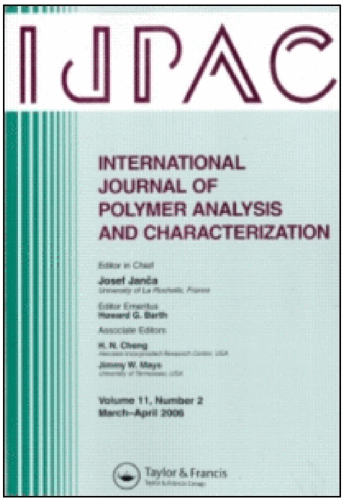

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Preparation and Characterization of Poly (vinyl alcohol)/Lactic Acid Compounded Polymeric Films

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Abstract: Poly (vinyl alcohol) (PVA) and L-lactic acid (LA) were compounded to get biodegradable polymeric film with useful mechanical, thermal, and bacteriostatic properties for possible medical or packaging applications. Samples with various concentrations of LA were prepared by using the solvent cast technique and characterized by tensile tests, differential scanning calorimetry, Fourier-transform infrared spectroscopy, thermogravimetry, evolved gas analysis, and bacteriostatic tests, and their biodegradability was investigated under aquatic and aerobic conditions. The films show a rapid increase in elasticity and decrease in glass transition temperatures due to the presence of LA. A bacteriostatic effect on *Pseudomonas putida, Staphylococcus epidermis*, and *Micrococcus sp.* was proved. The biodegradation of all samples by mixed microflora was completed within 250 hours; however, the course of biodegradation was influenced by both esterification of PVA and the presence of molecules of LA in the polymeric films.

Keywords: Bacteriostatic; Biodegradable compound; DSC; FTIR; Lactic acid; Poly (vinyl alcohol); TGA

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INTRODUCTION

Research and development of hydrophilic (water-soluble) materials for various applications have been the subject of great scientific and commercial interest. For example, their use in medicine as skin covers[1] and wound dressing,[2] coatings of items[3] has been investigated. Their applications can be also found in packaging, as water-soluble and biologically degradable materials,[4] and in electrochemical devices, such as batteries or displays.[5]

Poly (vinyl alcohol) (PVA) is a synthetic polymer that is applied in all the areas mentioned above. It is a biologically friendly polymer due to its full biodegradability and biocompatibility.[6,7] Moreover, its properties, such as water solubility, can be adjusted easily by controlling the degree of hydrolysis of acetate groups during its polymerization.[8] PVA can be processed in two basic ways. First, it can be cast and applied as a functional film, including use in biomedical materials.[9,10] Cast films of PVA combined with natural polymers like collagen, gelatin,[11] and lactose or calcium lactate[12] have been investigated for possible medical purposes. Second, PVA is also extrudable, and it is processed to provide temporary biodegradable packaging, such as bags or seed-germination tapes.[4] Applications of PVA together with poly (vinyl pyrrolidone) and other components (e.g., metal salts) in electrochemical devices are reported[13] for polymer electrolyte systems that provide good mechanical properties and proper electrode/electrolyte contact in advanced high-energy electrochemical devices.[5]

In spite of extensive research on modification of PVA, the demand for new materials with tailored properties still exists. In this study, we represent a new material, a combination of PVA and lactic acid. Lactic acid (LA) is a fermentation product of lactose, miscible with water or ethanol, and found in natural foodstuffs, like sour milk, yoghurt, and cottage cheese, and in animal metabolic systems. Chemically, LA occurs as two optical isomers, a dextro (D) and a levo (L) form. The commercial use of LA includes applications in food-processing and pharmaceutical industries, in leather tanning and textile dyeing, in manufacturing inks, solvents, and lacquers, and, last but not least, in production of the polymer poly lactic acid (PLA).[14,15] The antibacterial effect of LA against some pathogenic bacterial species is also known, and it has been used in food protection against microbial spoilage.[16]

Good material properties of PVA and the biological activity of LA have encouraged us to prepare and characterize polymeric films based on these materials for the production of biodegradable and bacteriostatic polymeric film with possible multiple applications, such as medical or packaging materials. In addition, LA used for the preparation of this compound can be obtained via fermentation of waste, as reported by, for example, Oda et al.,[15] which is convenient from both economic and environmental points of view. Mechanical and thermal properties, physicochemical characterization, bacteriostatic effects, and biodegradability of the materials containing PVA and LA are investigated in the present work.

EXPERIMENTAL SECTION

Materials

Poly (vinyl alcohol) PVA 49′000 (Mw ~ 49000, degree of hydrolysis 86–89 mol·%) was purchased from Fluka. L-lactic acid (analytical grade) was produced by Lachema (Czech Republic). Bacterial species *Pseudomonas putida* and *Staphylococcus epidermis* used in this work were isolated from natural sources. *Micrococcus sp.* was bought from CCM Brno (Czech Republic).

Preparation of Polymer Films

Aqueous polymer solution (10 wt% solution of PVA in distilled water) was prepared by dissolving polymer granules in water at 70°C for 30 min under continuous stirring. Then the relevant portion of LA (see Table I) was added to the polymer solution and stirring of this mixture continued for another 15 min. Thereafter, the solution was poured into an acrylic mold and dried at 35°C for 48 h in a temperature-controlled incubator. The thicknesses of transparent films were about 150 μm.

Characterization of the Compounds

Static Tensile Measurements

Mechanical properties of pure PVA and PVA/LA films, which were stored inside closed polyethylene bags to prevent moisture absorption,

Table I. Composition of samples

Sample index	Lactic acid (wt%)[a]
PVA	0.00
PVALA10	9.20
PVALA20	19.35
PVALA30	32.42
PVALA40	41.86
PVALA50	48.90

[a] Related to total amount of polymers, water content considered.

were determined on a TIRAtest 2160 at 23°C, 40% relative humidity. The initial length of samples was 50 mm, with a width of 10 mm and a thickness of about 150 μm. The speed of the moving clamp was 50 mm·min^{-1}. Tensile properties were determined according to Czech Governemental Norm ISO 5271-3 standard.

Differential Scanning Calorimetry (DSC)

DSC was used for the assessment of the glass transition temperature (T_g) of PVA and its compounds with LA (PVA/LA). Approximately 4 mg of the sample was sealed in a DSC stainless steel pan and analyzed on Perkin Elmer Pyris 1 DSC, calibrated for temperature and heat flow using indium. In the procedure the samples were heated from $-5°$ to 165°C at 20°C·min^{-1}, which was followed by holding samples at 165°C for 15 min to avoid moisture influence (first scan). The samples were then cooled to -5°C and conditioned at this temperature for 1 min before starting the second step, heating from $-5°$ to 165°C. The value of T_g was determined in the second heating cycle at the midpoint stepwise increase of the specific heat associated with glass transition.

Fourier-Transform Infrared Spectroscopy

The structure of samples was studied by Fourier-transform infrared spectroscopy (FTIR). The form of the samples enabled the use of the method of attenuated total reflectance (ATR), which was conducted on the thin film using a Nicolet 320 FTIR. The device was equipped with an ATR accessory utilizing a Zn-Se crystal and the Omnic software package over the range of 4000–800 cm^{-1} at room temperature. Uniform resolution of 2 cm^{-1} was maintained in all cases. The differential spectra were obtained by subtraction of spectra of polymeric mixtures (PVA/LA) and pure PVA.

Because of possible Zn-Se crystal damage, the reference spectrum of pure LA was taken on another spectrometer, Digilab's Scimitar. A droplet of concentrated LA (80%) was spread on the rough side of a single-sided polished IR transparent silicon wafer, and the measurement was carried out in the transmission mode.

Thermogravimetry and Evolved Gas Analysis

The composition and thermal behavior of samples were also studied by were thermobalance (Setaram Setsys Evolution 1200) coupled with evolved gas analysis (Digilab Scimitar FTIR spectrometer). The spectrometer is equipped with a transmission cell adapted for gases, which is connected to the thermogravimeter by a heated transfer line. The temperature of both gas cell and transfer line was kept at 200°C. The samples were examined under inert atmosphere of He (5.5 purity, SIAD TP, Czech Republic), and the gas flow was 30 mL/s. The temperature was increased at the rate of 20°C/min in the range from ambient temperature to 1000°C.

Bacteriostatic Properties

To determine the long-lasting bacteriostatic effect of PVA and PVA/LA polymeric material, the investigation was carried out in the presence of different species of pathogenic bacteria (*Staphylococcus epidermis*, *Micrococcus sp.*, and *Pseudomonas putida*). A piece of each sample (diameter 9 mm, thickness 150 μm) was placed on the surface of an individual nutrient agar plate containing the test organisms. The plates were then incubated at 37°C up to 24 h for bacterial growth. The zones of inhibition, which appeared on the surface, were measured in five directions and average values were used for calculations of the zone area.

Biodegradability

The environmental impact of PVA and its compounds with LA were investigated through Zahn-Wellen's method (ISO 9888), on the basis of measurements of total organic carbon concentration (TOC). The laboratory tests were carried out in Erlenmeyer flasks (500 mL) under continuous shaking at 160 rpm at room temperature (25°C). Activated sludge from a municipal wastewater treatment plant (Zlin-Malenovice, Czech Republic) was used as a source of mixed microorganisms. The sludge was filtered, decanted, centrifuged (3000 rpm for 10 min), and resuspended in mineral medium. It was aerated for not less than 24 h prior to the test.[17] The polymer samples were dissolved in distilled water (at 50°C), and an equivalent volume of polymer solution (TOC was up to 100 mg·dm^{-3}) was introduced into the reactor. TOC was measured on a Shimadzu 5000 A, and biodegradation of samples was calculated from

$$B_t(\%) = \left[1 - \frac{(C_t - C_b)}{(C_a - C_{ba})}\right] \times 100 \tag{1}$$

where B_t is biodegradation at time t (%), C_t and C_b are respectively TOC values (mg·dm^{-3}) in the test mixture and blank at the time of sampling, and C_a and C_{ba} represent TOC values in the test mixture and blank three hours after the beginning of the test.

The data of biodegradation B_t were evaluated by using a simple first-order kinetics equation (Equation (2)) and regression-processed by the least squares method applying the "Solver" subprogram of Microsoft Excel 7.0.

$$B = B_{MAX}\left(1 - e^{-k(t-t_{LAG})}\right) \tag{2}$$

where B [%] is TOC removal at the time t[h] of biodegradation, B_{MAX} [%] means maximum removal of TOC, $-k$ [h^{-1}] represents the rate constant, and t_{LAG} [h] is the lag phase of biodegradation.

RESULTS AND DISCUSSION

Generally, the effect of LA in polymer mixtures on various properties was followed.

Mechanical and Thermal Properties

The influence of LA in the compounds with PVA on the properties of tested samples is significant. The tensile properties of pure PVA and its compounds with LA are shown in Figure 1. As can be seen, the value of Young's modulus (E) drops from 3068 MPa (pure PVA) to 454 MPa in the case of PVALA10. Another considerable decrease in E is observed with further increase in LA concentration (to 78 MPa for PVALA20). At high concentrations of LA the relative drop of modulus is not so striking; however, the value of E is very low in comparison to that of unmodified PVA film. PVALA50 shows Young's modulus only around 50 MPa.

A similar trend was observed for tensile strength. The difference (decrease) between tensile strength of pure PVA and PVALA10 is more than 40 MPa, and even 80 MPa for PVALA50.

While the values of both E and tensile strength decrease with rising concentration of LA in the mixtures, strain at break sharply increases already at the lowest investigated LA content. The observed increase was from 8% (pure PVA) to 258% (PVALA10). Further addition of LA causes fluctuation around this value, and at high concentrations (above 30 wt%) it slowly decreases. The sample labeled PVALA50 shows the lowest strain at break of all compounds containing LA (181%); however, it is still much higher than for pure PVA. Similar results were reached by Caner et al.,[18] who studied mechanical properties of chitosan cast films. They observed uniquely high values of elongation at break for these films formed from lactic acid solutions.

In the PVALA systems investigated in this study LA seems to work as a plasticizer, increasing flexibility, workability, and extensibility of the rigid plastic. The idea of LA incorporation in PVA structure is supported by quite good compatibility of both components due to their polarity, changes of free volume, and consequent decreases of glass transition temperatures, T_g. The intensity of these changes is visible in Figure 2,

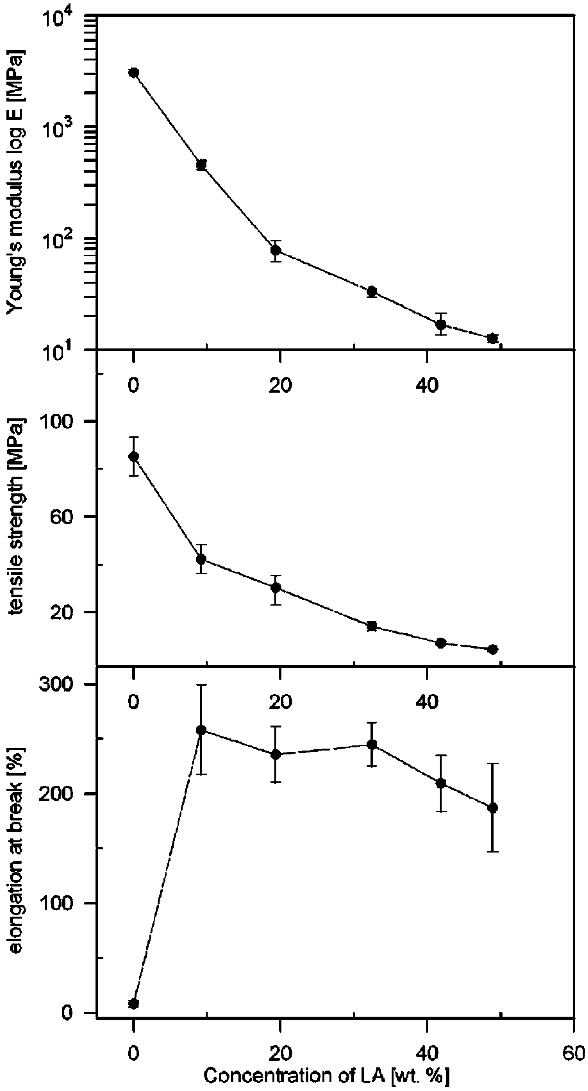

Figure 1. Tensile properties of PVA/LA blends.

where parts of DSC curves of pure PVA and PVALA50 are presented as an example. The plasticizing effect of LA is proved by a significant decrease of the recorded T_g (69°C for pure PVA and 51°C for PVALA50). More detailed studies of T_g dependence on LA concentration in the PVA/LA systems show that the most noticeable change of T_g occurs already at 10 wt% LA. Further increase of LA concentration shifts the

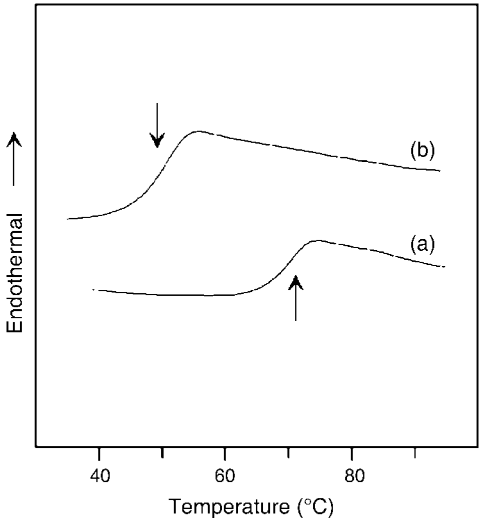

Figure 2. DSC curves of pure PVA (a) and PVALA50 (b).

glass transition temperatures towards lower values; however, these declines are not as steep at low concentrations (Figure 3).

Structural Characterization

The differential FTIR spectra obtained by subtraction through the Omnic software do not give exact information on the quantity of constituent

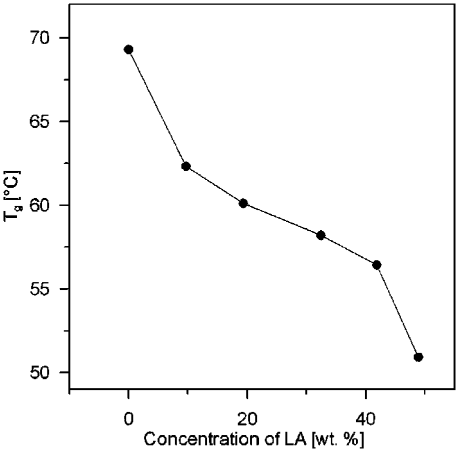

Figure 3. Glass transition temperature vs. concentration of LA.

elements; nevertheless, they can be useful for observation of qualitative changes inside of the investigated systems, and they provide (through intensity changes) semiquantitative information about the trends in absorption. The spectra of neat components and their compounds are depicted in Figure 4. As can be seen, pure PVA has a very broad absorption peak at 3287 cm^{-1}, which corresponds with O–H groups in condensed phase. Another interaction of O–H groups could be represented by strong absorption at 1021 cm^{-1}. Most of the remaining peaks, at 1084, 1232, 1250, and 1415 cm^{-1} can correspond to C–O groups. The response of C–H groups, on the other hand, can be found at 2935 and 1371 cm^{-1}. Due to incomplete hydrolysis of PVA, two peaks of middle intensity (presence of C=O) appear at 1731 and 1712 cm^{-1}. These results are in agreement with the observation reported by Yang et al.[19]

The FTIR spectra of LA show characteristic absorption peaks at 3486 cm^{-1} (O–H groups), 1734, and 1726 cm^{-1} (C=O, aliphatic esters) and 1232, 1130, and 1047 cm^{-1} (C–O groups). In fact, commercial LA in aqueous solution exists in the monomeric form; nevertheless, it can

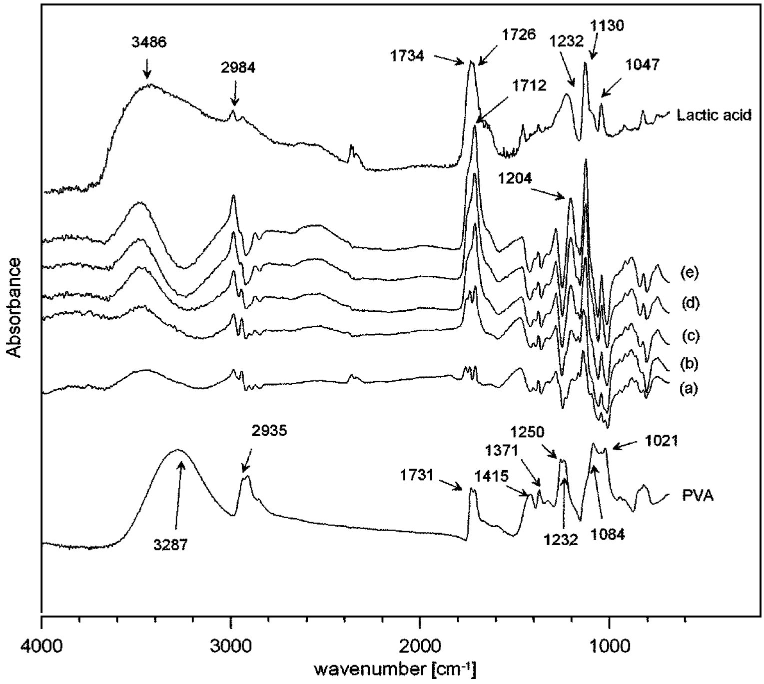

Figure 4. FTIR spectra of PVA and LA and differential spectra of PVALA10 (a), PVALA20 (b), PVALA30 (c), PVALA40 (d), and PVALA50 (e).

also consist of dimers and/or higher mers.[20] This could be connected with the appearance of an intensive peak at 1726 cm^{-1}.

In the case of differential spectra of the compounds (Figure 4, tracks (a)–(e)), increases or decreases of some peaks can be observed in accordance with changing concentration of components in the system. With higher content of LA the peaks around 3400 cm^{-1} grow and shift to higher wavenumbers. Furthermore, a growth of peaks at 2984, 1734, and 1130 cm^{-1} can be seen. On the other hand, downward peaks, occurring at 1250, 1084, and 1021 cm^{-1}, correspond to the decrease in PVA concentration in the system. The chemical reaction between PVA and LA (esterification) can be expressed in rising peaks at 1204 cm^{-1} and 1712 cm^{-1}. These results reveal that only a part of present LA is involved in this chemical reaction. It corresponds to work presented by Carlotti et al.,[20] where the partial formation of a PVA lactic acid ester was proved on the basis of nuclear magnetic resonance (NMR) measurements. The preponderant part of LA seems to work as a plasticizer, as could be supposed on the basis of results from mechanical and thermal characterizations of PVA/LA films.

Thermogravimetric Characterization and Evolved Gas Analysis

Another approach to structural investigation used was the method of thermogravimetry (TG) connected with evolved gas analysis. TG curves allow observation of sample mass losses during heating, and the released gaseous products are identified by molecular spectroscopy. Furthermore, due to the on-line experimental setup, it is possible not only to distinguish species, but also their origin (physical or chemical bonding environment). TG curves have an integral character and significant changes are manifested in steps. The dTG curve is that obtained by numerical differentiation of TG, and its negative value (-dTG) is shown in the graph so that it can be easily compared with Gram-Schmidt (GS) chromatograms obtained from FTIR spectrometry. A GS chromatogram shows the general intensity of IR absorption measured on gaseous products flowing through the gas cell of the spectrometer. Hence a GS chromatogram is also a curve of differential character with the shape related to the dTG curve. The processes are then manifested as peaks in both GS and dTG methods. Moreover, each point of the GS curve carries full information about the FTIR absorption spectrum of the examined gas in a discrete time interval.[21]

The results may be demonstrated in Figures 5 and 6, which compare the thermal behavior of pure PVA and one representative PVA/LA compound (sample PVALA40) under inert atmosphere of He. The heating rate was chosen relatively high (20°C/min) in order to suppress

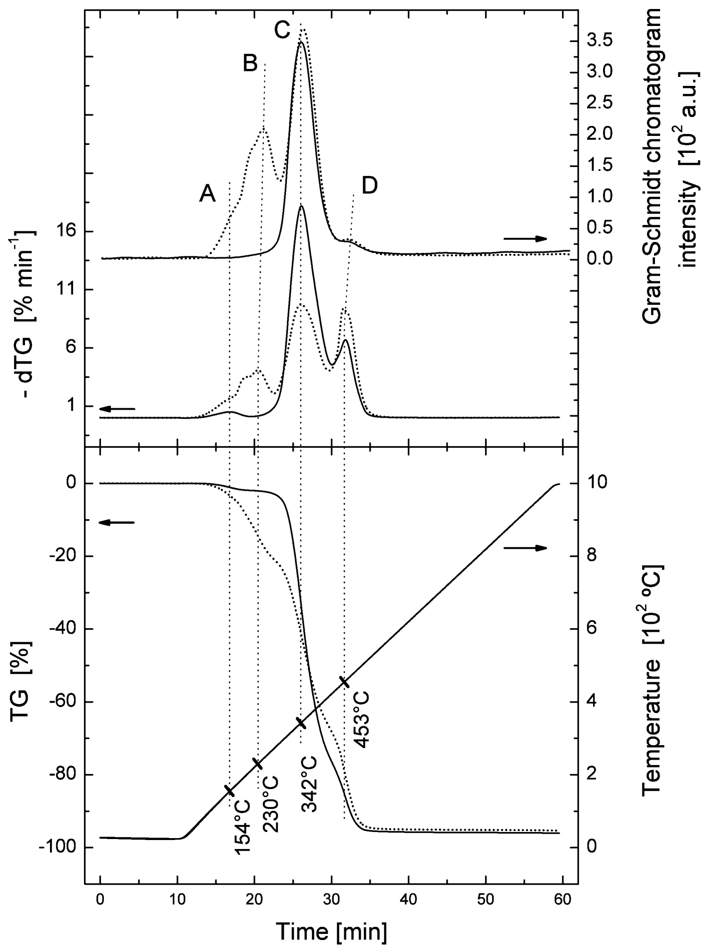

Figure 5. TG-FTIR analysis of PVA and PVALA40 samples.

elimination and other reactions on side groups and thus shifts the degradation process more to the polymer backbone cleavage occurring at higher temperatures. For FTIR spectra identification, see the NIST Standard References Database.[22] Figure 5 presents the results of TG analysis of pure PVA (solid lines); mass loss curve and temperature growth are shown in the lower graph window. The initial isothermal phase at ambient temperature allows stabilizing of the system. Then, after the start of temperature rise the initial heating phase shows only a small step on the TG curve and a weak signal for water on FTIR absorption spectra (not shown here). The corresponding dTG peak A at 154°C is ascribed to the release of a small amount of water present in the foil made of pure PVA

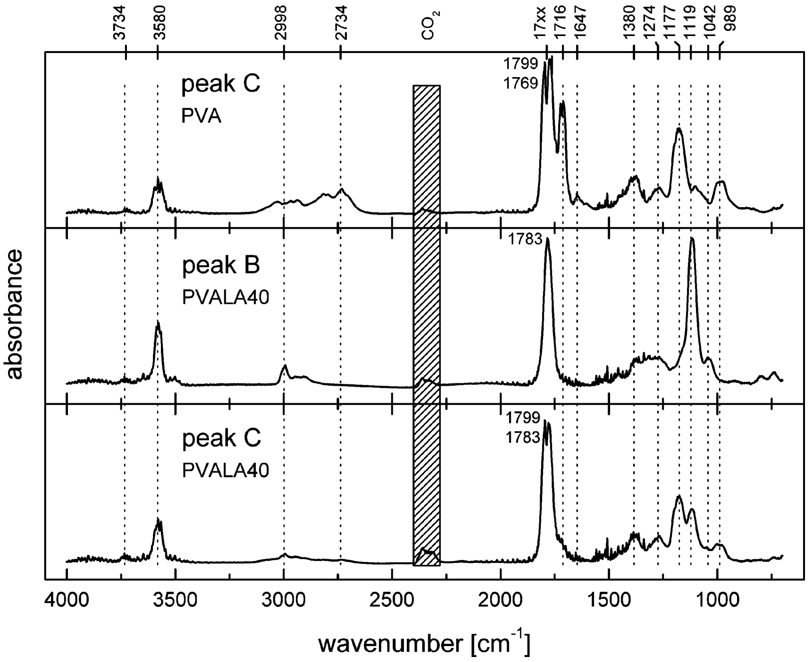

Figure 6. FTIR spectra of evolved gas for selected peaks in Gram-Schmidt chromatograms from Figure 5.

due to the sample preparation procedure. The thermal degradation of PVA starts at higher temperatures, and the maximum degradation rate is reached at 342°C (peak C in dTG). Peaks A and C are well resolved.

The upper FTIR absorption spectrum in Figure 6 is taken from the GS chromatogram at the peak C maximum and shows clearly that during PVA degradation mainly acetaldehyde (note especially the double peak centered at 1716 and the broad peak at 2734 cm^{-1}) is released and traces of vinyl acetate (note the peak at 1647 and the doublet at 1769 and 1799 cm^{-1}) are present in the evolved gas as PVA is hydrolyzed from about 86 to 89 mol·%. Peak D in Figure 5 at 453°C corresponds to final carbonization of the nonvolatilizable remainder, and some low-molecular hydrocarbons released by elimination reactions were detected (spectra not shown here). The char content is 4 wt% of the sample weight.

The analysis of PVALA40 compound is presented in Figure 5 by dotted lines curves. Water desorption from the sample is not separated from LA release. Therefore, feature A is manifested only as a shoulder of peak B in differential curves. The maximum weight loss rate appears at the temperature of 230°C (peak B). The spectrum taken from the maximum of peak B on the GS curve is shown in the middle graph window in

Figure 6, and it is unambiguously assigned to the absorption spectrum of lactic acid in gas phase (note peaks at 1119, 1783, and 2998 cm^{-1}). Thus, peak B is ascribed to LA desorption, and the quantity of LA volatilized at lower temperature (peak B) together with water (low-temperature shoulder A in peak B) is estimated at about 20% of the sample weight, i.e., roughly only one-half of LA content in the material. Another part of LA is released simultaneously with PVA degradation manifested in peak C. It can be clearly seen in the lower spectrum in Figure 6 (taken from peak C in the GS curve) that acetaldehyde formation is highly suppressed (decrease of spectral density at 2734 and 1716 cm^{-1}). Besides LA, absorption bands typical of LA esters (1177 cm^{-1}), suggesting esterification of PVA hydroxyl groups, are also manifested here. The peaks of vinyl acetate at 1647 and 1769 cm^{-1} do not appear in this spectrum, which can be explained by reesterification of residual PVA acetate groups by LA during the compound preparation. The char content (about 4 wt%) is the same as in pure PVA.

The results from TG FTIR agree with those obtained from ATR FTIR spectroscopy, confirming that a part of lactic acid is bonded in ester form with PVA, and they also prove the presence of nonbonded lactic acid in the materials. The change in chemical structure is expected to influence polymer biodegradability, as discussed further.

Bacteriostatic Properties and Biodegradability

The inhibition of bacterial growth occurs in all cases where LA is present. This was confirmed by circular inhibition zones that appeared due to the diffusion of LA as an antimicrobial ingredient from the sample into the surrounding medium in the presence of *Pseudomonas putida*. The dependence of inhibition area on the concentration of LA (Figure 7) shows that bacteriostatic properties of PVA/LA compounds are more or less the same for bacterial species *Staphylococcus epidermis* and *Micrococcus sp.* In the case of *Pseudomonas putida* the inhibition zone is slightly smaller. The increasing areas of inhibition zones correspond with rising contents of LA in polymer compounds up to approximately 30 wt% (PVALA30); above this concentration, the bacteriostatic effect is nearly constant. Thus a concentration of 30 wt% is sufficient to achieve the optimum effect. In addition, the inhibition zones were measured again after more than a month, and the results were found to be the same. Similar results of prolonged antimicrobial action are reported by Ostrovidova et al. for polyfunctional polymer films containing PVA, LA, and poly (vinyl pyrrolidone).[23]

Biological degradation of PVA has been investigated since the early 1970s. It has been found that that PVA biodegradation can be

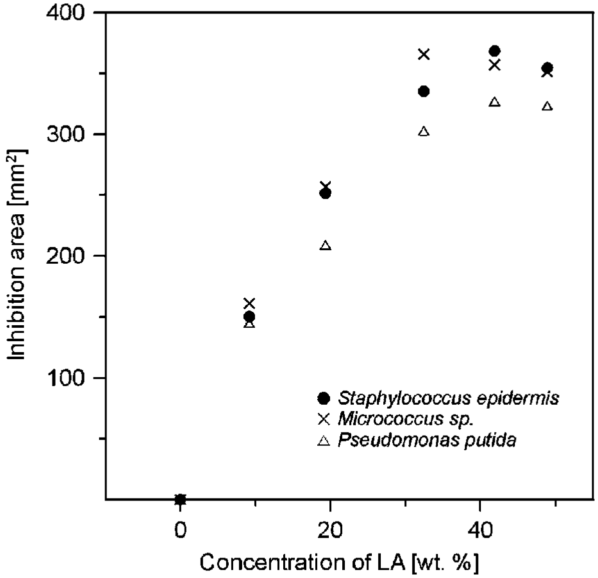

Figure 7. Bacteriostatic properties of PVA/LA blends.

mediated by certain microorganisms, e.g., bacterial strains *Pseudomonas, Alcaligenes*, and *Bacillus* and fungal strains *Phanerochaete chrysosporium, Saccharomyces, Lipomyces, Rhodotorula*, and *Endomyces*.[24] Our study of biodegradability by mixed microflora present in the activated sludge of a municipal wastewater treatment plant also identified of the bacterial strains introduced above.[17]

Generally, all samples showed complete biodegradation within 250 hours of the test. A one-phase biodegradation course with a lag phase of around 80 hours was observed (Figure 8) for pure PVA due to the absence of any low-molecular component. On the other hand, the materials containing LA evidently show two-phase biodegradation (Figure 8). The first phase represents a preferential utilization of the easily degradable component (LA), while the polymeric part of the mixture is degraded in the second phase. More detailed description of the biodegradation course can be obtained from Table II, where kinetic constants obtained by applying the first-order kinetics Equation (2) on biodegradation data are presented.

As mentioned above, two-phase biodegradation occurs only in the presence of LA in compounds. In the first phase, the values of maximum biodegradation, B_{MAX}, as well as the rate constant, $-k$, increase with rising content of modifier. The concentration of LA is the decisive factor for the reaction at this stage. The assumptions that LA works both as a

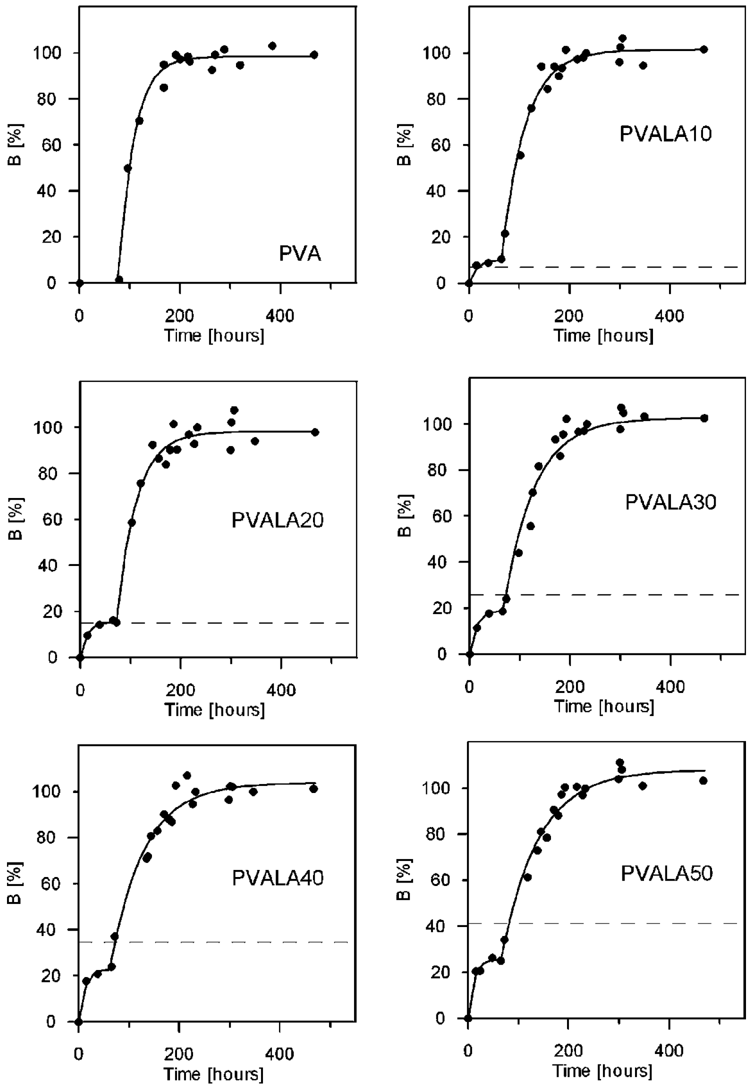

Figure 8. Biodegradation of PVA and PVALA polymer films (vertical dashed lines represent theoretical TOC calculation for LA).

plasticizer (in nonbonded form) and the agent in the esterification reaction with PVA are also supported by theoretical calculations of TOC, as a contribution of LA present in the given substrate. This TOC calculation is shown as a dashed vertical line in Figure 8. As can be seen, with increasing content of LA it evidently exceeds the values of B_{MAX} in the first phase. This can mean that the first phase represents only biodegradation of nonbonded

Table II. Kinetic constants of first-order equation describing biodegradation course of PVA and PVALA polymer films

Sample index	B_{MAX} [%]		$-k$ [h^{-1}]		t_{LAG} [h]	
	1st phase	2nd phase	1st phase	2nd phase	1st phase	2nd phase
PVA	—	98.33	—	0.033	—	77.86
PVALA10	10.21	101.8	0.059	0.021	0	60.03
PVALA20	15.48	98.19	0.065	0.025	0	65.24
PVALA30	18.76	102.3	0.078	0.016	0	54.199
PVALA40	22.94	103.8	0.079	0.015	0	44.72
PVALA50	25.58	107.2	0.091	0.013	0	45.64

LA, and the rest may be grafted on the backbone chain of the polymer. This could cause the changes of kinetic constants in the second phase (Table II), where the rate constant ($-k$) gradually decreases with rising content of LA in the system. The shortening of lag phase, t_{LAG} (more than 30 hours for PVALA50 in comparison with pure PVA), can also provide evidence of the chemical reaction between PVA and LA as a result of the presence of new centers available for possible microbial attacks. However, the influence of the first phase cannot be excluded.

CONCLUSIONS

The aim of this work was the preparation and characterization of a new polymeric film for possible medical or packaging applications. For this purpose, chemical compounding of biodegradable poly (vinyl alcohol) and lactic acid (LA), an agent with antibacterial properties, was used.

The structural characteristics provided by Fourier-transform infrared spectroscopy reveal a possible chemical reaction (esterification) between PVA and part of LA; this hypothesis was supported by thermogravimetry with subsequent analysis of evolved gases. However, we also suppose that the preponderant part of LA works as a plasticizer. Thus, the compounding of PVA and LA yields a flexible material with significantly increased strain at break in comparison with unmodified PVA film. The assumption of the role of LA as a plasticizer is proved by the results from glass transition temperature determination (DSC).

The prepared films show good bacteriostatic properties against pathogenic bacterial species *Staphylococcus epidermis*, *Micrococcus sp.*, and *Pseudomonas putida*, which could be utilized in medical applications and also in protective packaging. The latter use demands environmental compatibility of the packaging material after its useful lifetime. Generally, the research has shown that the total biodegradation of samples is not influenced by LA and complete decomposition is reached within 250 hours in all cases. A different course is, however, observed due to the introduction of LA into the compounds. The biodegradation of mixtures containing PVA and LA evidently proceeds in two phases. Low-molecular LA is degraded preferentially in the first and the LA-grafted polymer in the second phase.

In addition to improvement of the material properties, the use of LA for modification of polymers also has other advantages: LA is easily available from renewable sources or from dairy waste, which is convenient from the environmental point of view, and its preparation can be relatively undemanding from the economic point of view.

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