Modification and Characterization of Poly(ethylene-*co*-vinyl alcohol) by Glycosidation Reaction

Binyuan Liu,[1] Zhixin Xue,[2] Lu Liu,[1] Li Zhang,[1] Fang Liu[1]

[1]*Institute of Polymer Science and Engineering, School of Chemical Engineering, Hebei University of Technology, Tianjin 300130, China*
[2]*School of Chemical Engineering, Qingdao University, Qingdao 266071, China*

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ABSTRACT: Poly(ethylene-*co*-vinyl alcohol) was modified by the covalent bonding of a glucose ester via acetal formation of a surface hydroxyl group using acid as the catalyst. Grafted copolymers were characterized by ^{1}H-NMR, Fourier transform IR spectroscopy, differential scanning calorimetry, and thermogravimetric analysis. © 2006 Wiley Periodicals, Inc. J Appl Polym Sci 102: 227–232, 2006

Key words: polyolefins; poly(ethylene-*co*-vinyl alcohol); glycosidation reaction; graft copolymers; functionalization of polymers

INTRODUCTION

Synthetic polymers having pendant sugar residues as side chains, which are referred to as "glycopolymers," are of great interest, not only for simplified models of biopolymers bearing oligosaccharides but also for artificial glycoconjugates in biochemistry and medicine,[1,2] which have a variety of potential applications,[3–8] such as macromolecular drugs,[3] drug delivery systems,[4] cell culture substrates,[5,6] and the stationary phase in separation.[7,8] In general, the creation of synthetic glycopolymers can be classified into two main methods[1,2]: the polymerization of sugar-bearing monomers and the postmodification of synthetic polymers with saccharide-containing reagents.

Although the polymer reaction method frequently results in glycopolymers having less regular structures because of incomplete reactions due to steric hindrance, the latter method is more simple and convenient than the former polymerization method, because the synthesis of sugar-bearing monomers often requires tedious multistep reactions. Several studies described the incorporation of a sugar group onto the polymer backbone by a polymer analogous reaction.[6,9–12] For example, Bahulekar et al.[6] utilized this strategy to graft glucose and galactose onto polyacrylamides. Takaksu et al.[9] reported that *N*-acetyl glucosamine and chitobiose substituted poly(vinyl alcohol). Galgali and coworkers succcessfully incorporated glucose, sucrose, and lactose onto poly(styrene-maleic anhydride) copolymers using a polymer analogous reaction.[10] Alvarez et al. reported that sucrose was also grafted onto butadiene acrylic acid copolymers and poly(butadiene carboxylate) by the postmodification method.[11] These works showed dramatic improvement in the rates of biodegradation of these polymers and/or cell compatibility.[9–12]

Ethylene vinyl alcohol copolymer (EVOH32) consists of segments of a hydrophobic ethylene and a hydrophilic vinyl alcohol with reactive hydroxyl groups, which have excellent mechanical properties, barrier properties to gases and hydrocarbons, biocompatibility, and refractoriness in the body environment. These qualities favor their applications as food packing and use in clinical applications as a hollow fiber dialyzer for hemodialysis.[13] Many works on the modification of EVOH32 by the introduction of different amounts of functional groups, such as carboxyl groups, sulfonic groups, heparin, lysine, and ε-caprolactone, were reported to enhance its biocompatibility and/or biodegradability.[14–21] Although there were a few studies on blends of EVOH32 with polysaccharide,[22] no report was made on the modification of EVOH32 by incorporating sugar moieties onto the polymer backbone.

In the present study, the chemical modification of the hydroxyl groups of EVOH32 was carried out by the covalent bonding of a glucose ester via a glycosidation reaction. Grafted copolymers were characterized by ^{1}H-NMR, Fourier transform IR (FTIR), differential scanning calorimetry (DSC), and thermogravimetric analysis (TGA). The effects of the molar ratios of the OH/aldehyde group of the glucose ester on the degree of grafting were also investigated.

Correspondence to: B. Liu (byliu@jsmail.hebut.edu.cn).
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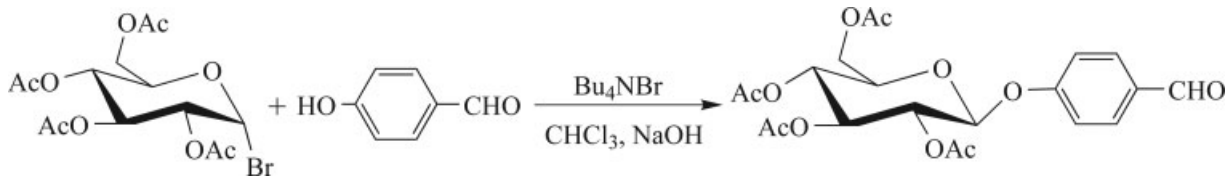


Scheme 1 The synthesis of 2,3,4,6-*tetra*-*O*-acetyl-1-*O*-benzaldehyde-*β*-glucopyranose.

EXPERIMENTAL

Materials

The EVOH32 used in this study is a commercial product from Kuraray, consisting of 32 mol % ethylene. *N*,*N*-Dimethylformamide (DMF) was dried over calcium hydride and distilled under reduce pressure. Chloroform, alcohol, ether, deionized water, magnesium sulfate anhydride, concentrated sulfuric acid, sodium hydroxide, and tetrabutylammonium bromide (Bu_4NBr) were purchased and used without further purification. *P*-Hydroxybenzaldehyde was recrystallized from deionized water. 2,3,4,6-*tetra*-*O*-Acetyl-*α*-D-glucopyranose bromide was prepared according to the literature.[23]

Synthesis of 2,3,4,6-*tetra*-*o*-acetyl-1-*o*-benzaldehyde-*α*-glucopyranose (compound I)

The synthesis of compound **I** was carried out according to the method reported in the literature[24,25] with slight modification. In the typical process, Bu_4NBr (0.65 g, 2.10 mmol), deionized water (10 mL), and $CHCl_3$ (10 mL) were added to a 150-mL three-necked flask with stirring at 50.0°C. Then, the flask was bubbled with nitrogen for 10 min. The solution of *P*-hydroxybenzaldehyde (0.77 g, 6.30 mmol) and NaOH (2.80 g, 6.90 mmol) in 10.0 mL of deionized water and a solution of 2,3,4,6-*tetra*-*O*-acetyl-*α*-D-glucopyranose bromide (2.50 g, 6.10 mmol) in 10 mL of $CHCl_3$ were slowly added dropwise during a 1.5-h period. The reaction mixture was stirred for 6 h under N_2 at 50.0°C. After cooling to room temperature, the solution was extracted 3 times with 30 mL of $CHCl_3$. The $CHCl_3$ layer was washed with deionized water followed by brine. Then, the $CHCl_3$ layer was separated, dried with magnesium sulfate anhydride, and filtrated. The solvent was removed by distillation. The residue was recrystallized in alcohol, giving 1.93 g of a white solid, and dried *in vacuo* at 50°C for 24 h (mp lit.[25] 144.0–145.0°C).

ANAL. Calcd for $C_{21}H_{24}O_{10}$: C, 55.75%; H, 5.35%. Found: C, 55.72%; H, 5.36%. IR (KBr, cm^{-1}): 3076 ($\nu_{Ar—H}$, w), 2952 ($\nu_{as,C—H}$, w), 2844 ($\nu_{s,C—H}$, w), 1746 ($\nu_{C=O}$, ester), 1696 ($\nu_{C=O}$, aldehyde), 1602 ($\nu_{C=C}$, Ar), 1505 ($\nu_{C=C}$, Ar), 1499 and 1378 ($\delta_{C—H}$), 1231 (Ar—O, C—O), 1047 ($\nu_{C—O—C}$), 911 ($\delta_{C1—H}$, *β*-glucopyranose). ^{1}H-NMR (300 MHz, $CDCl_3$, *δ*): 2.50 (CH_3CO), 3.40–5.40 (glucopyranose ring), 7.10 and 7.80 (Ar═H), 9.93 (CHO).

Synthesis of *tetra*-*o*-acetyl-D-glucose substituted EVOH32

In a typical experimental process, 0.25 g of EVOH32 ([OH] = 4.4 mmol) was dissolved in 20 mL of DMF at 65.0°C and cooled to room temperature, and several drops of concentrated sulfuric acid were added under nitrogen with stirring until a homogenous solution was attained. Then, a solution of compound **I** in 5 mL of DMF was added to the solution by syringe and the reaction mixture was stirred for 20 h under N_2 at room

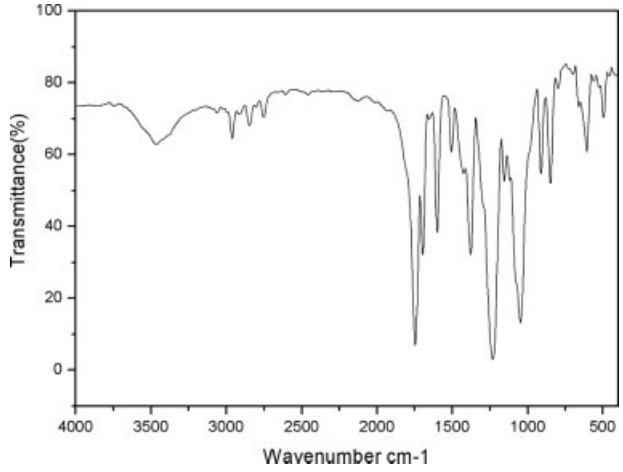


Figure 1 The FTIR spectrum of compound **I** (KBr).

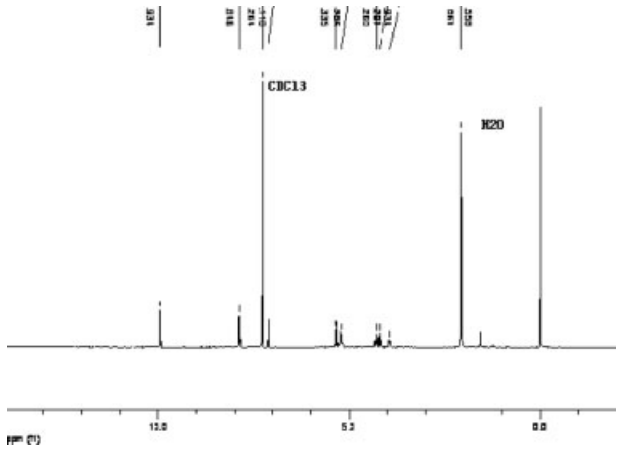
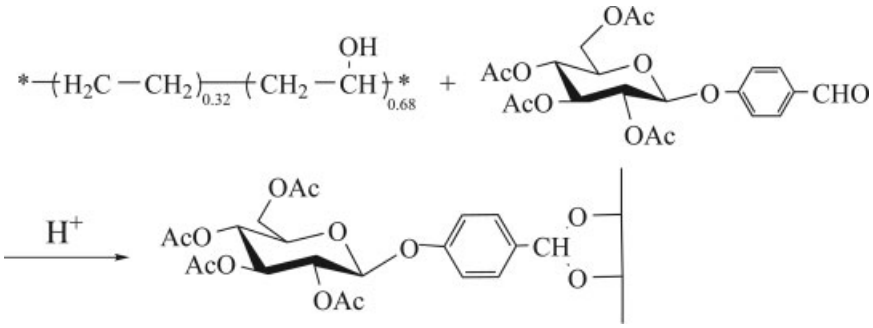


Figure 2 The ^{1}H-NMR spectrum of compound **I** ($CDCl_3$).



Scheme 2 The reaction of EVOH32 with sugar aldehyde via acetal formation.

temperature. After the reaction was completed, ether was added and the polymer was precipitated. The precipitate was washed with alcohol followed by deionized water. The procedure was repeated 3 times. The polymer was dipped in alcohol overnight, filtrated, and dried *in vacuo* at 50.0°C for 24 h. The dried polymer was stored in a desiccator.

Measures and characterizations

The FTIR transmission spectra were obtained on a Vector 22 spectrometer using KBr pellets for compound **I** from 400 to 4000 cm^{-1} at a resolution of 4 cm^{-1} (16 scans collected). Unless otherwise noted, samples were measured as films cast from the solution of DMF, which was dried for 20 h at 50°C under a vacuum. ^{1}H-NMR analyses were performed on a Varian Mercury 300 spectrometer (300 MHz) for compound **I** and EVOH32. Grafted polymers were examined on an Inova 500 spectrometer (500 MHz). Chemical shifts are reported in parts per million using tetramethylsilane as internal reference for the ^{1}H-NMR spectra. Elemental analyses were performed on a Varioel spectrometer.

DSC thermograms were recorded on PerkinElmer Diamond DSC. The samples (6.0 ± 1.0 mg) were heated from 50 to 250°C at a rate of 10°C min^{-1} in the first scan and then rapidly quenched to 50 °C. The second heating scan was performed in the same way. The melting temperature (T_m) and melting enthalpy (ΔH) of EVOH32 and/or grafted polymer were determined from the second heating scan. The TGA was performed on a Dupont TG 2000 apparatus in a temperature range from 40 to 550°C at a scanning speed of 10°C/min under a nitrogen atmosphere.

RESULTS AND DISCUSSION

Monomer synthesis

Compound **I** was prepared by phase transfer catalyst according to the procedure described in Scheme 1. The ^{1}H-NMR and FTIR spectra of the monomer are reported in Figures 1 and 2. In combination with the various peak assignments and melting point agreement with the literature,[25] the structure was confirmed.

It is well known that aldehyde reacts with the hydroxyl group of binary alcohol to form acetal when using sulfuric acid as the catalyst by nucleophilic addition. Scheme 2 shows the reaction scheme of EVOH32 with sugar aldehyde via acetal formation. The reactions were investigated with molar ratios of the aldehyde group of compound **I** to the hydroxyl of EVOH32 ([OH]/[CHO]) at 1:5 and 1:15, respectively. The FTIR spectra of the modified EVOH32 are presented in Figure 3. It was observed from Figure 3 that the band at 1744 cm^{-1}, which was characterized as the carbonyl corresponding to the glucose ester moieties, appeared on the grafted polymer and the intensity increased with the increase of the molar ratio of [OH]/[CHO]. It can be also seen by comparing spectra a and b in Figure 3 that the intensity of the band at around 3500 cm^{-1} decreased and the intensity of the bands at 1512 and 1600 cm^{-1} corresponding to the phenyl ring increased with the increase of the molar ratio of [OH]/

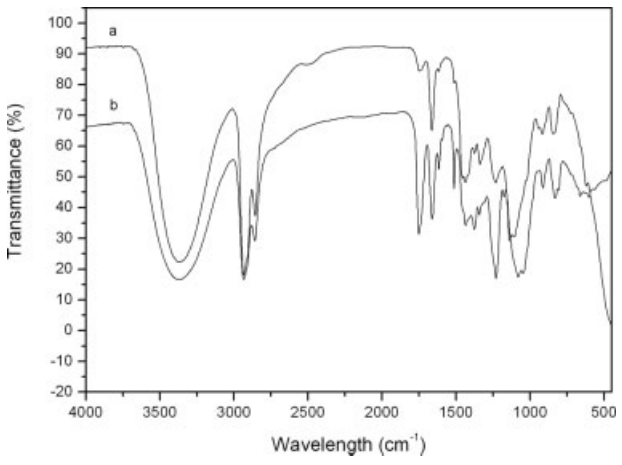


Figure 3 FTIR spectra of EVOH32 modified by glucose ester at [OH]/[CHO] = 1:5 (spectrum a) and [OH]/[CHO] = 1:15 (spectrum b). The other reaction conditions are [OH] = 4.4 mmol at room temperature for 20 h with 25.0 mL of DMF.

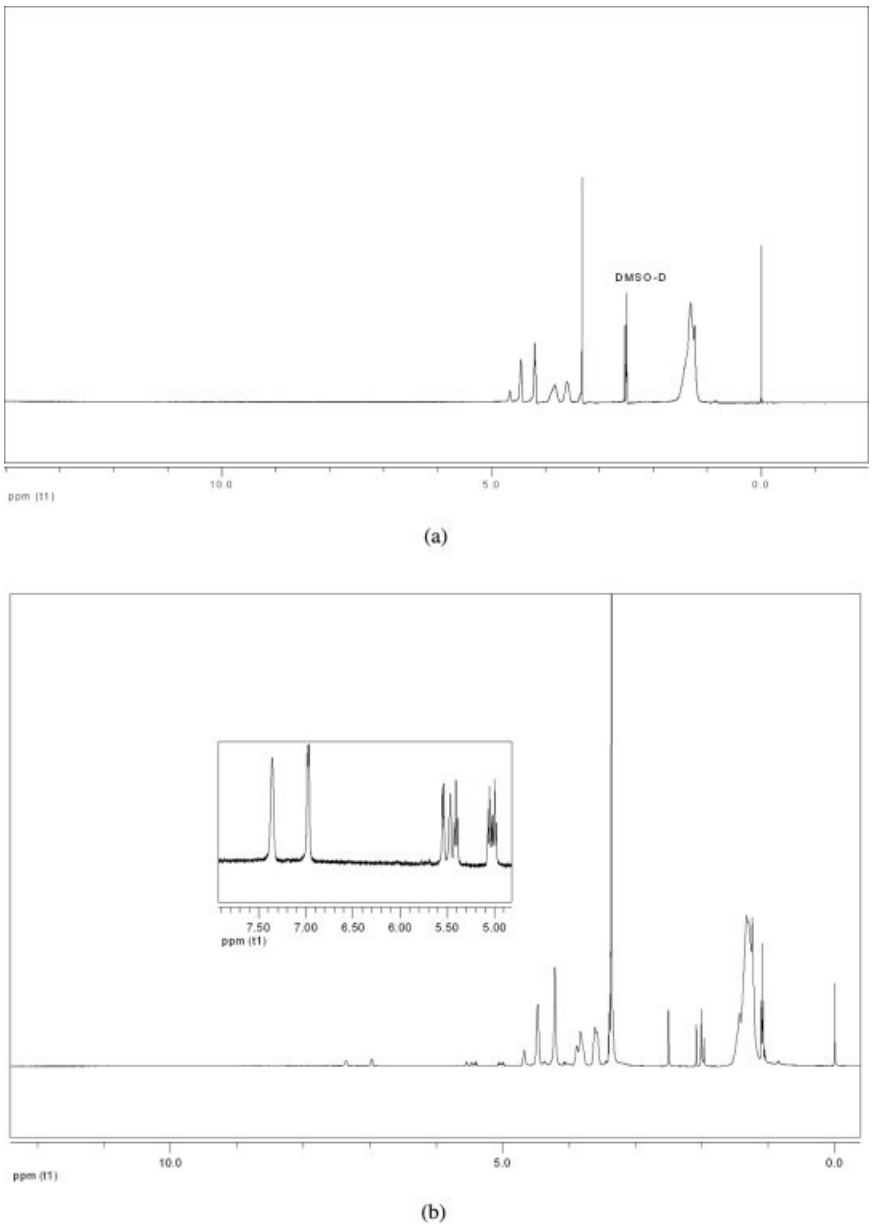


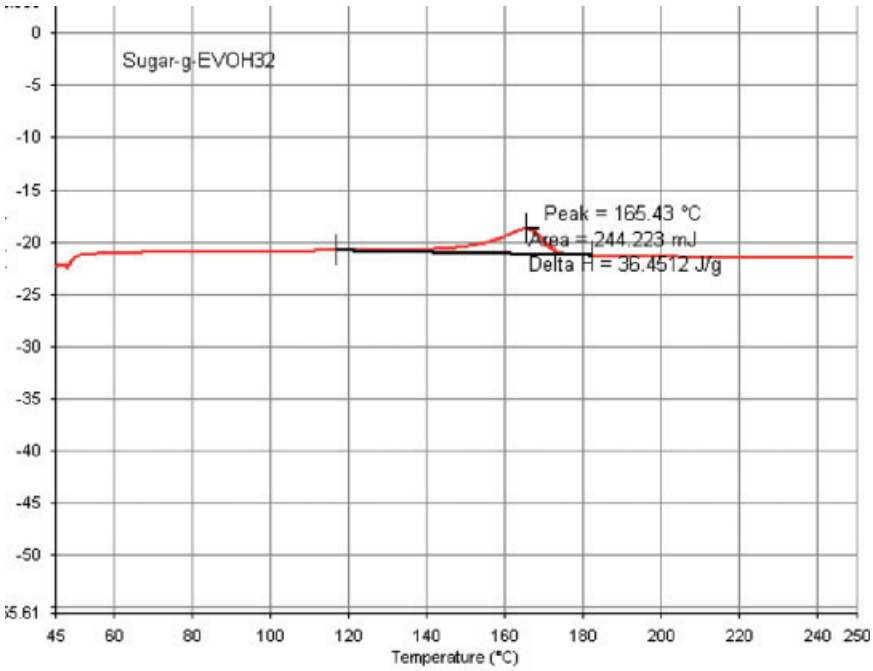
Figure 4 ^{1}H-NMR spectra of (a) EVOH32 (DMSO-d_6) and (b) EVOH32 modified by glucose ester (DMSO-d_6). The reaction conditions are at room temperature for 20 h with 25.0 mL of DMF, [OH] = 4.4 mmol, and [OH]/[CHO] = 1:15.

[CHO]. In comparison with the IR spectrum of compound **I** (seen Fig. 2), the band at 1696 cm^{-1} for the aldehyde group of the glucose ester disappears. These results indicated that the acetal-forming reaction had actually taken place.

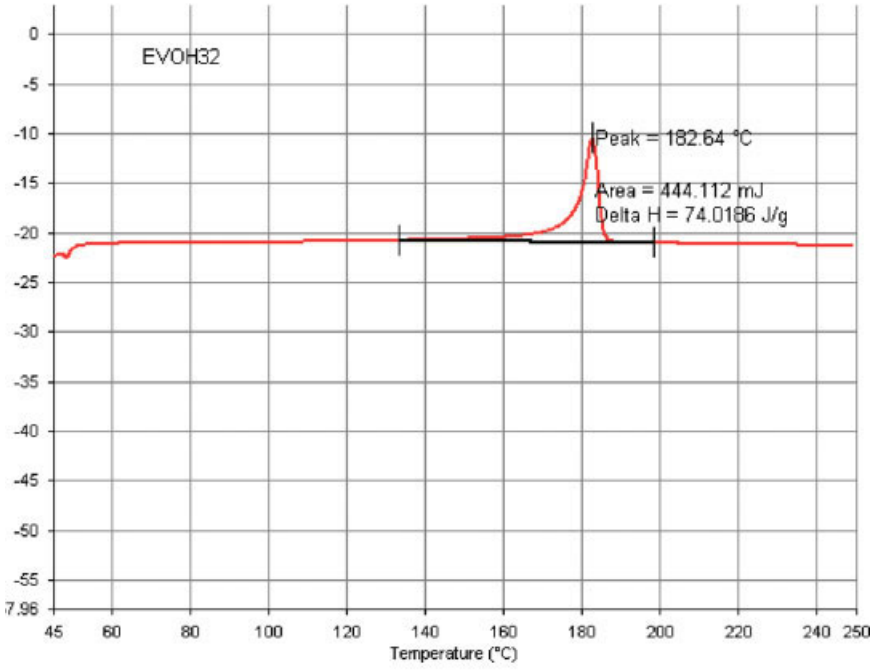
Figure 4(b) shows the ^{1}H-NMR spectra of EVOH32 modified with glucose ester at a [OH]/[CHO] molar ratio of 1:15. Compared to the ^{1}H-NMR spectra of EVOH32 in spectrum a in Figure 4, spectrum b shows new peaks at 2.0 and 7.0–7.5 ppm, which were attributed to the CH_3 of CH_3CO and phenyl ring protons of the glucose ester moieties. Then, multipeaks at 5–5.5 ppm corresponding to a sugar ring proton appeared. The proton of the aldehyde of the glucose ester at 9.93 ppm (Fig. 1) also disappeared in spectrum b in Figure 4. These results suggested that the sugar moieties successfully incorporated onto the EVOH32 backbone.

Thermal properties of polymers

DSC thermograms of the EVOH32 as well as the grafted EVOH32 at a [OH]/[CHO] molar ratio of 1:15 are shown in Figure 5. The T_m values of EVOH32 and glucose ester-*graft*-EVOH32 were 182.6 and 165.4°C, respectively. The T_m of the glucose ester substituted EVOH32 shifted to a lower temperature by 17.2°C compared with unmodified EVOH32. The ΔH values of EVOH32 and glucose ester substituted EVOH32 were 73.6 and 36.7 J/g, respectively. The crystallization of EVOH32 was inhibited by the introduction of



(a)



(b)

Figure 5 DSC curves of (a) sugar modified EVOH32 and (b) EVOH32. The reaction conditions are at room temperature for 20 h with 25.0 mL of DMF, [OH] = 4.4 mmol, and [OH]/[CHO] = 1:15. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

the sugar group as evidenced by the decrease of the T_m and ΔH. The decreasing trends in the T_m and ΔH presumedly resulted from incorporation of bulky glucosyl moieties onto EVOH32, subsequently weakening the intramolecular hydrogen bonds of the modified EVOH32.

Thermal degradation of EVOH32 and modified EVOH32 at molar ratio of [OH]/[CHO] = 1:15 was analyzed by TG/derivative TG (DTG) experiments. Figure 6 represents the TG curves obtained for EVOH32 and modified EVOH32. It can be seen from the figure that the degradation of modified EVOH32 happened at a lower temperature than that of EVOH32. To obtain further decomposition information, the DTG curves were recorded in Figure 7. Note that the curves of EVOH32 and modified EVOH32

show two main peaks, corresponding to the maximum degradation rate, of each component. For EVOH32, the first peak at about 363.4°C can be attributed to the major component, poly(vinyl alcohol). The second peak, observed at higher temperatures, can be attributed to the ethylene cocomponent.[26] Comparing modified EVOH32 with EVOH32, the first degradation peak of modified EVOH32 is shifted to higher temperature values by about 16.1°C, possibly because of the inhibition of the elimination of hydroxyl groups in the poly(vinyl alcohol) unit. The second peak temperature values were unchanged, which was due to the decomposition of the ethylene segment in EVOH32.

CONCLUSIONS

The incorporation of glucose ester into EVOH32 by acetal formation using acid as a catalyst was confirmed by IR and ^{1}H-NMR spectra. The melting temperature and melting enthalpy of modified EVOH32 had lower values than those of EVOH32. The TG/DTG results showed that EVOH32 and modified EVOH32 had two decomposition stages. The modified EVOH32 at the first degradation peak shifted to higher temperature values. Studies on the effect of glucose ester on the biodegradability, wetting, and barrier properties of EVOH32 are underway.

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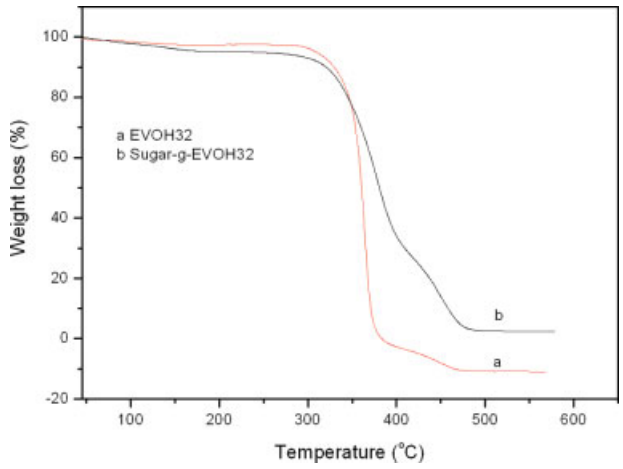

Figure 6 TGA curves for EVOH32 (curve a) and glucose ester modified EVOH32 (curve b) samples at a heating rate of 10°C min^{-1}with [OH] = 4.4 mmol and [OH]/[CHO] = 1:15. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

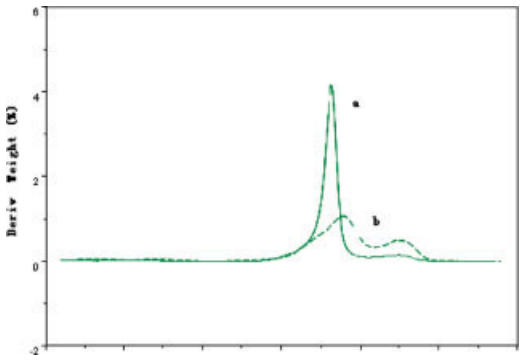

Figure 7 DTG curves for EVOH32 (curve a) and glucose ester modified EVOH32 (curve b) samples at a heating rate of 10°C min^{-1}with [OH] = 4.4 mmol and [OH]/[CHO] = 1:15. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

References

1. Wang, Q.; Dordick, J. S.; Linhardt, R. J. Chem Mater 2002, 14, 3232.
2. Varmaa, A. J.; Kennedy, J. F.; Galgalia, P. Carbohydr Polym 2004, 56, 429.
3. Murata, J. I.; Ohya, Y.; Ouchi, T. Carbohydr Polym 1996, 29, 69.
4. Caneiro, M. J.; Fernandes, A.; Figneiredo, C. M.; Fortes, A. G.; Freitas, A. M. Carbohydr Polym 2001, 45, 135.
5. Hubbell, J. A. Trend Polym Sci 1994, 2, 20.
6. Bahulekar, R.; Tokiwa, T.; Kano, J.; Matsumura, T.; Kojima, I.; Kodama, M. Carbohydr Polym 1998, 37, 71.
7. Liu, X. C.; Dordick, J. S. J Polym Sci Part A: Polym Chem 1999, 37, 1665.
8. Gruber, H.; Knaus, S. Macromol Symp 2000, 152, 95.
9. Takasu, A.; Niwa, T.; Itou, H.; Inai, Y.; Hirabayashi, T. Macromol Rapid Commun 2000, 21, 764.
10. Galgali, P.; Puntambekar, U. S.; Gokhale, D. V.; Varma, A. J. Carbohydr Polym 2004, 55, 395.
11. Alvarez, C.; Strumia, M.; Bertorello, H. Polym Bull 1988, 19, 521.
12. Takasu, A.; Takada, M.; Itou, H.; Hirabayashi, T.; Kinoshita, T. Biomacromolecules 2004, 5, 1029.
13. Lagaron, L. M.; Powell, A. K.; Bonner, J. G. Polym Test 2001, 20, 569.
14. Park, E. S.; Kim, H. S.; Kim, M. N.; Yoon, J. S. J Appl Polym Sci 2005, 96, 1064.
15. Park, E. S.; Kim, M. N.; Yoon, J. S. J Polym Sci: Part B Polym Phys 2002, 40, 2561.
16. Bakr, N. A.; Ishra, M. Polym Test 2002, 21, 571.
17. Avramescu, M. E.; Sager, W. F. C.; Wessling, M. J Membr Sci 2003, 216, 177.
18. Marconi, W.; Marcone, R.; Piozzi, A. Macromol Chem Phys 2000, 201, 715.
19. Matsumuraa, K.; Hyona, S. H.; Nakajimaa, N.; Iwataa, H.; Watazub, A.; Tsutsumia, S. Biomaterials 2004, 25, 4817.
20. Bruzaud, S.; Levesque, G. Macromol Chem Phys 2000, 201, 1758.
21. Giménez, V.; Mantecón, J. A.; Cádiz, V. Acta Polym 1999, 50, 187.
22. Stephanie, S.; Edwin, T. Polymer 1998, 39, 5587.
23. Redemann, C. E.; Niemann, C. Org Synth 1942, 22, 1.
24. Dess, D.; Kleine, H. P.; Weinberg, D. Synthesis 1981, 13, 883.
25. Li, W.; Liu, H. M. Chin J Org Chem 2002, 12, 1034.
26. Alvarez, V. A.; Ruseckaite, R. A.; Vázquez, A. J Appl Polym Sci 2003, 90, 3157.