Comparison of Rheological Characteristics and Mechanical Properties of Fossil-Based and Bio-Based Polycarbonate

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Abstract: Fossil-based PC, bisphenol-A polycarbonate (BPA-PC), is polymerized using bisphenol-A, which is derived from fossil-fuel based chemicals. Bio-based polycarbonate (bio-based PC) is polymerized using isosorbide, which is taken from plants. Accordingly, bio-based PC does not contain toxic polymerization chemicals. The rheological characteristics of fossil-based PC and bio-based PC samples, including viscosity, storage and loss moduli, and melt tension, were studied and compared. The mechanical properties of tensile behavior and impact strength were also measured and discussed. The shear viscosity curves and storage and loss moduli patterns of the bio-based PC were found to be somewhat different from those of fossil-



based PC. The bio-based PC had higher tensile strength and elastic modulus than the fossil-based PC. The fossil-based PC exhibited a stress jump in the high strain region of the stress-strain curve, while the bio-based PC exhibited no stress jumps. The bio-based PC had a lower impact strength than the fossil-based PC. The cross-section of the fractured impact specimen of the bio-based PC showed only mirror regions, while that of the fossil-based PC showed both mirror regions and misted regions.

Keywords: bio-based polycarbonate, fossil-based polycarbonate, rheological property, melt tension, mechanical property.

1. Introduction

Polymers are generally classified as fossil-based polymers or bio-based polymers, depending on the type of material used in polymerization. Fossil-based polymers, which account for most of the polymers in use today, are polymerized using a monomer obtained from fossil-fuel based chemicals.¹⁻³ Bio-based polymers are polymerized using monomers obtained from plant sources.⁴⁻⁶ Some fossil-based polymers are polymerized using toxic chemicals. However, the monomers used in the polymerization of bio-based polymers are safe, since they come from natural plant sources. As a result, from a chemical safety viewpoint, bio-based polymers are considered superior to fossil-based polymers. Bio-based polymers have other social advantages, because they can reduce environmental waste and oil consumption.⁷⁻¹⁰

Polycarbonate (PC) is one of the most widely used engineering plastics, and is utilized for automobile parts, electrical products, and a wide range of consumer products.¹¹⁻¹⁵ Fossil-based PC is polymerized using bisphenol-A and phosgene, and is also known as BPA-PC. Fossil-based PC was first commercially developed by Bayer in 1958.² Sabic is the now the single biggest supplier of fossil-based PC, and many other companies including Dow, Mitsubishi Chemical, LG Chemical, Samyang, Lotte Chemical, *etc.*, also supply fossil-based PC.^{16,17} Bio-based PC was commer-

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cialized by Mitsubishi Chemical in 2012.⁸ Bio-based PC is polymerized using biomass instead of the fossil-fuel based chemical, bisphenol-A. The biomass used in the polymerization of bio-based PC is an isosorbide that comes from corn.⁴⁻⁶ This bio-based PC is also called isosorbide-PC or bio-PC. Bio-based PC does not use toxic chemicals.

The respective chemical structures of fossil-based PC and bio-based PC are shown in Figure 1. It is meaningful to study the physical properties of fossil-based PC and bio-based PC. Our group has previously studied a wide range of physical properties of fossil-based PC and bio-based PC and bio-based PC and bio-based PC. I⁸ The optical properties of bio-based PC, such as transmittance, haze and birefringence were found to be superior to that of the fossil-based PC, while its thermal resistance was inferior to that of the fossil-based PC. I⁸ In particular, the bio-based PC was found to be highly suitable for lens applications since the bio-based material has excellent low birefringence after molding.

The differences between the physical properties of fossil-based PC and bio-based PC are produced by their chemical structures. The mechanical properties and rheological characteristics of the polymers are very important for both determining suitable applications and for fabricating the product. Large numbers of papers have been published reporting on he rheological properties of fossil-based polymers including linear and branched PC.¹⁹⁻²⁷ The melt elasticity of PC has also been discussed,^{28,29} as well as the tensile properties and impact properties of fossil-based PC.³⁰⁻³⁶ However, to date there have only been a limited number of studies investigating these properties in bio-based PC.

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(b) Bio-based PC (Isosorbide PC)

Figure 1. Chemical structure of fossil-based PC and bio-based PC used in this study.

In this study, the rheological characteristics of fossil-based PC and bio-based PC, including viscosity, storage and loss moduli, and melt tension, were measured and compared. Mechanical properties such as tensile behavior and impact strength were also measured and discussed. This extensive investigation of rheological and mechanical characteristics may be very important for determining and developing applications and the setup molding conditions of bio-based PC.

2. Experimental

2.1. Material

The materials used in this study were fossil-based PC and biobased PC, to compare their rheological and mechanical properties. TRIREX 3022IR and TRIREX 3027IR were used for the fossil-based PC1 and fossil-based PC2, respectively, and were supplied by Samyang Co. The fossil-based PCs were polymerized by the interfacial polymerization process using bisphenol A and phosgene.^{4,12} Durabio D7340IR was used for bio-based PC, as supplied by Mitsubishi Chemical Co. The bio-based PC was polymerized using isosorbide, which comes from corn.⁸ Figure 1 shows the chemical structures of the fossil-based PCs and bio-based PC used in this study.

2.2. Measurement of molecular information

The molecular weights and molecular weight distributions of the fossil-based PCs and bio-based PC were measured by gel permeation chromatograph (GPC), EcoSEC HLC-8320 (Tosoh). Chloroform (CHCl₃) was used as the solvent in the GPC measurement, and the temperature was maintained at 40 °C during measurement. The flow speed was set to 1.0 mL/min. The number average molecular weight (M_n) and weight average molecular weight (M_w), molecular weight distribution (MWD), and molar mass at maximum peak (M_p) were measured for the fossil-based PCs and the bio-based PC.

2.3. Measurement of rheological properties

The rheological properties of the molten fossil-based PCs and bio-based PC were measured to examine their flow characteristics. Complex viscosity, storage modulus, and loss modulus were measured by RDS (ARES-G2, TA Instruments) with a frequency sweep of 10% of strain. The rheological properties were measured for various temperatures.

Melt tension was measured in a capillary rheometer (Rheograph 6000, Göttfert) as shown in Figure 2. The solid polymer was melted in the reservoir and it flowed through the die due to the movement of the piston. The die could be changed to adjust the length to diameter ratio of the die (L/D). The melt from the die exit passed through a gap between two rollers. The two rollers were turned in opposite directions and the melt tension was calculated by measuring the torque of the rollers. The variables in the measurement of melt tension were piston speed, die temperature, roller speed, and the ratio of die length to die diameter (L/D).

2.4. Measurement of mechanical properties

Tensile specimens were fabricated according to regulation ASTM D638 by injection molding with various molding temperatures. The molding temperatures of the tensile specimens were 260, 280, and 300 °C for the fossil-based PCs and 240, 260, 280, and 300 °C for the bio-based PC. Tensile testing was conducted using an Instron (EZ20, LLOYD Instruments) with 5 mm/min of tensile speed. Generally, for viscoelastic materials, the tensile properties are dependent on the extension rate. Accordingly, the tensile tests were also performed at various tensile speeds, of 1, 5, 10, and 20 mm/min. These tensile tests can provide some informa-



Figure 2. Schematic drawing of melt tension measurement.

tion about the rate dependent properties, viscoelasticity, of the solid material. $^{\rm 28,29}$

Impact testing was conducted with an Izod impact tester (KR/SIP-250, Sunwoo Industrial Machinery). The Izod impact specimens were fabricated according to regulation ASTM D256 by injection molding at various molding temperatures. Two different thicknesses were used in the impact tests and their results compared. Fractured sections were observed after the impact test using an optical microscope (SV-35, Sometech). The fractured section can provide information about the impact resistance of the material, which is related to impact strength.

3. Results and discussion

3.1. Molecular information of the material

Table 1 summarizes the GPC results for the fossil-based PCs and bio-based PC. The number average molecular weight (M_n) of the fossil-based PC1, fossil-based PC2, and bio-based PC were 18,300, 21,200, and 11,100 respectively. The weight average molecular weight (M_w) for the fossil-based PC1, fossil-based PC2, and bio-based PC were 46,500, 63,800, and 18,200 respectively. And their molecular weight distributions (MWD) were 2.54, 3.00, and 1.65 respectively. The fossil-based PC2 sample had a higher molecular weight and wider molecular weight distribution than the fossil-based PC1. The bio-based PC had a lower molecular weight and narrower molecular weight distribution compared with the fossil-based PCs.

3.2. Complex viscosity, storage modulus, and loss modulus

The complex shear viscosity curves for the fossil-based PCs and bio-based PC are shown in Figure 3. The viscosity curve patterns of the fossil-based PCs and bio-based PC were different. The fossil-based PCs showed constant viscosity, or so called Newtonian viscosity, at a low frequency range, which is a very common phenomenon in the shear viscosity of polymers. However, the bio-based PC did not show a Newtonian viscosity region. The details are followed. The fossil-based PC1 had low viscosity and a wide Newtonian viscosity region compared with fossil-based PC2. The fossil-based PC1 had a lower molecular weight than the fossil-based PC2. It is well known that a low molecular weight polymer also exhibits low viscosity.¹⁹⁻²² The fossil-based PCs exhibited a shear thinning phenomena after showing Newtonian viscosity, while the bio-based PC did not show a Newtonian viscosity region, and the viscosity decreased as frequency increased.

The patterns of decreasing viscosity with temperature were similar for the fossil-based PCs. However, the pattern of decreasing viscosity with temperature in the bio-based PC was differ-



Figure 3. Complex viscosity (η^*) curve of the fossil-based PCs and biobased PC.

ent from that of the fossil-based PCs. The viscosities of the biobased PC at low temperatures, 260 and 280 $^{\circ}$ C, decreased as the frequency increased in the low frequency range. Then in

Table 1. Results of GPC measurement for fossil-based PCs and bio-based PC

Material	M_w^a	M_n^{b}	MWD ^c	M_p^{d}
Fossil-based PC 1 (TRIREX 3022 IR)	46,500	18,300	2.54	44,600
Fossil-based PC 2 (TRIREX 3027 IR)	63,800	21,200	3.00	60,900
Bio-based PC (DURABIO D7340 IR)	18,200	11,100	1.65	25,300

 ${}^{a}M_{n}$: Number average molar mass. ${}^{b}M_{w}$: Weight average molar mass. ${}^{c}MWD(M_{w}/M_{n})$: Dispersivity. ${}^{d}M_{p}$: Molar mass at maximum peak.

the high frequency range the viscosities did not decrease very much and exhibited an almost flat viscosity. However, at high temperature, 300 °C, the pattern of decreasing viscosity with temperature of the bio-based PC showed the shear thinning phenomena at all tested frequencies.

The storage moduli for the fossil-based PCs and bio-based PC are shown in Figure 4. The storage moduli of the fossil-based PCs increased as frequency increased. The dependency of the storage modulus on the temperature was quite similar for both, and the curves were shifted to a lower value as the temperature increased for the fossil-based PCs. The storage modulus of the bio-based PC also increased as the frequency increased. However, the increment was much smaller than those of the fossilbased PCs. The storage modulus of the bio-based PC was not very dependent on frequency. The patterns of the storage modulus curves with temperature at 280 and 300 °C were similar to each other. However, at a temperature of 260 °C the storage modulus was different from those of other temperatures; it was very close to the storage modulus at 280 °C in the low frequency range and it increased drastically after 40 rad/s. The storage mod-







Figure 5. Loss modulus (*G''*) curve of the fossil-based PCs and biobased PC.

ulus of the bio-based PC was about ten times higher than those of the fossil-based PCs in the low frequency range. However, the storage modulus of the bio-based PC was about a hundred times lower than those of the fossil-based PCs in the high frequency range, near 500 rad/s. The dependency of the storage modulus of the bio-based PC on frequency was much smaller than that of the fossil-based PCs.

The loss moduli of the fossil-based PCs and bio-based PC are shown in Figure 5. The loss moduli of the fossil-based PCs increased as frequency increased. The patterns of the loss modulus of the fossil-based PCs according to temperature were very similar to each other. The increment in the loss moduli of the fossil-based PCs in the high frequency region decreased compared with results in the low frequency range. The loss modulus for the bio-based PC increased as the frequency increased, and the increment at higher frequencies was larger than at the lower frequency range. The difference in loss modulus for the bio-based PC according to temperature increased steadily as frequency increased, while for the fossil-based PCs it grew smaller as the frequency increased. The loss modulus of the fossil-based PCs was about ten times higher than that of the bio-based PC. These patterns of storage modulus and loss modulus of the fossil-based PCs were very similar to those of other polymers.^{37,38} However, those of the bio-based PC were unusual.

3.3. Melt tension

Melt tension is the tensile force needed to elongate a melt strand at a designated speed. The melt tension of a material is considered important for polymer processing that involves uniaxial and biaxial stretching processes, since the melt needs to main-

Table 2. Melt tension experiment and measured results for fossil-based
PC1 (TRIREX 3022IR)

Experiment number	Exp. ①	Exp. (2)
Piston speed (mm/s)	0.5	0.5
Die temperature (°C)	280	300
Roller speed (mm/s)	1800	1800
L/D of die	30/2	30/2
Measured melt tension (N)	0.032	0.032

tain its shape during the shaping process. The typical uniaxial stretching process is fiber spinning. Film blowing and extrusion blow molding are typical biaxial stretching processes.

In this study, the melt tensions of the fossil-based PCs and bio-based PC were measured and discussed. The variables for the melt tension measurement were the L/D of the die, die temperature, piston speed, and roller speed. Table 2, Table 3, Table 4, and Table 5 list the melt tension experiments of the for fossil-based PCs and bio-based PC. The experimental melt tension results are summarized in Figures 6, 7, and 8.

Figure 6 shows the melt tension of the fossil-based PCs and the bio-based PC according to die temperature. The fossil-based PC2, which had a higher molecular weight, showed a higher melt tension than the fossil-based PC1. The melt tension of the fossil-based PC2 decreased as temperature increased whereas the melt tension of the fossil-based PC1 showed a steady value over all temperatures. The melt tensions of the fossil-based PCs for temperature were distributed between 0.066 N and 0.02 N. The melt tension of the bio-based PC was 0.038 N and 0.017 N at temperatures of 240 and 280 °C, respectively.

Although the molecular weight of the bio-based PC was much

Table 3. Melt tension experiment and measured results for fossil-based PC2 (TRIREX 3027IR) for 30/2 of L/D

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L/D of die					30/2 (15)				
Piston speed (mm/s)					0.5				
Die temperature (°C)		280			300			320	
Experiment number	Exp. (1)	Exp. (2)	Exp. ③	Exp. (4)	Exp. (5)	Exp. (6)	Exp. (7)	Exp. (8)	Exp. (9)
Roller speed (mm/s)	600	1200	1800	600	1200	1800	600	1200	1800
Measured melt tension (N)	0.054	0.059	0.066	0.031	0.037	0.042	0.023	0.024	0.025

Table 4. Melt tension experiment and	measured results for fossil-based PC2	(TRIREX 3027IR)	for 10/0.5 of L/D
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L/D of die	10/0.5 (20)								
Piston speed (mm/s)					0.5				
Die temperature (°C)		280			300			320	
Experiment number	Exp. 10	Exp. (1)	Exp. (12)	Exp. (13)	Exp. (14)	Exp. (15)	Exp. (16)	Exp. (17)	Exp. (18)
Roller speed (mm/s)	600	1200	1800	600	1200	1800	600	1200	1800
Measured melt tension (N)	0.013	0.02	0.025	0.021	0.023	0.024	I	Not availabl	е

 Table 5. Melt tension experiment and measured results for bio-based PC (DURABIO D7340IR)

Experiment number	Exp. (1)	Exp. (2)	Exp. ③	Exp. (4)	Exp. (5)	Exp. (6)	Exp. (7)
Piston speed (mm/s)	0.5	1	0.5	0.5	0.5	0.5	0.1
Die temperature (°C)	240	240	240	240	240	280	240
Roller speed (mm/s)	600	-	1900	600	1900	1900	600
L/D of die	10/0.5	10/0.5	10/0.5	30/2.0	30/2.0	30/2.0	30/2.0
Measured melt tension (N)	0.024	Not available	0.030	0.032	0.038	0.016	0.033



Figure 6. Melt tension of the fossil-based PCs and bio-based PC based on die temperature.



Figure 7. Melt tension of the fossil-based PC2 based on roller speed and die temperature.



Figure 8. Melt tension of the bio-based PC based on roller speed and the L/D of the die.

lower than those of the fossil-based PCs, its melt tension did not decrease much or was similar to those of the fossil-based PCs. Figure 7 shows the melt tension of the fossil-based PC2 based on roller speed, L/D, and die temperature. The melt tension increased as roller speed increased regardless of die temperature. A higher L/D (10/0.5) resulted in a higher melt tension than a lower L/D (30/2). The melt flow in the die should be stable at a higher L/D, and this enhanced the melt tension.^{39,40} The lower die temperature resulted in a higher melt tension, and the change

in melt tension was large at lower temperatures.

Figure 8 shows the melt tension of the bio-based PC based on roller speed and L/D at the die temperature of 240 °C. A higher melt tension was observed at higher roller speed. Melt tension at a smaller L/D (30/2) was higher, and this was the opposite result of the fossil-based PC2. At a smaller die diameter, the shear rate is higher for the same flow rate (the same piston speed in this experiment). When the melt flows inside the die viscous heating occurs. Subsequently melt temperature increases. Melt tension decreases as the melt temperature increases are the top based PC had a low thermal resistance than the fossil-based PC.¹⁸ For these reasons, the bio-based PC showed a lower melt tension in a smaller die diameter. For temperature sensitive material, a large diameter of die can affect melt tension since a thick strand is extruded with a large die diameter. Subsequently, high melt tension was observed with the large die diameter.

3.4. Tensile property

The stress-strain curves for the fossil-based PCs and bio-based PC are shown in Figure 9. For the fossil-based PCs, stress increased as strain increased and then showed peak values, about 60.3 MPa and 61.3 MPa for the fossil-based PC1 and the fossil-based PC2, respectively. After showing peak value, the stress drastically dropped and then remained at a flat value. The sizes of the stress drops after maximum stress were about 12 MPa and 10 MPa for the fossil-based PC1 and fossil-based PC2, respectively. The lower molecular weight fossil-based PC1 $(M_w: 46,500)$ demonstrated a larger stress drop than the higher molecular weight fossil-based PC2 (M_w : 63,800). The flat stress value remained until the strain reached about 0.7. Then the stress shifted to a higher value, and finally the specimen was fractured. The polymer molecules aligned after showing maximum stress, as the strain increased. This alignment of polymer molecules proceeded until the strain reached about 0.7. Following the completion of the alignment of polymer molecules the stress increased as the strain increased $\overline{^{i_1 \cdot 44}}$ and then finally the specimen was fractured. The level of increase in stress after the flat value was higher in the higher molecular weight material. This implies that the molecular orientation effect was higher in the higher molecular weight fossil-based PC. All of the fossil-based PCs tested in this study showed these phenomena regardless of the molding temperature of the specimen.

For the bio-based PC the stress increased drastically in the low strain region and showed maximum value as the strain increased, as shown in Figure 9(c). The stress dropped after showing maximum value and then showed a steady value as the strain increased. The stress drop was about 18 MPa, and this was much higher than those of the fossil-based PCs. Stress slightly decreased and then jumped to a little higher value when the strain passed 0.7. After that the specimen was finally fractured. The size of the jump in stress was much smaller than those of the fossil-based PCs. The molecular weight of the bio-PC was much lower than those of the fossil-based PCs, and this led to the smaller jump in stress.

The tensile strength and elastic modulus of the fossil-based PCs and bio-based PC were compared based on the molding tem-





Figure 9. Stress-strain curve for the fossil-based PCs and bio-based PC.

perature of the specimen, and the results are shown in Figure 10. The tensile strength and elastic modulus of the fossil-based PC1 showed a steady value regardless the molding temperature of the specimen. However, for the fossil-based PC2 specimen, these properties decreased as the molding temperature of the specimen increased. The tensile strength of the fossil-based PC1 was slightly lower than that of the fossil-based PC2. However, the elastic moduli of the fossil-based PC1 specimens molded at 280 and 300 °C were higher by 17% and 25% than those of fossil-based PC2. The molding temperatures of those materials were different because of different their flow properties.

The tensile strengths of the bio-based PC were higher than



(c) Bio-based PC (DURABIO D7340IR)

Figure 10. Tensile strength and elastic modulus of the fossil-based PCs and bio-based PC.

those of the fossil-based PCs by about 17%, except for the specimen with a molding temperature of 300 °C. The tensile strength of the bio-based PC for the 300 °C molding temperature specimen was slightly higher than those of the fossil-based PCs, and the standard deviation was very large. The bio-based PC used in this study had an aliphatic chemical structure.⁴⁵ Generally, an aliphatic chemical structure has lower thermal resistance than an aromatic chemical structure.^{18,45} Thus, at high molding temperature, the tensile strength of the bio-based PC specimen fluctuated and was lower, compared with the specimen at low molding temperature.

Figure 11 compares fracture stress and elongation at break





Figure 11. Fracture stress and elongation at break of the fossil-based PCs and bio-based PC.

for the fossil-based PCs and bio-based PC. The fracture stress and elongation at break increased as the molding temperature of the fossil-based PCs specimens increased except for the fossil-based PC1 at a molding temperature of 300 °C. This result was due to the lower thermal resistance of the lower molecular weight PC. Fossil-based PC1 had a lower molecular weight than that of fossil-based PC2. These results suggested that the optimum process temperature for fossil-based PC1 and fossil-based PC2 were 280 and 300 °C, respectively. The fracture stress and elongation at break for the fossil-based PC1 were distributed between 52.50 and 58.18 MPa and from 72.24% to 90.63%, respectively. The fracture stress and elongation at break for the fossil-based PC2 was distributed between 60.25 and 62.25 MPa, and from 80.53% to 100.22%, respectively.

The fracture stress and elongation at break for the bio-based PC decreased as the molding temperature of the specimen increased from 240 to 300 °C, as shown in Figure 11(c). The elongation at break for a molding temperature of 300 °C was 16.48%, and this was the lowest value of elongation at break for the bio-based PC. The bio-based polymer had lower thermal stability and at a high specimen molding temperature this resulted in a lower fracture stress and elongation at break, compared with the fossil-based PC. The fracture stress and elongation at break for the bio-based PC was distributed between 50.99 and 56.86 MPa, and from 16.48% to 93.84%, respectively. These results suggest that the optimum process temperature for the bio-based PC was between 240 and 260 °C.

Most polymers show viscoelastic behaviors in the solid state as well as in the molten state. One of the viscoelastic properties of molten polymer is modulus, a value which is divided into storage and loss moduli, as discussed in the section on rheological properties. The tensile behaviors of the solid state fossilbased PC2 and bio-based PC based on tensile speed were examined. The stress-strain curves according to tensile speed are shown in Figure 12. The tensile specimens were fabricated at optimum molding temperatures, which were 300 and 260 °C for the fossil-based PC2 and bio-based PC, respectively. The tensile speeds were 1, 5, 10, and 20 mm/min.

The bio-based PC showed higher tensile strength than the fossil-based PCs for all tested tensile speeds. Tensile strength increased as tensile speed increased and the patterns of the stress-strain curves were similar for tensile speed. Figure 13 compares the tensile strengths of the fossil-based PC2 and bio-based PC for tensile speed. The tensile strengths of the fossil-based PC2 and bio-based PC increased by about 3% and 7%, respectively when the tensile speed increased from 1 to 20 mm/min.

In the solid state, the tensile strength of the bio-based PC was a little more sensitive to tensile speed than the fossil-based PC2. In the solid state, the bio-based PC might have higher viscoelastic properties than the fossil-based PC2. Having a higher storage modulus of melt is considered having a higher viscoelastic property. From this point of view, the fossil-based PCs had higher viscoelastic properties in the melt state, as discussed in the results for rheological properties. The viscoelasticity of the fossil-based PC2 and the bio-based PC in the solid state and the melt state was different and opposite.

Figure 14 shows the elastic modulus of the fossil-based PC2 and bio-based PC according to tensile speed. The bio-based PC showed higher elastic modulus than the fossil-based PC for all tested tensile speeds. The differences in elastic modulus for tensile speed were not significant.

3.5. Impact property

The impact strengths of the fossil-based PCs and bio-based PC are compared in Figure 15. The fossil-based PCs had much higher



Figure 12. Stress-strain curves of the fossil-based PC2 and bio-based PC according to tensile speed.

impact strength than the bio-based PC for the specimen with 3.2 mm thickness. The higher molecular weight fossil-based PC2 had a higher impact strength than that of the lower molecular weight fossil-based PC1. The impact strengths of the fossil-based PCs for the specimen with 3.2 mm thickness were distributed between 91.92 and 107.03 kg_fcm/cm whereas those of the bio-based PC were distributed between around 15.53 and 16.40 kg_fcm/cm. The molding temperature of the specimen did not affect the impact strength except for the fossil-based PC1, the low molecular weight fossil-based PC. For the fossil-based PC1, the impact strength decreased as the molding temperature of the specimen ture of the specimen increased.

The results of impact strength for thick specimens (6.4 mm) were different than those of thin specimens (3.2 mm). The impact strengths of 6.4 mm thick fossil-based PCs were much lower than those of 3.2 mm thickness. The impact strengths of the 6.4 mm thickness fossil-based PCs were distributed between 13.41 and 18.13 kg_rcm/cm. Those were about $15\%\sim20\%$ of the impact strengths of the 3.2 mm thickness bio-based PC were distributed between strengths of the 6.4 mm thickness bio-based PC were distributed between 7.62 and 8.65 kg_rcm/cm, which were about 50% of those of the 3.2 mm thick specimens. The geometry dependence of the impact strength of the bio-based PC was more sta-



Figure 13. Tensile strength for the fossil-based PC2 and bio-based PC according to tensile speed.



Figure 14. Elastic modulus for the fossil-based PC2 and bio-based PC according to tensile speed.

ble than for the fossil-based PCs.

Photos of the cross-section of the impact specimens are shown in Figure 16. The fractured cross-section of the 3.2 mm thick fossil-based PC1 showed a misted surface over the entire region. This implied it contained high impact energy. The fractured cross-section of the 6.4 mm thick fossil-based PC1 showed both a misted region and a mirrored region. Generally, a mirrored region is observed in the fractured cross-section of brittle materials.^{34-36,46}

The impact strength of the 6.4 mm thick of fossil-based PC1 was less than that of the 3.2 mm thick specimen, since it contained a mirrored region, which indicates brittle fracture. The fractured cross-sections of both the 3.2 and 6.4 mm thick biobased PC specimen showed a mirrored surface over the entire region. This implies brittle fracture, which causes the impact strength to be low.



Figure 15. Impact strength of the fossil-based PCs and bio-based PC.

4. Conclusions

Bio-based polymers were developed to meet demands for safe materials. Bio-based PC is polymerized using isosorbide, which is derived from corn. In this study fossil-based PCs (Bisphenol-A PC) and bio-based PC were investigated. First of all, the molecular information of the fossil-based PCs and bio-based PC was analyzed. The rheological characteristics, tensile behaviors, and impact properties of the fossil-based PCs and bio-based PC were then studied and compared.

The rheological characteristics of shear viscosity, storage modulus, loss modulus, and melt tension were examined. The shear viscosity of the fossil-based PCs was found to be higher than in the bio-based PC. The pattern of shear viscosity curve for the bio-based PC was unlike those of the fossil-based PCs. No Newtonian viscosity was observed in the bio-based PC, and at low temperature the viscosity of the bio-based PC became steady in the medium shear rate region. The patterns of storage modulus curves for the bio-based PC were different from those of the fossil-based PCs and other polymers, and the values were much smaller than those of the fossil-based PCs. The melt tension of the fossil-based PCs and bio-based PC were diverse, depending on temperature, die geometry, and flow rate. Generally, the bio-based PC showed a little lower melt tension than those of the fossil-based PCs.

For the study of mechanical properties, tensile behaviors such as tensile strength, elastic modulus, fracture stress, and elongation at break were analyzed. Impact strength was also examined. The bio-based PC had higher tensile strength, while the fossil-



Figure 16. Fractured surface after impact test.

based PCs had higher impact strength. In the stress-strain curves, the fossil-based PCs showed stress jumps in the high strain region, due to molecular orientation. In contrast, there were no stress jumps in the stress-strain curves of the bio-based PC. The fracture surface of the bio-based PC showed mirror regions over the entire cross-section. However, the fossil-based PC showed both misted regions and mirrored regions.

The rheological properties of the fossil-based PCs were more shear rate sensitive than the bio-based PC. However, the sensitivity of tensile strength to tensile rate was higher in the fossilbased PC than the bio-based PC.

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