

## RHEOLOGICAL CHARACTERISTICS OF OXIDISED POTATO STARCH

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The aim of the work was to examine rheological behaviour and texture of gels formed by oxidised potato starch of a low degree of substitution [0.001 (SB) and 0.004 (SZ)]. Independently of gel concentration, lower oxidation of starch resulted in increased storage and loss moduli, whereas higher oxidation affected a decrease in these moduli compared to those of native starch. Rheological behaviour of 6% and 8% gels was different. The 6% gels behaved like viscoelastic fluids characterised by Herschel-Bulkey and Bingham models, whereas the 8% gels manifested behaviour of viscoelastic fluids fitted to Cross model. The influence of oxidation degree on gel texture was confirmed as well. Hardness of gels made from slightly oxidised SB and native starch was similar and always higher than that of the SZ gels. Adhesiveness of SB gels reached always the lowest values. An extremely high increase in adhesiveness was found for the 8% gel made of highly oxidised SZ. Different pasting, flow, and viscoelastic properties suggested diversified application of the oxidised potato starch examined.

### LIST OF SYMBOLS

$A_r$  – relative hysteresis area (Pa),  $A_{up}$  – area under curve at increasing shear rate (Pa),  $A_{down}$  – area under flow curve at decreasing shear rate (Pa),  $A$  – initial stress in Weltmann model (Pa),  $B$  – time coefficient of thixotropic breakdown in Weltmann model (Pa),  $K$  – structural parameter in Herschel-Bulkey and Bingham models (Pa s),  $T$  – temperature (°C),  $t$  – time (s),  $k$  – structural parameter in Cross equation (-),  $n$  – flow behaviour index (-),  $G'$  – storage modulus (Pa),  $G''$  – loss modulus (Pa),  $S$  – area of the thixotropy hysteresis loop – CR mode (Pa/s),  $\omega$  – angular velocity (rad/s),  $\gamma$  – shear rate ( $s^{-1}$ ),  $\tau$  – shear stress (Pa),  $\tau_0$  – yield stress (Pa),  $\eta_0$  – viscosity at  $\gamma = 0$  (Pas),  $\eta_\infty$  – viscosity at  $\gamma \rightarrow \infty$  (Pas),  $\eta_p$  – apparent viscosity (Pas), and  $\eta^*$  – complex viscosity (Pas).

### INTRODUCTION

Oxidised starch is produced by starch reaction with a specified amount of an oxidising reagent under controlled temperature and pH. Among a variety of oxidising reagents sodium hypochlorite is the oldest and most popular commercial oxidant. Hydroxyl groups on starch molecules are first oxidised to carbonyl groups and then to carboxyl groups. Therefore, the number of carboxyl and carbonyl groups on oxidised starch indicates the level of oxidation [Kuakpetoon & Wang, 2001; Li & Vasanthan, 2003]. The oxidised starch granules remain intact and possess the pure B-type pattern of crystallinity which is typical of potato starch granules

[Lewandowicz *et al.*, 2003; Manelius *et al.*, 2000]. However, by introducing carbonyl and carboxyl groups, oxidation results in lower gel viscosity and minimises retrogradation of amylose [Morikawa & Nishinari, 2000].

Popular oxidised starches of higher oxidation degree (even above 1%) are produced mainly for the paper and textile industry. Nowadays, the application of slightly oxidised starches in the food industry is increasing because of its low viscosity, high stability, clarity, film forming and binding properties. In Poland for many years the basic food grade modified starch was the oxidised starch, especially that of a low degree of substitution [Walkowski *et al.*, 2004]. According to the Polish Standards, the quality of jellies and puddings, which are the most popular products with the addition of oxidised starch, is now evaluated by sensory methods and the classification made even by experienced experts is subjective [Lewandowicz *et al.*, 2003]. The objective, standardised, instrumental method for industrial evaluation of such products quality should be developed. In the first stage of studies, the numerical expression of characteristics of oxidised starch gels has to be established.

The influence of oxidation on the chemical structure of potato starch has already been deeply recognised [Zhu & Bertoft, 1997; Zhu *et al.*, 1998] but only few works have discussed rheological properties of high oxidised potato starch [Manelius *et al.*, 2000, Morikawa & Nishinari, 2000]. Among physicochemical properties of starch gels the most important characteristics is rheological behaviour during and after gelatinisation, which gives the proper features as viscosity,

consistency or texture to the final product. The rheological behaviour of oxidised starches of other origin has been widely studied [Autio *et al.*, 1996; Li & Vasanathan, 2003], thus the presented results can be a good pattern for planning and discussing the experiments with oxidised potato starch. First of all, fluid behaviour in steady shear flow at constant or changing temperature and time and rheological structure of gels are studied [Parker & Ring, 2001]. Generally, gelatinised native starch dispersions demonstrate a non-Newtonian, time-dependent and viscoelastic behaviour. Although their rheological properties are highly dependent on the gelatinisation procedure they are usually represented by power law or Herschel-Bulkey model in the wide range of shear rate [Hoover, 2001; Larrigue & Alvarez, 2001]. Yet, other models, such as Bingham plastic or Casson, and even a linear model have also been postulated [Larrigue & Alvarez, 2001]. Time dependence of starch gels using typical rheological tests, *i.e.* relaxation and creep and shear stress decay, has also been widely studied [Larrigue & Alvarez, 2001; Nguyen *et al.*, 1998]. The structure of starch gels was characterised by oscillatory testing as an almost non-destructive method [Larrigue & Alvarez, 2001; Morikawa & Nishinari, 2000; Ortega-Ojeda *et al.*, 2004; Rosalina & Bhattacharya, 2002]. Quite a large number of existing versions of procedures mentioned above allows to evaluate comprehensively rheological behaviour of potato oxidised starch, thus enabling the production of oxidised starch of required physicochemical characteristics.

The aim of this work was to determine the influence of oxidation degree on the texture and rheological properties of gelatinised suspensions of oxidised potato starch.

## MATERIAL AND METHODS

**Material.** Commercial starch preparations with 0.03% (SB) and 0.11% (SZ) content of carboxyl groups produced in Poland (WPPZ S.A., Luboń) from native potato starch (SN) were examined. Rheological characteristics of all starches was carried out at 6% and 8% w/w concentrations which are used for the production of puddings and jellies, respectively. Further in the text, the samples of 6% and 8% concentration were referred to as: SN6, SB6, and SZ6 and SN8, SB8, and SZ8, respectively.

**Methods.** The degree of substitution of carboxyl groups in oxidised potato starch preparations was determined according to the FAO committee (Joint Expert Committee on Food Additive) recommendations [FAO Food and Nutrition, 1997]. The method consists in the conversion of carboxyl groups into the acidic form with 0.1 mol/L hydrochloric acid, washing with distilled water till complete removal of the chloride anion, and titration with 0.1 mol/L sodium hydroxide.

Gelatinisation was monitored using a Brabender viscosograph for 6% starch suspensions under the following conditions: measuring cartridge 0.07 Nm, heating/cooling rate 1.5°C/min, and thermostating time 30 min.

The 6% and 8% (w/w) suspensions of native (SN6 and SN8) and oxidised (SB6, SB8 and SZ6, SZ8) potato starch in water were heated over pasting temperature, *i.e.* 90°C, and examined after 2-h storage at room temperature. Temperature was accepted as that usually used in dessert home cooking.

The rheological studies were carried out in a RheoStress 1

(ThermoHaake, Germany) using a cone-plate device (diameter 35 mm, cone angle 2°, minimal gap 0.105 mm) monitored by a RheoWin RS1 Software (Haake, Germany). The samples were allowed to rest for 10 min after loading, before measurement at a temperature of 20±0.5°C.

Viscoelastic behaviour of gels was measured in an oscillation mode at a frequency ranging from 1 to 10 s<sup>-1</sup> which corresponds to the radial speed from 6.28 to 62.8 rad/s, respectively. Storage modulus, G', loss modulus, G'', and complex viscosity,  $\eta^*$ , were accepted as parameters characterising changes in viscoelastic properties.

Time dependence was studied using two methods: hysteresis loop and shear stress decay. The hysteresis loop was obtained by registering shear stress at a shear rate from 1 to 120 s<sup>-1</sup> in 60 s and down in 60 s (CR mode). The percentage of relative hysteresis area [Tarrega *et al.*, 2004] was calculated according to the formula:

$$A_r = (A_{up} - A_{down})/A_{up} \times 100 \quad (1)$$

The stress decay was determined by applying a shear rate of 100 s<sup>-1</sup> for 240 min. Experimental data were fitted to the Weltmann model using the RheoWin RS1 software:

$$\sigma = A - B \ln(t) \quad (2)$$

where A is the initial shear stress and B – the time coefficient of thixotropic breakdown [Tarrega *et al.*, 2004].

Flow behaviour was determined with a controlled shear rate (CR mode) from 1 to 120 s<sup>-1</sup> after previous destroying of the structure responsible for thixotropy [Nguyen *et al.*, 1998]. Samples were presheared at a shear rate of 200 s<sup>-1</sup> for 2 h to break down material structure to equilibrium and remove the thixotropic effects.

Texture properties of the examined gels were measured using a TA-XT2 texture analyser (Stable Micro System, UK). The sample was penetrated twice with a cylindrical aluminium probe of 35 mm diameter with flat end until 25 mm was reached at the penetration speed of 1.0 mm/s. Hardness, adhesiveness, springiness, cohesiveness, and gumminess were accepted as texture parameters. Five replicates were made for each probe.

A statistical analysis of results was carried out with a Statistica ver.5 (StatSoft, USA) program [General Convention and Statistics, 1995].

## RESULTS AND DISCUSSION

The examined SB and SZ starches were characterised by a very low degree of substitution. The contents of carboxyl groups in both treated starches (Table 1) confirmed their slight oxidation, which allowed to classify them not as oxidised (E 1404) but rather as bleached starches (E 1403) [FAO Food and Nutrition, 1997].

TABLE 1. Degree of substitution in potato starch preparations.

Preparation type	Content of carboxyl groups (%)	Degree of substitution
SB	0.03	0.001
SZ	0.11	0.004

Slight oxidation processes resulted in especially significant changes of pasting characteristics of potato starch (Figure 1). The most important effect of oxidation is an increase in the final viscosity, which could indicate an increase in gelling properties. Higher oxidation of SZ starch resulted in a significant decrease of peak and final viscosity and pasting temperature. The viscosity of SZ starch was significantly lower than that of SB and native starch because of higher depolymerisation (partial rupture of glucosidic linkages) of SZ starch granules resulting in a decrease in molecular weight of molecules. The extensive depolymerisation of starch granules along with oxidation processes was also postulated by other authors [Kuakpetoon & Wang, 2001; Li & Vasanthan, 2003; Manelius *et al.*, 2000]. It resulted in weakening of paste network molecules which did not maintain the integrity during shearing.

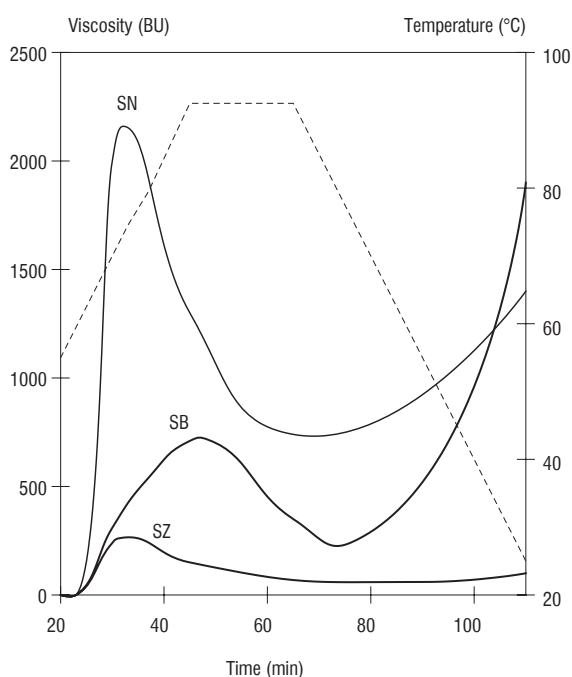


FIGURE 1. Brabender viscosity curves for 6% suspensions of native (SN) and oxidised (SB and SZ) potato starches.

Dynamic oscillatory measurements were conducted within linear viscoelastic range of the examined material. Stress amplitude sweep method, in which the applied stress was ramped from 1 to 100 Pa at an angular frequency of 6.48 rad/s (1 Hz), was used. Storage moduli were collected and plotted as a function of the stress applied. Central point on curve plateau responded to  $\tau=10$  Pa and 2 Pa for 8% and 6% gels, respectively, and these values were accepted as applied stress in the oscillatory test.

Degree of starch oxidation resulted in different changes of the viscoelastic properties of gels. Independently of starch concentration, values of storage and loss moduli for SB gels were always higher than those for SN gels, whereas these values for SZ gels were always the lowest (Figure 2). The 8% gels showed  $G'$  and  $G''$  significantly higher than 6% gels (Figure 2). Generally, the concentration dependence of the storage modulus should be influenced by the type of starch, especially by the ratio of amylose to amylopectin or concentration

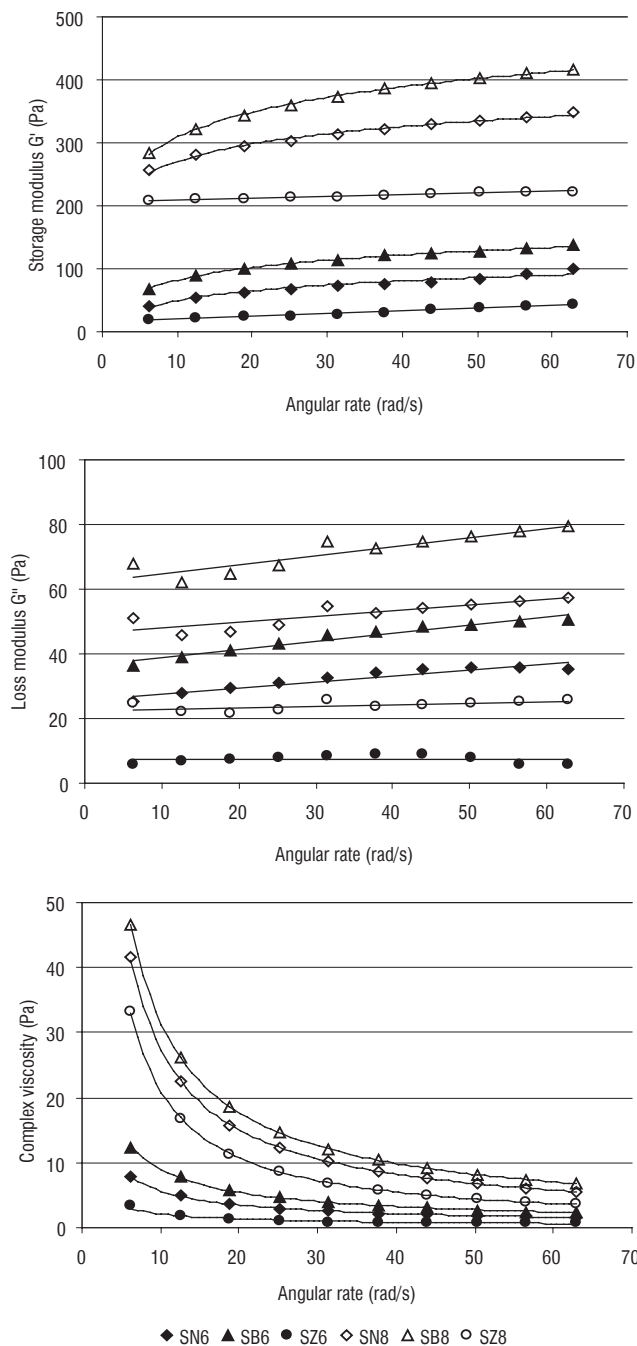


FIGURE 2. Dynamic frequency sweep data for storage modulus  $G'$ , loss modulus  $G''$ , and complex viscosity  $\eta^*$  of native (SN) and oxidised (SB and SZ) potato starch gels.

range of starch [Nguyen *et al.*, 1998]. The results obtained are consistent with findings of Morikawa & Nishinari [2000] about concentration dependency of the storage modulus  $G'$  for native potato starch after being heated at 95°C, which varied with concentration (C) as  $C^{2.8}$ . This type of spectrum is associated with rather strong gel behaviour [Rosalina & Bhattacharya, 2002]. The use of indices  $n'$  and  $n''$  from frequency dependence of  $G'$  and  $G''$ , *i.e.*  $G'=G_0'\omega^{n'}$  and  $G''=G_0''\omega^{n''}$ , respectively, is a convenient way to estimate the liquid/solid behaviour because the values close to 2 or 0 for  $n'$ , and/or 1 or 0 for  $n''$ , represent liquid or solid behaviour, respectively [Ortega-Ojeda *et al.*, 2004]. The storage (except SZ8) and loss moduli (except SZ6 and SZ8) were dependent on the frequency, *i.e.*  $G'$  clearly ( $0.13 < n' < 0.35$ ) and  $G''$

slightly ( $0.08 < n < 0.17$ ). The storage modulus was always higher than the loss modulus, about twice for SN6 and SB6, 4 times for SZ6, 6 times for SN8 and SB8, and 9 times for SZ8. It is worth attention that  $G'/G''$  ratio for both SZ gels was almost twofold higher than that for SN and SB gels. This type of spectrum is associated with strong-gel behaviour [Rosalina & Bhattaharaya, 2002; Ortega-Ojeda et al., 2004], thus SN and SB gels could be classified as viscoelastic solids. The SZ gels, whose  $G'$  and  $G''$  were not dependent on the frequency, could be classified as stronger gels.

Results of dynamic oscillatory test, which did not destroy gel structure, clearly showed rheological properties of the examined gels to be more viscous than elastic. Thus, another rheological test was used for more accurate rheological characteristics.

The course of ascending curves for 6% gels can be precisely described for SN6 and SB6 by Hershel-Bulkey equation (3) as well as Bingham equation (4) for SZ6 (Figure 3, Table 2).

$$\tau = \tau_0 + K\gamma^n \tag{3}$$

$$\tau = \tau_0 + K\gamma \tag{4}$$

Very good fitting of models to experimental data of SN6, SB6 and SZ6 (with correlation coefficients 0.9996, 0.9992, and 0.9767, respectively) allowed to classify these gels as non-Newtonian fluids with initial yield stress (Table 2). Yet, SN6 and SB6 showed behaviour of viscoplastic fluid whereas Bingham fluid behaviour characterised the SZ6 gel. The course of curves was almost the same for SN6 and SB6 gels, except small difference of  $\tau_0$  values (6.190 and 7.437 Pa, respectively), thus parameters of Herschel-Bulkey equation confirmed the same rheological character of both gels. SZ6 flow curve of different rheological character ran below the other curves according to the above-mentioned lower viscosity of SZ6 gel.

The course of ascending curves of 8% gels (Figure 3) was not so typical, except SB8 of typical viscoplastic behaviour, but viscosity of SZ appeared again the lowest. At low shear rates SB8 gel exhibited lower viscosity but it became more viscous than SN8 gel when higher shear rates were reached. Cross rheological equation,

$$\tau = \gamma (\eta_\infty + (\eta_0 - \eta_\infty) / (1 + k^n)) \tag{5}$$

described accurately flow curve course for SN8 and SZ8 with correlation coefficients 0.9617 and 0.9798, respectively

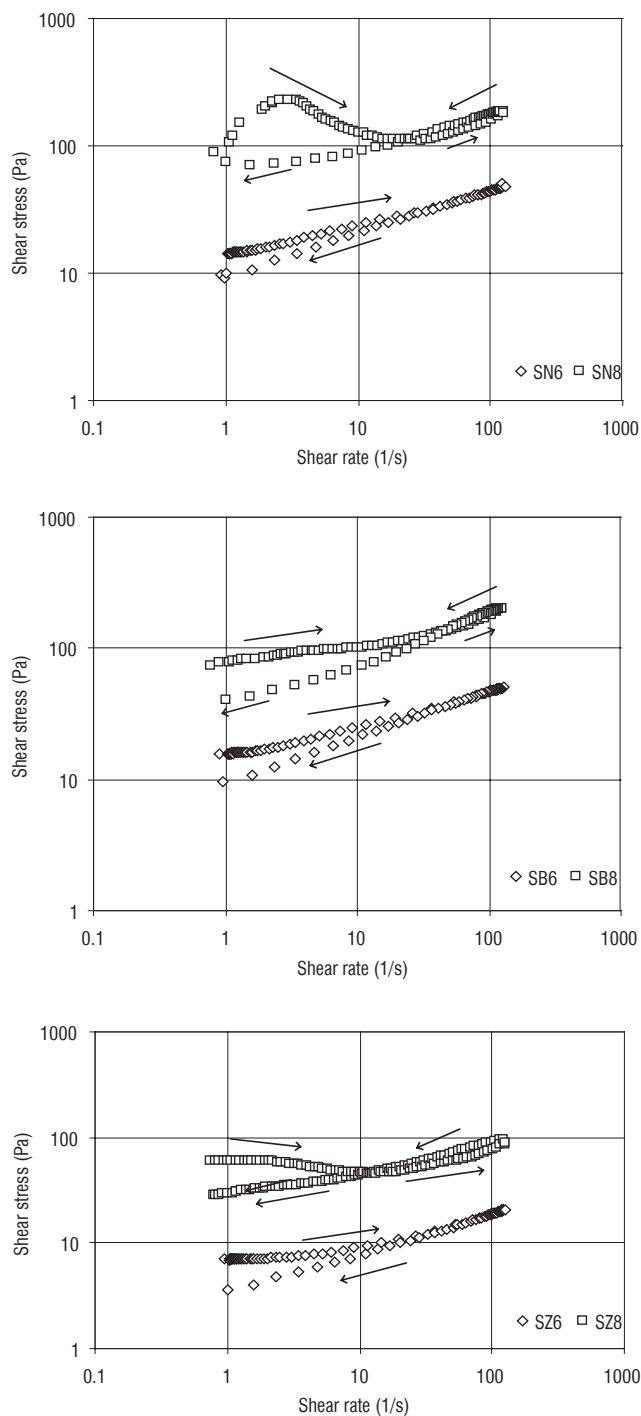


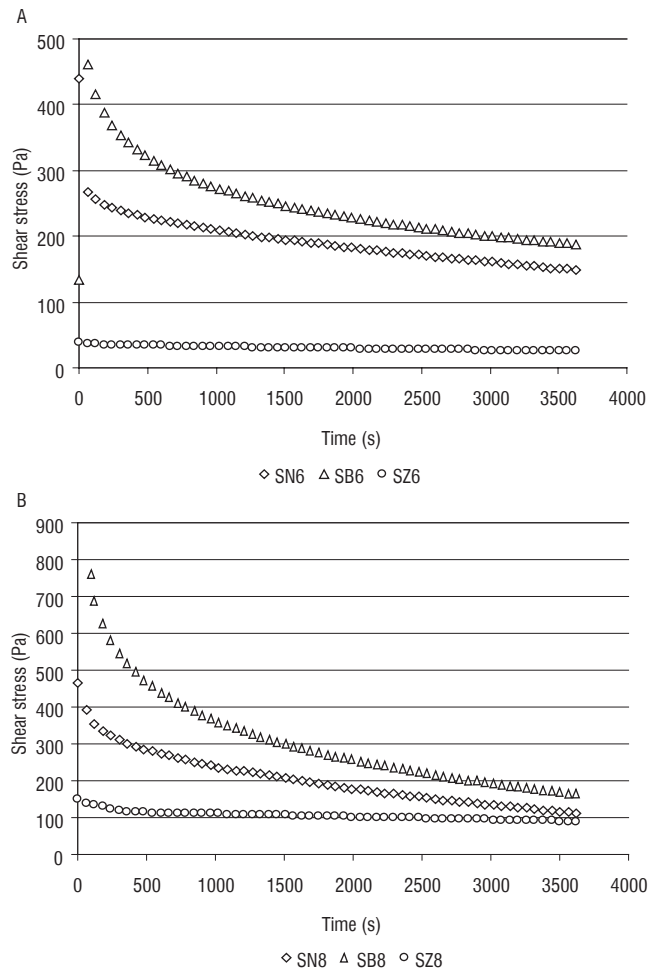
FIGURE 3. Hysteresis loop for native (SN) and oxidised (SB and SZ) potato starch gels.

TABLE 2. Parameters of rheological models for 6% and 8% native and oxidised starch gels.

Gels	Parameters of models									Correlation coef.
	Bingham		Herschel-Bulkey			Cross				
	$\tau_0$	K	$\tau_0$	K	n	$\eta_0$	$\eta_\infty$	$\gamma_b$	n	
SN6			6.190	7.846	0.346					0.9996
SB6			7.437	7.804	0.352					0.9992
SZ6	7.167	0.121								0.9767
SN8						278.0	1.328	1.516	1.622	0.9617
SB8			85.67	2.590	0.796					0.9991
SZ8						471.8	0.516	0.214	1.208	0.9798

TABLE 3. Thixotropy of 6% and 8% native and oxidised starch gels

Gels	Hysteresis loop		Parameters of Weltman model	
	$\Delta A$ (Pa)	$A_{rel}$ (%)	A (Pa)	B (Pa)
SN6	141	3.1	737	66.7
SB6	363	7.4	718	70.5
SZ6	74	4.0	123	12.1
SN8	770	4.4	1132	121.4
SB8	544	3.0	1422	154.2
SZ8	763	4.4	361	33.0

FIGURE 4. Shear stress decay at a constant rate  $100 \text{ s}^{-1}$  for 6% (A) and 8% (B) native (SN) and oxidised (SB and SZ) potato starch gels.

(Table 2). Such type of flow curve describes fluids of changeable shearing characteristics – both thinning and thickening occurred during shearing [Ferguson & Kembrowski, 1995].

TABLE 4. Rheological parameters of equilibrium flow curves' models of 6% and 8% native and oxidised starch gels.

Gels	Herschel-Bulkey			Cross				Correlation coef.
	$\tau_0$	K	n	$\eta_0$	$\eta_\infty$	$\gamma_b$	n	
SN6	9.140	2.678	0.5454					0.954
SB6	7.629	3.990	0.5164					0.982
SZ6				30.21	0.58	0.425	0.318	0.989
SN8	16.110	4.680	0.5977					0.961
SB8	18.500	5.968	0.6755					0.992
SZ8				74.39	0.600	0.528	0.875	0.958

Rheological character of SB8 remained like that of SB6 although values of respective indices were different (Table 2). Especially spectacular was an increase of  $\tau_0$  (7.437 and 85.67 for SB6 and SB8, respectively), which can be explained by stronger network and higher consistency of SB8 gel of higher concentration of starch [Larrigue & Alvarez, 2001].

Evans & Haisman [1979] and Self *et al.* [1990] studied the rheological behaviour of potato starch suspensions of 0.5–10% concentrations gelatinised at temperatures below  $100^\circ\text{C}$ , *i.e.* under conditions similar to those applied in this work. According to Evans & Haisman [1979], flow curves of gelatinised potato starch could be accurately described by Herschel-Bulkey model and power law model at low and high shear rates, respectively, whereas Self *et al.* [1990] proposed the concentration power law and Bingham plastic models for 3–6% starch.

The return flow curves showed regular thixotropy hysteresis loop for all 6% gels; smaller (for SZ6) or higher (for SB6) for oxidised starch gels than for the native starch gel SN6 (Figure 3, Table 3). The hysteresis appeared at shearing of gels whose network restoration at a decreased rate is lower than network deformation at an increased rate of shearing. Although the hysteresis is strongly affected by the shearing cycle time, the past shear history and the maximum shear rate selected [Nguyen *et al.*, 1998; Abu-Jdayil, 2003] the results obtained are useful for qualitative demonstrating that the starch gel examined were non-Newtonian, shear thinning and thixotropic fluids. During shearing of all 8% gels overthixotropy was found at the beginning of return curve and regular thixotropy at lower shear rate. Assuming that a hysteresis loop is an index of energy needed to destroy the structure responsible for flow time dependence [Tarrega *et al.*, 2004], the experimental data showed that the 8% gels needed higher energy to structure breakdown than the 6% gels (Table 3). Considering the relative thixotropic areas the different values were found only for SB6.

High-viscosity thixotropic fluid may, however, show a larger hysteresis than a lower viscosity one even if the latter undergoes a stronger structural destruction [Tarrega *et al.*, 2004].

At a  $100 \text{ s}^{-1}$  shear rate, the shear stress values decreased rapidly with time within the beginning of shearing. The differences of oxidation degree and concentration of gels resulted in the rate and extent of shear stress decay (Figure 4). The experimental data fitted well to the Weltmann model (Table 3). The higher values of initial shear stress and time coefficient for the 8% gels were obtained showing their stronger structure. Results of this experiment confirmed similar resistance for shearing in time for native SN and low oxidised SB whereas that for higher oxidised SZ was always lower.

After previous shearing of the examined gels, equilibrium flow curves were obtained (Figure 5). Experimental data for SN and SB of both concentrations fitted very well to the Herschel-Bulkey model, whereas SZ6 and SZ8 flow curves were described accurately by Cross model (Table 4). After eliminating thixotropy by shearing, gels showed shear-thinning with measurable initial resistance. Then, quantitative and qualitative differences were found in the rheological behaviour between SN and SB, and SZ gels, as before.

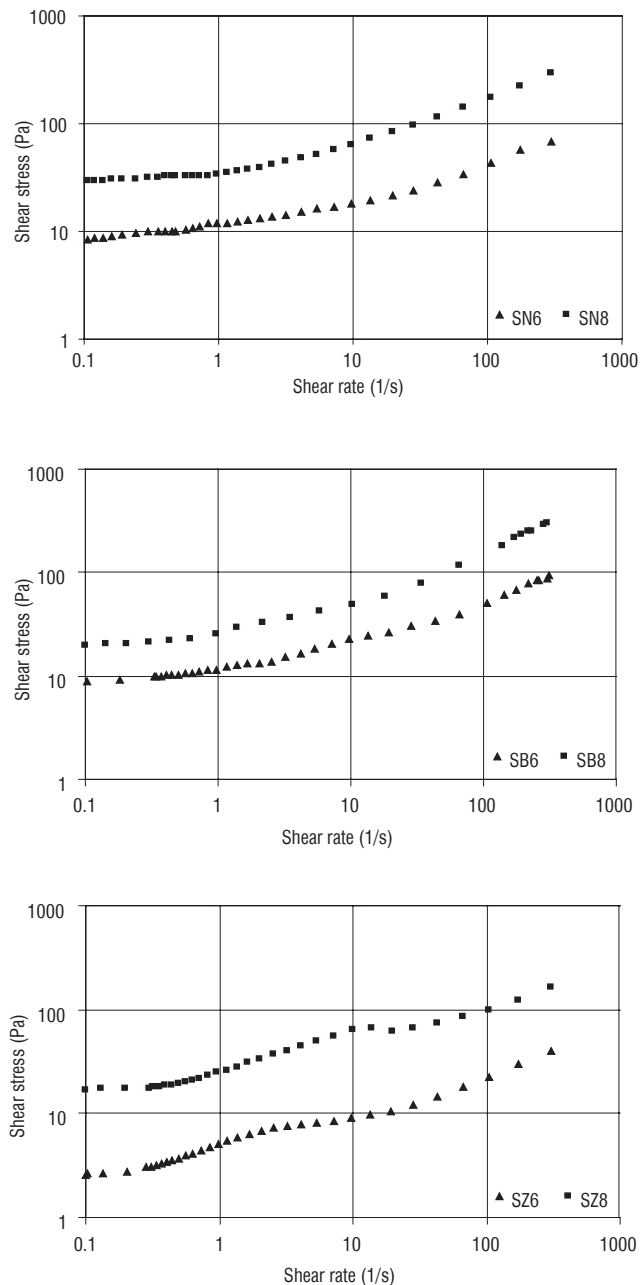


FIGURE 5. Equilibrium flow properties of native (SN) and oxidised (SB and SZ) potato starch.

Presentation of rheological behaviour of the examined starch gels in the form of the relationship  $\eta = f(\dot{\gamma})$  is more useful in industrial practice [Rodd *et al.*, 2000; Tarrega *et al.*, 2004]. Changes in viscosity appearing during shearing of native SN6 and slightly oxidised SB6 gels are practically the same and SZ6 gels showed the lowest viscosity at a whole

range of shear rate (Figure 6, Table 5). The course of viscosity curves of SN8 and SB8 gels was again similar with characteristic inflection of curve at a shear rate of *ca.*  $3 \text{ s}^{-1}$  and both gels did not show the character of shear-thinning fluid before this point. The viscosity of SZ8 appeared again the lowest one and inflection point could be probably observed at a shear rate lower than  $1 \text{ s}^{-1}$ . It was worthy attention that the SB8 gel exhibited lower viscosity at low shear rates but became more viscous than the SN8 gel when higher shear rates were reached. The influence of the concentration of starch on gels viscosity was pointed out especially by different rheological models of viscosity curves, *i.e.* Herschel-Bulkey (6) and Cross (7) for 6% and 8% respectively.

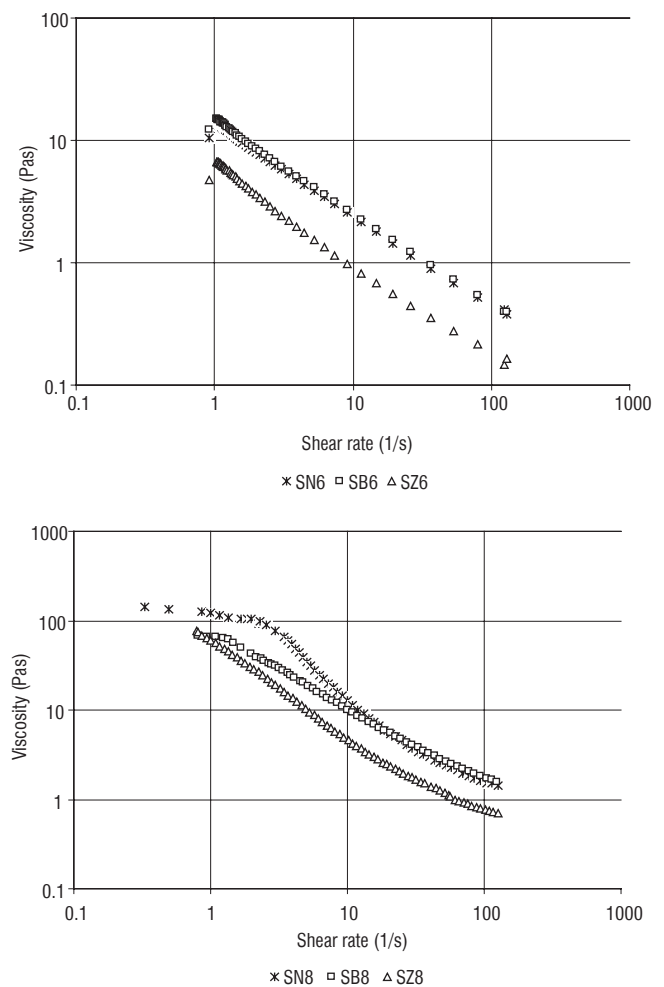


FIGURE 6. Viscosity curves for 6% (A) and 8% (B) gels from native (SN) and oxidised (SB and SZ) potato starch.

$$\eta = \tau_0/\dot{\gamma} + K\dot{\gamma}^{n-1} \quad (6)$$

$$\eta = \eta_\infty + (\eta_0 - \eta_\infty)/(1 + k\dot{\gamma}^n) \quad (7)$$

Certainly, rheological parameters of models for both 6% and 8% gels are similar for native and slightly oxidised starch gels. The highest  $\eta_0$  value for SZ8 gel suggested its different structure.

The effect of starch oxidation degree on gel texture, except springiness which was near 1.0 for all cases, was confirmed (Figure 7). Independently of starch concentration, hardness

TABLE 5. Rheological parameters of viscosity curves' models for 6% and 8% native and oxidized potato starch gels.

Gels	Herschel-Bulkey			Cross				Correlation coef.
	$\tau_0$	K	n	$\eta_0$	$\eta_\infty$	$\gamma_b$	n	
SN6	11.49	2.826	0.831					0.9994
SB6	11.4	2.29	0.5751					0.9993
SZ6	11.5	2.77	0.5875					0.9994
SN8				153.2	2.706	2.711	2.223	0.9988
SB8				145.4	1.138	0.877	1.101	1.000
SZ8				182.6	0.742	0.589	1.387	1.000

of gels made from slightly oxidised preparation of SB and native potato starch was similar and always higher than that of the SZ gels. Adhesiveness of SB gels reached always the lowest values but an extremely high increase of adhesiveness was determined for the 8% gel made of a highly oxidised preparation.

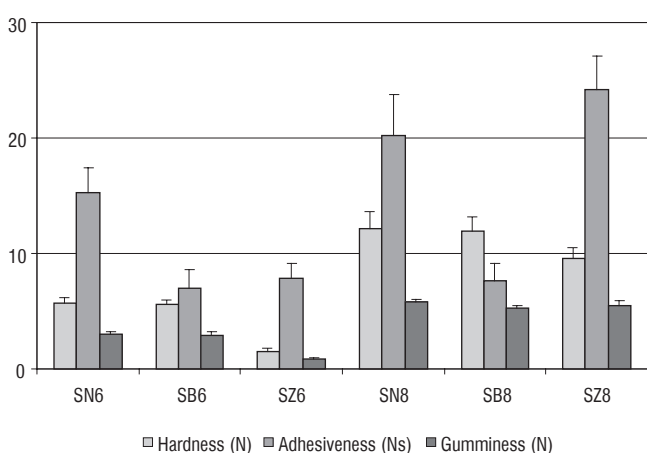


FIGURE 7. Characteristics of texture properties of 6 and 8% native (SN) and oxidised (SB and SZ) potato starch gels.

## CONCLUSIONS

1. Independently of starch concentration, in the gels examined the highest values of storage and loss moduli were reported for low oxidised SB, while the lowest ones for the higher-oxidised SZ.

2. Slightly oxidised SB as well as native potato starch revealed similar values of rheological parameters in both time dependence and steady flow behaviour that were found different from those of SZ, the starch of higher degree of oxidation.

3. Different pasting, flow, and viscoelastic properties confirmed hypothesis of diversified application of the produced oxidised potato starch.

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## REOLOGICZNE CHARAKTERYSTYKI UTLENIONYCH SKROBI ZIEMNIACZANYCH

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Wysoko utlenione skrobie (nawet powyżej 1%) są powszechnie używane w przemyśle włókienniczym i papierniczym. Wydaje się, że przemyśle spożywczym można natomiast wykorzystywać słabo utlenione skrobie ze względu na ich niską lepkość i wysoką stabilność przy dużej zdolności wiązania wody. Celem pracy było zbadanie charakteru reologicznego i tekstury żeli ze słabo utlenianej skrobi ziemniaczanej charakteryzującej się niskim stopniem podstawienia (0.001 w przypadku skrobi SB i 0.004 dla skrobi SZ) wyprodukowanych ze skrobi ziemniaczanej przez WPPZ S.A. w Luboniu.

Analiza właściwości reologicznych żeli skrobiowych wykonana przy pomocy testu oscylacyjnego wykazała, że w porównaniu z żelami ze skrobi natywnej (niezależnie od stężenia skrobi) żele ze skrobi o niższym stopniu utlenienia wykazywały wzrost wartości modułów sprężystości i stratności, podczas gdy wyższy poziom utlenienia powodował spadek ich wartości. Podobne charakterystyki reologiczne wykonane dla stałego płynięcia oraz zmienności właściwości reologicznych w czasie otrzymano dla skrobi natywnej SN i słabiej utlenionej SB, lecz charakterystyka reologiczna mocniej utlenionej skrobi SZ była odmienna. Reologiczny charakter żeli zależał również od stężenia skrobi. Żele o stężeniu 6% skrobi zachowywały się jak lepkosprężyste ciecze opisywane modelami Herschel-Bulkey'a i Bingham'a, podczas gdy żele 8% wykazywały właściwości cieczy lepkosprężystych opisywanych modelem Cassona.

Potwierdzono również istotny wpływ stopnia utlenienia na teksturę badanych żeli. Twardość żeli przygotowanych ze skrobi natywnej i słabiej utlenionej SB była podobna i zawsze niższa niż twardość żeli z mocniej utlenionej skrobi SZ. Adhezyjność żeli SB była z reguły najniższa, przy czym szczególnie wysoką adhezyjnością charakteryzował się 8% żel z mocniej utlenionej skrobi SZ.

Potwierdzone zróżnicowane właściwości lepkosprężyste oraz charakter płynięcia badanych niżej i wyżej utlenionych skrobi SB i SZ sugerują zatem ich odmienne zastosowanie w przemyśle spożywczym.