentrated, dissolved in chloroform, and washed with brine. **20** was isolated by column chromatograpy with chloroform as the eluent and the mixture of cis and trans diols obtained as a white solid. For characterization purposes, **20*** was isolated by recrystallization from the earliest column fractions. ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.41 – 7.33 (m, 4H), 7.30 – 7.26 (m, 4H), 7.23 – 7.15 (m, 2H), 3.62 (d, *J* = 5.5 Hz, 2H), 3.04 (d, *J* = 1.1 Hz, 4H), 1.95 – 1.81 (m, 2H), 1.11 (d, *J* = 1.2 Hz, 6H). ^{13}C NMR (151 MHz, $CDCl_3$) δ 139.33, 130.77, 127.97, 125.71, 81.09, 44.55, 34.80, 26.50. [M+Na]: 319.17; Found 319.17



Crystallographic information files (CIF) for compounds **20** are available for download on the World Wide Web at http://pubs.acs.org.

8 was synthesized according to the general procedure and isolated in 79% yield. ^{1}H NMR (500 MHz, DMSO) δ 4.46 – 4.33 (m, 2H), 3.33 (s, 2H), 3.30 (d, J = 5.3 Hz, 1.25 H), 1.62 – 1.45 (m, 8H), 1.43 – 1.16 (m, 12H). ^{13}C NMR (125 MHz, DMSO) δ 78.67, 78.34, 45.23, 44.21, 32.94, 26.42, 24.01, 23.24, 22.97. [M+Na]: 247.17; Found: 247.17.

9 was synthesized according to the general procedure and isolated in 83% yield. ^{1}H-NMR (500 MHz, $CDCl_3$) δ 3.75 (d, J=12 Hz, 0.41H), 3.55 (d, J=5.5 Hz, 0.66H), 3.42 (d, J=6 Hz, 0.35H), 3.33 (d, J=6Hz, 0.30H), 3.15 (d, J=6.5Hz, 0.24H), 1.80-1.92 (m, 2H), 0.9-1.8 (m, 16H), 0.88 (m, 6H). ^{13}C NMR (125 MHz, $CDCl_3$), δ 80.4, 79.4, 44.0, 38.8, 32.7, 32.0, 31.9, 31.5, 30.2, 25.1, 22.4, 22.3). [M+Na]: 275.20 Found: 275.20.

10 was synthesized according to the general procedure and isolated in 72% yield. ^{1}H NMR (500 MHz, $CDCl_3$) δ 3.21-3.79 (m, 2H), 2.74 (m, 1H), 2.42 (m, 1H), 2.35 (m, 4H), 1.92 (m, 4H), 1.45-1.65 (m, 4H), 1.38 (m, 2H). ^{13}C NMR (125 MHz, $CDCl_3$) δ), δ 80.7, 81.2, 44.0, 38.8, 31.1, 29.6, 28.8, 27.3, 25.8 22.2. [M+Na]: 261.17; Found: 261.17

18 was synthesized according to the general procedure and isolated as a mixture of *syn* and *anti* diols which could be identified in a 3:2 ratio, respectively, in the ^{1}H NMR. *syn*-**18**: ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.52 – 6.69 (m, 20H), 4.74 (d, *J* = 5.3 Hz, 2H), 3.04 (d, *J* = 15.2 Hz, 4H), 2.88 (d, *J* = 15.1 Hz, 4H), 1.49 (d, *J* = 5.3 Hz, 2H). *anti*-**18** ^{1}H NMR (600 MHz, $cdcl_3$) δ 7.52 – 6.69 (m, 20H), 4.09 (d, *J* = 6.4 Hz, 2H), 3.16 (s, 4H), 2.55 (s, 4H), 1.75 (d, *J* = 6.4 Hz, 2H). *syn*/*anti* mixture: ^{13}C NMR (151 MHz, $CDCl_3$) δ 138.69, 138.36, 138.23, 130.95, 130.09, 129.98, 128.34, 128.07, 128.02, 126.22, 126.11, 125.83, 76.74, 74.19, 49.42, 47.92, 42.39, 37.17, 33.53. [M+Na]: 471.23; Found 471.23

Crystallographic information files (CIF) for compounds **19** and **20*** are available on the World Wide Web at http://pubs.acs.org.

References

1. Leibfarth, F. A.; Kang, M.; Ham, M.; Kim, J.; Campos, L. M.; Gupta, N.; Moon, B.; Hawker, C. J. *Nat. Chem.* **2010**, *2*, 207-212.