Dariusz Wawro,
Janusz Kazimierczak

Institute of Biopolymers and Chemical Fibres,
Member of EPNOE,
European Polysaccharide Network of Excellence,
www.epnoe.eu
ul. M. Skłodowskiej-Curie 19/27
90-570 Łódź, Poland
E-mail: dwawro@ibwch.lodz.pl

Forming Conditions and Mechanical Properties of Potato Starch Films

Abstract
Presented herein are the results of investigations into the preparation of starch solutions and casting of film thereof. It was found that a dissolving temperature of 95 °C, time of 60 minutes, and the use of a special agitator system allowed a homogeneous starch solution suitable for film casting to be prepared. Aqueous solutions of commercial starch at up to 25.81% concentration are suitable for the preparation of film. The impact of minerals contained in water on the viscosity of the starch solution and the mechanical properties of the resulting film were examined. The dynamic viscosity of the aqueous starch solutions was in the range of 2.15 to 28.1 Pas at 89 °C. It was shown that water with a high mineral content is highly suitable for the preparation of starch aqueous solutions with lowered viscosity. The increase in relative humidity of the air results in a decrease in mechanical strength and increase in elongation at maximal stress of the film. The prepared starch film was characterised by the following parameter ranges: thickness of 20-149 μm, strength of 24.8-51.8 MPa, and elongation at maximal stress of 3.7-7.4%.

Key words: *potato starch, aqueous solutions, film, mechanical properties, moisture sorption, molecular characteristics.*

Introduction

The expansion of the food industry has led to an increase in demand for novel packaging materials. Crude oil-based and nature-derived materials are commonly used, but their advantages are encumbered with imperfections. Synthetic wrappings are not biodegradable, and therefore need to be utilisedreused or recycled. The packaging materials of natural polymers are practically all made of cellulose pulp as paper or cellophane, which are more expensive than the synthetics, and their manufacture causes serious environmental problems.

It is therefore a challenge to prepare new technologies for the manufacture of biodegradable, compostable film derived from natural renewable resources. Potato starch with defined properties may be regarded as the main component of such film. The relatively cheap starch is usually made of potato in Poland. It is used mainly by the food industry, although consumption is increasing in other industry sectors: paper, pharmaceuticals, cosmetics, and textiles.

For many years, research has been conducted aimed at investigating the suitability of starch and its derivatives such as esters and ethers for the preparation of starch film from solutions [1-7].

Methods of producing films of potato- or maize-derived thermoplastic starch (TPS) blended with starch derivatives or other polymers are also known. The film is directly cast from the polymer mixture by extrusion. Investigation in that direction is also being carried out in Poland [8, 9].

At the Institute of Biopolymers and Chemical Fibres, research is continuing into the preparation of film using enzyme-modified potato starch with a high content of the amylose component and film based on modified cellulose [10-14].

The objective of the present work was to define the suitability of the local (Polish) potato starch for the manufacture of film as a potential packaging material for alimentary products. The investigation was focused on the selection of the best conditions for preparing aqueous starch solutions, forming the film, and defining the mechanical and sorption properties of the obtained product.

Materials and reagents

Superior grade potato starch made by Potato Starch Works in Trzemeszno, Poland, was used in the investigations. It is characterised by a moisture content of 16.8%, pH of 7.5, and ash content of 0.13%. The producer recommends the material for uses in the alimentary, paper, pharmaceutical, textile, and mining industries.

On investigating the starch solutions, much attention was given to the properties of water used as a starch solvent. Water with varying contents of mineral components, electrical conductivities, and pH levels was used.

The following reagents were used: glycerol, ethanol, and dimethylsulfoxide (DMSO), all delivered by POCh (a Polish producer of reagents), and potassium iodide and iodine by Sigma.

Methodology

Preparation of aqueous solutions of starch

Aqueous solutions of starch were prepared with concentrations in the range of 5 to 25.81%. The weighed amount of starch was introduced into a mixing tank with a small amount of water with vigorous agitation, and then the remaining portion of water was added at 20 °C. The mixing tank was equipped with a special agitating system composed of a band stirrer running at 120 rpm and three stirrers running at 900 rpm counter-wise to the band agitator. The starch was dissolved for 15 to 60 minutes at 20 to 95 °C. Starch solutions were obtained which still contained some small amounts of undissolved starch granule fragments but were, however, suitable for forming film.

Formation of the film

The formation of film was accomplished at laboratory scale by casting the aqueous starch solution at 95 °C onto a heated flat surface. To provide a uniform thickness of the prepared film, the cast solution was spread by means of a prototype casting slot knife. The slot's height was controllable in the range of 0.2 to 1.4 mm. The

Wawro D., Kazimierczak J.; Forming Conditions and Mechanical Properties of Potato Starch Films.
FIBRES & TEXTILES in Eastern Europe January / December / B 2008, Vol. 16, No. 6 (71) pp. 106-112.

film was dried afterwards for 10 minutes to 24 hours at 20 to 100 °C and relative air humidity varying from 50 to 95%. After conditioning under assumed conditions, the film samples obtained were analysed to determine their mechanical properties, water sorption, and molecular structure.

Analytical methods

Amylose content of the starch

Colorimetric analysis with iodine to determine the amylose content was performed according to the method of McGrance et al. [15]. Iodine solution in potassium iodide was added to starch solution in DMSO, and absorbance was measured at a wavelength of 600 nm. The amylose content was determined from a standard curve prepared for amylose/amylopectin blends containing 25, 50, 75, and 100% amylose.

Distribution of the molecular weight of starch in the raw material and in the starch film by Gel Permeation Chromatography/Size Exclusion Chromatography (GPC/SEC)

The description of the GPC/SEC system and the parameters of the chromatography analysis can be found in [10]. The sample for the GPC/SEC analysis is made by preparing a dimethylacetamide (DMAc) solution of starch, which is then activated in a microwave oven. Dry lithium chloride is added to the mixture, which is then heated for 5 minutes at 70 °C and then agitated for 5 minutes and left for about 2 days to dissolve the starch. 1 ml of the prepared solution is diluted with DMAc to a volume of 10 ml to obtain 0.9 mg/ml of starch concentration in 0.8% of LiCl solution in DMAc. Prior to analysis, the solution is filtered through a 0.5 μm pore size filter.

Microscopic inspection of the aqueous starch solutions

Photographs were taken of the wet starch grains and aqueous starch solutions using a PZO (Polish Optical Works Co.) Biolar polarising microscope equipped with a camera and IMAL computer image analyser.

Dynamic viscosity of the aqueous starch solutions

The dynamic viscosity of the aqueous starch solutions was measured by means of a Brookfield LVT rotation viscometer.

Specific electrical conductance of the starch aqueous solutions

Direct measurements of the specific electrical conductance of the aqueous solutions were made with the use of the EC 214 stationary conductometer made by Hanna Instruments.

pH of water and aqueous starch suspension

The pH of water and aqueous starch suspension was measured by means of a METTLER TOLEDO pH-meter.

Scanning electron microscopy (SEM/ESEM) of the starch film

The Quanta 200 (W) scanning electron microscope produced by FEI Co. USA was used for the inspection of the cross-section and surface of the prepared starch film.

Moisture absorption and desorption by the starch film

The moisture absorption was measured in a desiccator at a relative humidity (RH) of 65% (NH_4NO_3) and ambient temperature with film samples dried to a constant weight. The moisture absorption was controlled by measuring the mass of the sample as a time function. On attaining a constant mass level, the film samples were transferred to a desiccator with 93% RH (KN03) and the time-dependent mass change was estimated. On attaining a constant mass level, the samples were again placed in the 65% RH desiccator to determine the moisture de-sorption of the tested material.

Mechanical properties of the starch film

The mechanical properties of the starch film were estimated according to appropriate standards:

- thickness of the film: PN-EN ISO 4593:1999
- mechanical properties: strength and elongation at maximal stress according to PN-EN ISO 527-3:1998

The film samples were tested on the Instron 5544 tensile tester. The tested film samples were 10 mm in length and 15 mm wide, and the elongation rate was 10 mm/min. For selected samples, the elastic modulus and tear strength were tested according to PN-EN ISO 6383-12005. All mechanical testing was carried out in an air-conditioned room at 65 ± 4% RH and 20 ± 2 °C, and for some selected samples additionally at 50 ± 5% RH and 23 ± 1 °C and at 100% RH and 20 ± 2 °C. Testing in "wet conditions" was performed for some samples. For this purpose, prior to testing, the film samples were immersed in water for 60 seconds after conditioning at 65 ± 4% RH and 20 ± 2 °C.

Research results and comments

Selection of starch and water for the preparation of film

The starch for the preparation of film was selected based on the authors' own experience and recommendations of companies producing food additives. The authors aimed to employ easily available cheap commercial food products for which adequate certificates could be presented. Potato starch was chosen as the basic material for the preparation of film.

For several years there has been an increasing interest in starch with high amylose content. This is explained by the valuable properties of the polymer such as its ability to form a strong water-resistant film, its ability to form thermoreversible gels easily, and its ability to thicken, its adhesiveness, and moreover the possibility of using it in food products [16-18].

Potato starch is one of the cheapest and most widely available products in Poland. In ***Table 1*** some properties of the native starch used in the research are presented.

As can be seen from the data in ***Table 1***, the starch used in the investigations was characterised by a high amylose content of 28.6% and weighed average molecular weight M_w = 1295 kDa, figures which promise suitability for the formation of film with good mechanical properties.

Table 1. *Selected properties of the native potato starch.*

Parameter	Unit	Volume
Amylose content	%	28.6
Amylopectin content	%	71.4
Humidity	%	16.6
pH of the aqueous extract	–	6.3
Number average molecular weight, $\bar{M}n$	kDa	272
Weight average molecular weight, $\bar{M}w$	kDa	1295
Polydispersion, Pd	–	4.8

Table 2. *Conditions for preparing the starch solutions.*

No	cations, mg/dm^3				anions, mg/dm^3				Total content of mineral components	Electrical conductance at 25 °C	pH	pH/temp of aqueous starch dispersion	Dynamic viscosity/ temperature
	calcium Ca++	magnesium Mg++	sodium Na+	potassium K+	Hydroxyy/ carbonate	chlorides Cl –	fluoride F –	sulfate	mg/dm^3	mS/cm			mPas/°C
1	114.50	23.10	12.7	5.40	488.1	8.5	0.30	–	709	678	7.39	6.86/–	2475/89
2	32.99	4.56	9.8	–	119.61	2.33	0.02	–	194.19	206	7.06	6.54/17.9	4850/89
3	49.10	3.64	1.9	0.80	146.5	6.3	0.10	14	238.74	270	7.78	6.44/17.2	3600/89
4	314.63	26.75	11.3	2.66	1083.1	3.55	0.18	–	1501.43	1254	5.71	5.71/17.6	2150/89
5	174.10	62.60	950.0	14.80	470.4	1659.2	0.86	55.0	3416.58	5440	6.30	6.15/23	–
6	120.70	10.40	–	–	331.4	41.7	0.15	82.4	586.75	703	7.36	6.79/17.6	4000/89
7[a)]	–	–	–	–	–	–	–	–	–	13.5	7.06	6.56/15.8	8150/89

Dissolving time 60 min at 95 °C; a) – demi water; 13.9% – starch concentration in solution.

Attention was given to the impact of the mineral components contained in the water used as a solvent on the properties of the starch solutions. The mineral component content and pH of the water used were varied (see ***Table 2***).

Preparation of the aqueous starch solutions

The structure of starch undergoes destruction under the influence of heating or processing with aqueous solutions of reagents, which cause disintegration of the crystalline areas and breaking of hydrogen bonds.

Aqueous starch solutions at 13.6 to 25.8% concentration were prepared for the investigations. For technological reasons, it is advisable to have the concentration of starch as high as possible. The solutions were prepared using prototype specialised equipment. The maximal starch concentration was assumed to be 26%. Potato starch with 28.6% amylose content and water with varied mineral component contents, pH levels, and electrical conductances were used. The water used to dissolve the starch was at ambient temperature, which enables satisfactory wetting of the starch granules. The time needed to attain the temperature of 95 °C was in the range of 60 to 70 minutes. After attaining that temperature, the dissolving was continued for 15 to 60 minutes. The increase in the starch concentration makes the solution prone to gelatinisation, particularly at low temperatures, causing a technological problem of unstable film casting. During attempts to prepare solutions with starch concentrations exceeding 25.8%, the solution began to rise up the agitator shaft due to high viscosity. The result was insufficient stirring and uneven temperature of the solution, and, ultimately, deterioration in the solution quality.

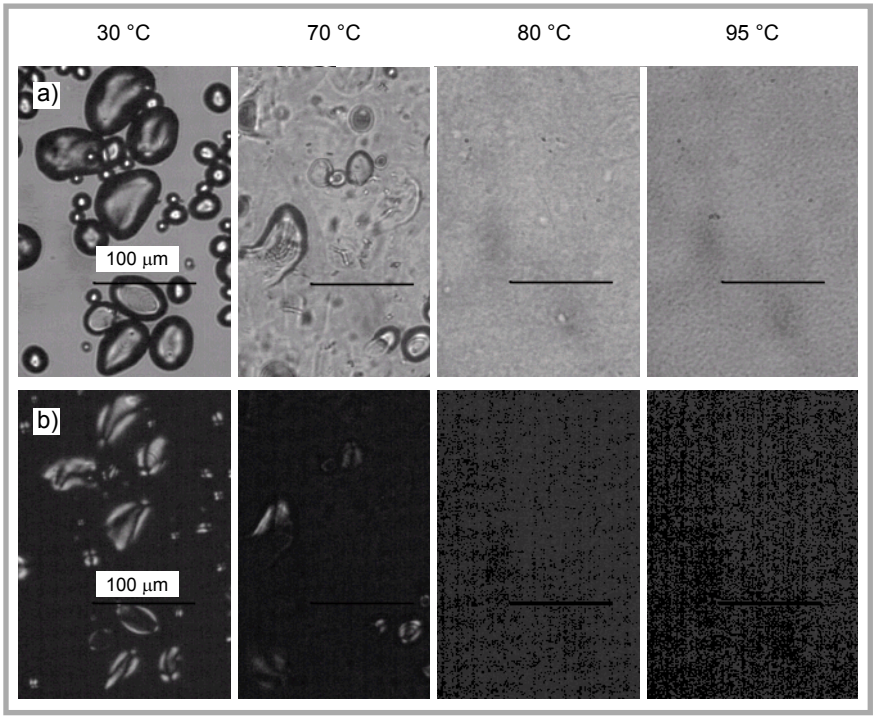

Figure 1. *Microscopic photographs of an aqueous starch solution showing the influence of temperature on the dissolving of starch in water. Starch concentration: 13.86%. Photographs taken in: a) normal light; b) polarised light.*

Impact of the temperature on the process of dissolving starch in water

It is well known that temperature is one of the most important factors influencing the dissolving of starch in water. The gelatinisation temperature of starch can be determined by DSC analysis. Above that temperature, starch begins to dissolve. In these investigations the influence of temperature on the dissolving was observed by means of an optical microscope. For technological reasons it is important to find the temperature at which a homogenous solution free of air bubbles with adequate viscosity can be prepared that is suitable for smooth formation of the film. Microscopic photos of the starch solution during the dissolving process are shown in ***Figure 1***. The starch concentration in the solution was 13.83% and the time taken to reach 95 °C was 60 minutes. The water used for the solution was characterised by a mineral component content of 709 mg/l, a pH of 7.4, and a specific electrical conductance of 678 μS/cm. The photographs were taken in both normal and polarised light.

The dimensions of the starch granules, as seen in ***Figure 1***, range from several micrometers to several tens of micrometers. The dissolution of the granules proceeds with increasing temperature and time. The decreasing amount of starch granules can be seen in the polarised light. At 70 °C a rapid decrease is observed in the

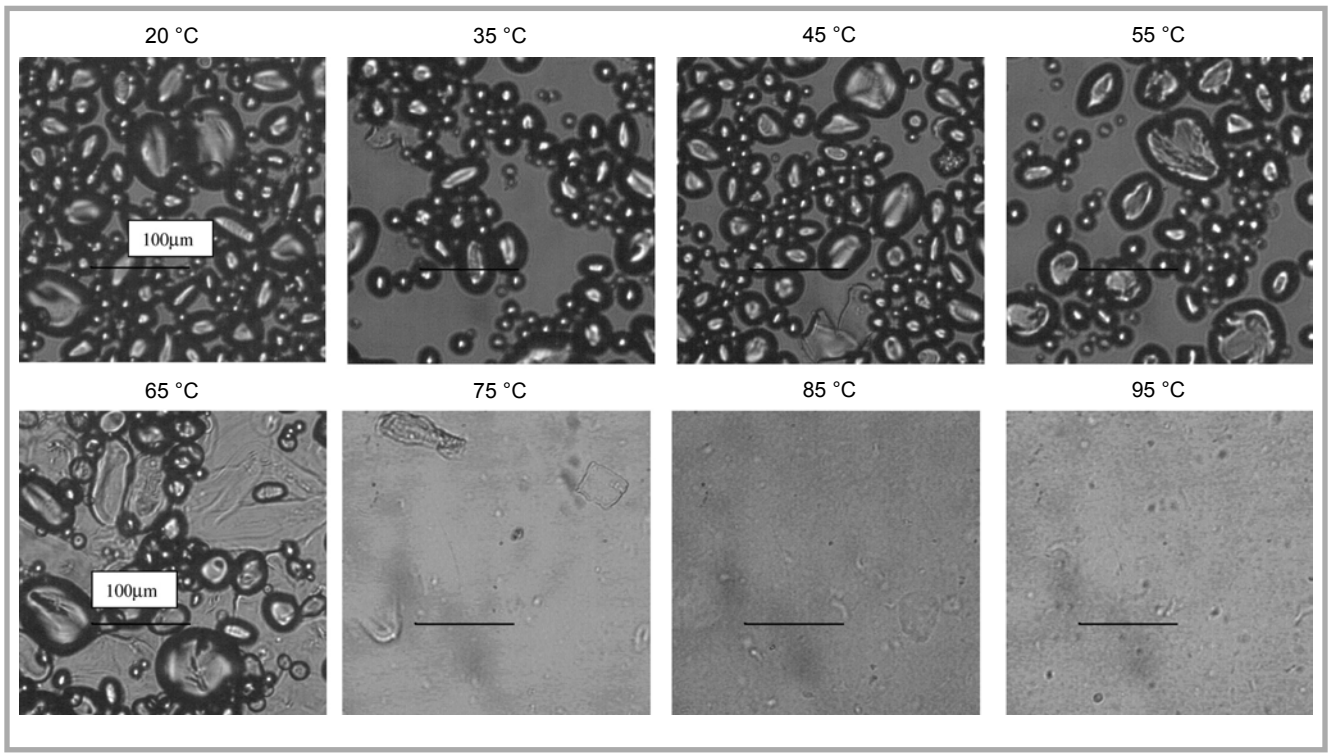

Figure 2. *Microscopic photographs of an aqueous starch solution (starch concentration: 25.81%) showing the influence of temperature on the dissolving process.*

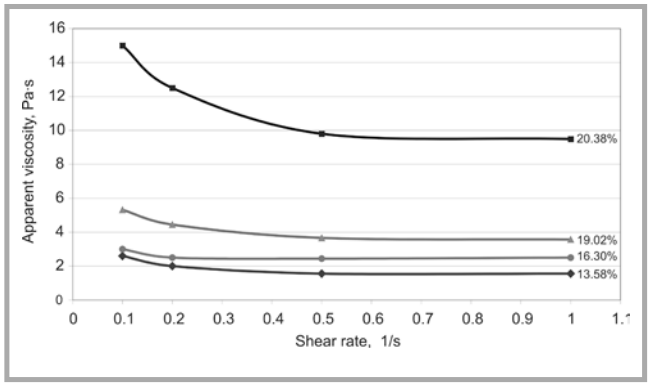

Figure 3. *Influence of the shearing rate on the dynamic viscosity of aqueous starch solution at 89 °C.*

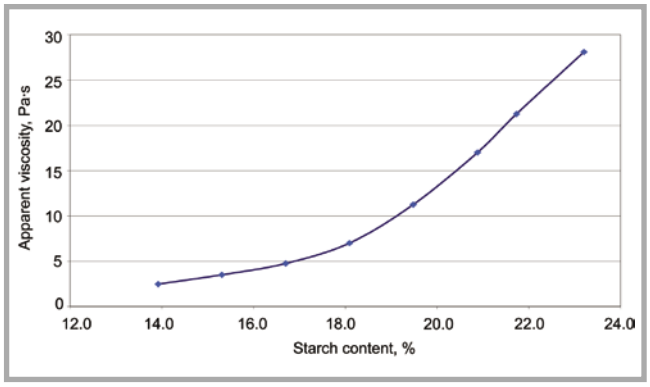

Figure 4. *The influence of starch concentration on the apparent viscosity of aqueous starch solutions; water with total mineral component content of 709 mg/l, electrical conductance of 678 µS/cm, and a pH of 7.39.*

amount of objects shining in polarised light, which is evidence of the presence of high crystalline areas. In the normal light, fragments of the outer walls of the granules and swollen granules are visible. On reaching 80 °C, the solution becomes clear and optically pure.

Microscopic photographs of the solution during dissolving in water with the same characteristics but at a starch concentration of 25.81% are presented in ***Figure 2*** for comparison. As can be seen, the influence of temperature on the dissolving process is close to that which occurred with the solution at 13.86% concentration. Hence, it may be concluded that in the examined range of concentrations, temperature appears to be the crucial parameter governing the dissolution of starch in water. The solutions obtained are suitable for the casting of film.

Dynamic viscosity of the aqueous starch solutions

Aqueous solutions of starch with concentrations of 13.58%, 16.30%, 19.02%, and 20.38% were prepared for the estimation of dynamic viscosity. The water used for the dissolution was characterised by a mineral component content of 709 mg/l, a pH of 7.4, and an electrical conductance of 678 µS/cm. Dissolution was carried out for 60 minutes at 95 °C. ***Figure 3*** shows the impact of the shear rate on the change in dynamic viscosity measured at 89 °C. From the shapes of the curves presented in ***Figure 3***, it is clear that an insignificant increase in the apparent dynamic viscosity by 3 Pas occurs with the increase in concentration in the range of 13-19%. With a further increase in concentration by 1%, there is a distinct increase in the apparent dynamic viscosity by 10 Pas. The shape of the curve is typical of liquid polymers. In the case of the solutions with the highest starch concentrations, an evident decrease in the apparent dynamic viscosity can be observed in the range of low shearing rates. A further increase in concentration to 23.20% is correlated with an increase in the dynamic viscosity to 28 Pas (see ***Figure 4***).

Impact of the varying concentration of mineral components in water on the properties of the aqueous starch solutions

Starch solutions were prepared with 13.9% concentration. The conditions in which the solutions were prepared are shown in ***Table 2***.

From the data in ***Table 2*** it may be concluded that the mineral component content of the water displays a distinct impact on the solution viscosity. With the water containing a mineral component content of 1,501.43 mg/l in total and a lowest pH of 5.71, a distinctly lower apparent dynamic viscosity was attained than that attained when the solution was prepared with demineralised water.

Considering the essential influence of the water mineral components on the viscosity of starch solutions, water with a higher mineral component content amounting to 3,416.58 mg/l was used. The conductance of the water was 5,440 µS/cm and the pH was 6.30.

Casting of film from the starch solutions

The formation of film from aqueous starch solutions at laboratory scale is a rather simple procedure consisting of the evaporation of surplus water from a solution layer spread on a flat surface. The aim of the work was to determine the conditions in which the film solidifies attaining adequate mechanical properties. Aqueous starch solutions with concentrations in the range of 15.29 to 23.63% were used in the investigations. The water used for dissolving contained 709 mg/l of mineral components, the conductance of the water was 678 µS/cm, and the pH was 7.39. Attention was paid to the film thickness, which is closely related to the amount of water to be evaporated. A prototype casting knife with a variable slot was prepared in order to spread the solution evenly. The drying temperature and air humidity, as well as the surface on which the solution was cast, were controlled.

From the results presented in ***Table 3***, it can be seen that the film obtained has a strength in the range of 24.8 to 46.7 MPa and elongation at maximal stress from 3.95 to 9.52%. It was found that among the range of investigations conducted, the starch concentration of the solution does not influence the mechanical properties of the prepared film. The highest coefficients of variations of thickness and of breaking force were found for the film with a thickness of 0.02 mm. Drying of the formed film at 60 °C for about 10 minutes gives a high strength to the film having a thickness of 0.028 mm.

Next, the molecular structures of film samples prepared from the starch solutions with varying concentrations were investigated. ***Figure 5*** presents the distribution curves of the molecular weights of the film samples. Water used for the dissolution was characterised by a mineral component content of 709 mg/l, a pH of 7.39, and specific electrical conductance of 678 µS/cm. Dissolving was carried out for 15 minutes at 95 °C.

Table 3. *Forming conditions and mechanical properties of starch film.*

Concentration	Drying time of the film	Temperature/ RH during the drying of film	Testing conducted in conditioned state 20 °C, 65+ 4%						
			Film thickness	Thickness coefficient of variation	Max. breaking force	Breaking force coefficient of variation	Strength	Elongation at max stress	Elongation coefficient of variation
%	h.	°C/%	mm	%	N	%	MPa	%	%
15.29	20	19/60	0.072	8.18	49.7	10.3	46.7	7.15	12.9
			0.100	3.81	64.8	4.88	43.2	9.36	10.2
			0.075	4.95	42.0	9.63	37.5	7.31	26.4
16.68	20	20/50	0.074	15.2	48.0	20.4	43.7	6.49	31.8
			0.106	7.81	69.6	4.15	44.2	9.01	14.0
18.07	20	20/50	0.024	37.1	10.2	38.8	29.2	3.95	41.2
			0.063	5.96	37.8	3.50	39.9	6.07	14.6
	10 min	60/50	0.028	37.0	17.8	30.4	42.4	5.54	13.2
19.46	20	19/50	0.083	6.21	53.7	6.07	43.4	7.78	26.8
			0.067	6.93	42.1	14.1	42.0	6.35	10.7
	10 min	60/50	0.140	2.26	70.1	13.9	33.4	8.49	19.1
23.63	20	19/50	0.020	21.8	7.7	49.1	24.8	4.31	59.4
			0.078	6.32	51.1	5.57	44.0	9.52	13.8

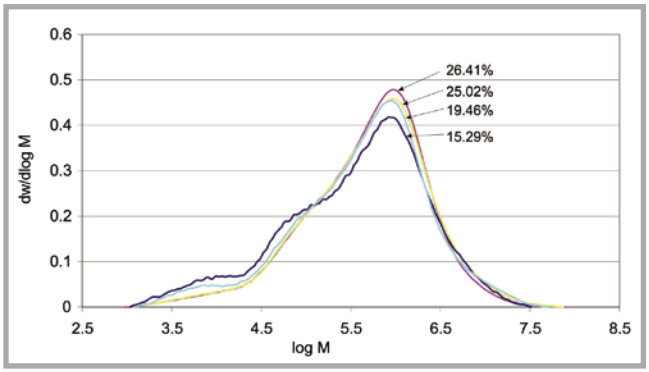

Figure 5. *Function of molecular weight distribution of starch film formed from solutions with varying concentrations.*

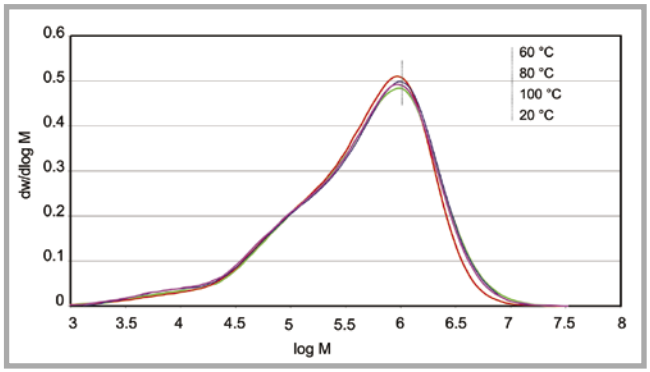

Figure 6. *Function of molecular weight distribution in starch film samples dried at varying temperatures.*

It was found that during the dissolving of starch in water its molecular characteristics undergo changes as the result of hydrolysis. The lower the concentration of starch in the solution, the greater the extent of the changes.
In the forming of the starch film, much attention was given to the impact of drying temperature and time. Since estimation of the humidity content of the film in the course of its formation is rather difficult, further drying of the film was needed. In the selected drying temperature range the impacts of the temperature on hygroscopicity, water absorption, and molecular changes of the starch were examined. Film prepared from a solution with a starch concentration of 15.31% was selected for the investigations.

Figure 6 (see page 111) presents the molecular weight distribution curves for starch films dried at 20, 60, 80, and 100 °C. Drying in the range of 60 to 100 °C for 15 minutes does not cause profound changes in the molecular characteristics, which is confirmed by the overlapping of the curves in ***Figure 6***.

Moisture sorption and desorption of the starch film

Starch film samples dried at 20, 60, 80, and 100 °C were examined with respect to water sorption and desorption according to the method described in the analytical methods chapter.

The moisture sorption proceeding at 65% air RH attained a maximum of 20%, after which the samples were placed in a desiccator at 93% RH, resulting in an increase in the moisture sorption to the range of 30-35%. The highest sorption of about 35% was found for samples dried at 80%, while those dried at 69% absorbed only about 30%. After a desorption at 65% RH, the humidity sorption of the film samples was about 30%, except for the samples dried at the ambient temperature, which showed a mere 20%.

Mechanical properties of the starch film

Considering the hygroscopic properties of starch and the film made thereof, care must be taken with regard to the air RH under which the testing is conducted. The mechanical properties were tested at 50, 65, and 100% RH and in "wet conditions". Besides the main properties, namely thickness, strength, and elongation at maximum stress, two other parameters, elasticity modulus and tear strength, were tested according to the methods described. The results are presented in ***Figures 7-10***. Testing was carried out with the film prepared of starch and water containing 3,416.58 mg/l of mineral components.

To prepare the film samples for mechanical testing, aqueous solutions of starch in water were first made with starch contents of 13.58%, 20.38%, and 25.81%. To improve the film formation and mechanical properties, glycerol was added to the solution containing 25.81% of starch as a plasticiser, with the amount of glycerol being 16.23% of the starch content.

From the results presented in ***Figure 7*** it was concluded that the film made of the solutions with 13.58% and 20.38% starch is characterised by a strength of about 50 MPa at 50% air RH.

The strength of the film made of the solution with the highest starch concentration containing glycerol was at the lower level of 35 MPa at 50 and 60% RH. The air RH exerts a distinct influence on the strength of the film: at 100% RH and in "wet conditions" the strength is as low as 10 MPa.

Figure 8 presents the influence of the air RH on the elongation of the starch film at maximum stress. The least elongation characterises the film samples tested at

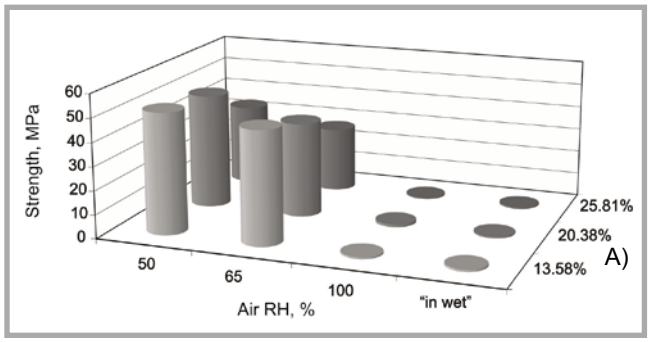

Figure 7. *Impact of air RH on the strength of starch film; A) per cent of starch in the spinning solution.*

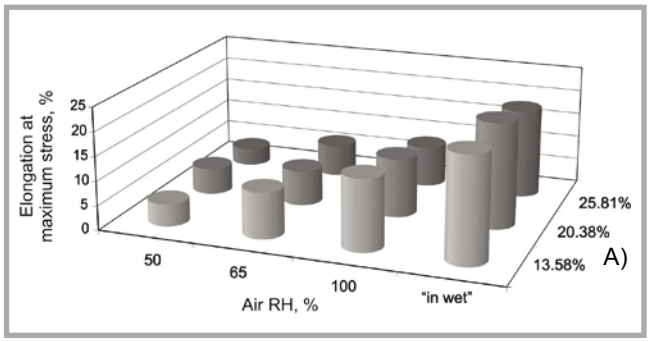

Figure 8. *Influence of air RH on the elongation of starch film at maximum stress; A) per cent of starch in the spinning solution.*

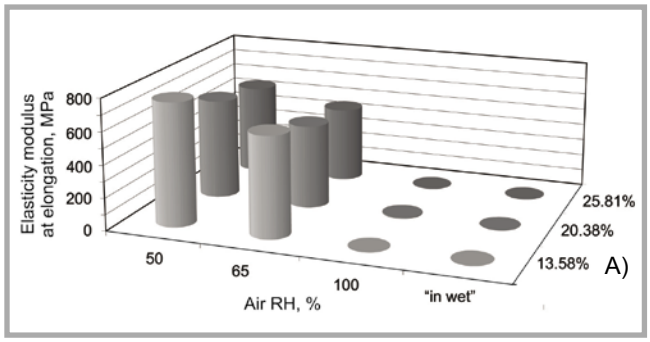

Figure 9. *Influence of air RH on the elasticity modulus at elongation of starch film; A) per cent of starch in the spinning solution.*

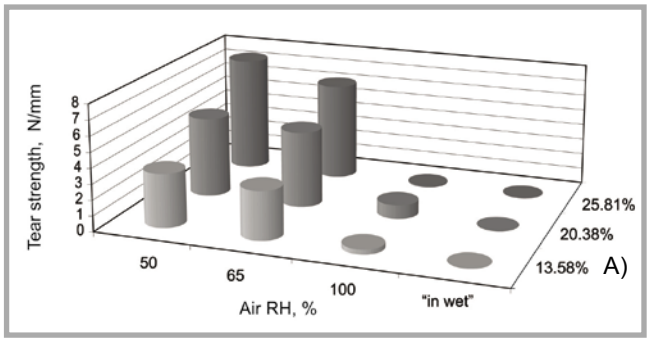

Figure 10. *Influence of air RH on the tear strength of starch film; A) per cent of starch in the spinning solution.*

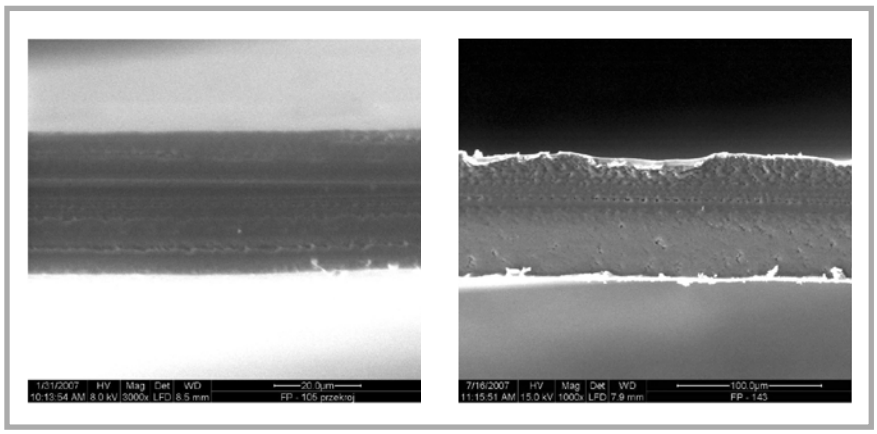

Figure 11. *SEM photographs of cross-sections of starch film cast from solutions: a) at 15.31% starch concentration; b) at 20.38% starch concentration.*

50% RH while at higher RH the elongation increases. The greatest elongation of 23% appears for film samples tested at 100% RH and in "wet conditions". Virtually no influence could be observed of the glycerol on the change in elongation of the starch film (25.81%).

The impact of the air RH upon the elasticity modulus was also examined. From the results shown in ***Figure 9*** it is seen that the highest elasticity values were found at 50% RH, and that the modulus decreases with increasing RH. In "wet conditions" the elasticity modulus was zero.

Based on the results presented in ***Figure 10*** it could be stated that the highest tear strength was found for the film made of the solution with the highest starch concentration (25.81%) at 50% air RH. The presence of glycerol did not cause any decrease in the tear strength at 50 and 65% RH.

However, a distinct influence of the RH on the strength of the glycerol-containing film can be seen: with increasing RH the tear strength drops dramatically. At 100% RH and in "wet conditions" the tear strength amounts to only 1.0 N/mm.

Figure 11 shows SEM photographs of starch films cast from starch solutions with different starch concentrations.

As can be seen, the film formed from the 15.31% solution is more homogeneous, compact, and without structural defects or pores when compared with the film cast from the 20.39% solution. The increase in the starch concentration of the solution exerts an evident effect on the film structure and, hence, on its mechanical properties.

Summary

It was evidenced that commercial potato starch is a material that can be used in the manufacture of starch film. A methodology was elaborated for the preparation of aqueous starch solutions with concentrations in the range of 13.58 to 25.81% which are suitable for film casting. The impact of temperature on the dissolution of starch in water was examined. It was found that starch film having a strength of 50 MPa could be made of a starch solution with 20.38% concentration prepared for 60 minutes at 95 °C. The water used as a solvent was characterised by a total mineral component content of 3,416.58 mg/l, an electrical conductance of 5,440 μS/cm, and a pH of 6.30. The dynamic viscosity of the aqueous starch solution was in the range of 2.15-28.1 Pas. Water with a high mineral component content appeared to be an excellent solvent for preparing starch solutions with high concentration and low viscosity. Increases in the relative humidity of the air decrease the film strength and increase its elongation. Starch film samples 20-140 μm thick were prepared and were characterised by strength in the range of 24.8-52.8 MPa and elongation at maximum stress with a range of 3.5-7.4% at a relative humidity of the air of 50%.

Acknowledgments

The research results presented were obtained through Project No. 3 TO8E 046 28, granted by the Polish Ministry of Science and Higher Education

References

1. *Lopez O.V., Garcia M.A., Zaritzky N.E., Carbohydrate Polymers, Vol. 73, No. 4, pp. 573-581, 2008.*
2. *Patent DE 19805925, WO 9940797, 1999.*
3. *Paes S.S., Yakimets I., Mitchell J.R., Influence of gelatinization process on functional properties of cassava starch films, Food Hydrocolloids, Vol. 22, No. 5, pp. 788-797, 2008.*
4. *Koskinen M., Suorti T., Autio K., Myllarinen P., Poutanen K., Effect of pretreatment on the film forming properties of potato and barley starch dispersions, Industrial Crops & Products Vol. 5, No. 1, pp. 23-34, 1996.*
5. *Lewandowicz G., Soral-Śmietana M., Starch modification by iterated syneresis, Carbohydrate Polymers Vol. 56, No. 4, pp. 403-413, 2004.*
6. *Fortuna T., Gałkowska D., Juszczak L., Comparison of the rheology properties of selected modified starch preparations, Acta Sci. Pol. Technol. Aliment. No. 3 (1), pp. 21-32, 2004.*
7. *Jansson A., Thuvander F., Influence of thickness on the mechanical properties for starch films, Carbohydrate Polymers Vol. 56, No. 4, pp. 499-503, 2004.*
8. *Mitrus M., Glass transition temperature of thermoplastic starches, International Agrophysics, Vol. 19, No. 3, pp. 237-241, 2005.*
9. *Mitrus M., Microstructure of thermoplastic starch polymers, International Agrophysics, Vol. 20, No. 1, pp. 31-35, 2006.*
10. *Kazimierczak J., Ciechańska D., Wawro D., Guzińska K., Enzymatic modification of potato starch, Fibres & Textiles in Eastern Europe, Vol. 15, No. 2 (81), pp. 100-104, 2007.*
11. *Wawro D., Struszczyk H., Biodegradable films made on the basis of biotransformed cellulose/starch blends, Fibres & Textiles in Eastern Europe, Vol. 7, No. 2 (25), pp. 49-51, 1999*
12. *PL191454, Method of obtaining biodegradable cellulose-starch film.*
13. *Jóźwicka J., Wawro D., Starostka P., Struszczyk H., Mikołajczyk W., Manufacturing possibilities and properties of cellulose-starch fibrids, Fibres & Textiles in Eastern Europe Vol. 9, No. 4 (35), pp. 28-32, 2001.*
14. *Wawro D., Struszczyk H., Ciechańska D., Bodek A., Microfibrids from natural polymers, Fibres & Textiles in Eastern Europe, Vol. 10, No. 3 (39), pp. 22-25, 2002.*
15. *McGrance S., Cornell H.J., Rix C.J., A simple and rapid colorimetric method for the determination of amylose in starch products, Starch/Stärke Vol 50, No. 4, pp. 158-163, 1998.*
16. *Jarowienko W., Encyclopedia of polymer science and technology, Vol. 12, p. 787, 1970.*
17. *US 4,971,723 Partially debranched starches and enzymatic process for preparing the starches, 1990.*
18. *Lourdin D., Della Valle G., Colonna P., Influence of amylose content on starch films and foams, Carbohydrate Polymers, Vol. 27, No. 4, 261-270, 1995.*

Received 18.12.2008 Reviewed 20.12.2008