Determination of oxygen permeability and mechanical properties of the aluminium paper foils

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Abstract

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The paper deals with the determination of the oxygen permeability and mechanical properties of butter and curd aluminium paper foils Radaflex applied in the food packaging. Foil Radaflex is a paper foil covered by the aluminium layer. The measurement of the oxygen permeability was realized according to the Standard STN EN 77 0333. The measurement of mechanical properties was realized according to the Standard STN EN ISO 1924-2. Determination of moduli of elasticity in the longitudinal and transversal direction were provided and tensile properties as maximal elongations, maximal tensile forces, tensile strengths, tensile indexes and strain at breaks of the longitudinal and transversal specimens were evaluated. The permeability of pure oxygen through aluminium paper foils was studied. Aluminium paper foil was not permeable for the oxygen.

Keywords: packaging; modulus of elasticity; butter; curd

Aluminium paper foils are often used for packaging of the curd or the butter. The strength of the metal and the flexibility of the paper provide very good conditions for the packaging. Knowledge of the tensile properties and the oxygen permeability of the composite metal-paper materials are very useful for their design and production. Wilbrink (2011) presented that paper and paperboards are widely used in packaging for transportation, storage and retail. Increasing demands on the shapes and mechanical durability of these products require innovation of their manufacturing techniques. First, the geometric and mechanical properties of the network of which paper consists were analysed. An inventory of the models that have been used to model paper's in-plane mechanical behaviour was given, in which a distinction was made between continuum models and discrete models. Gurav et al. (2003) investigated the mechanical properties of paper-pulp packaging. This included the determination of tensile and compressive strength of paper-pulp packaging and also finding out whether this material exhibits high variation in the earlier properties. Experiments were conducted on paper-pulp packaging used for the packaging of video recorders. Kibirkštis and Kabelkaité (2006) were interested in determination of mechanical characteristics of qualitative and defective paper/paperboard, and the effect of printing processes (one-side and two-side printing) on mechanical characteristics of the mentioned polygraphic materials. Božiková and Hlaváč (2012) presented thermal properties of selected cheeses.

The properties are very important for decision which packaging material is suitable of package of the different cheeses. Vozárová et al. (2011) introduced methods for moisture content, electrical properties and thermal behaviour of food materials. The possibilities of the packaging are directly dependent on the knowledge of the all parameters evaluated on the basis of these methods. Mechanical properties of butter and curd aluminium paper foils Radaflex such as max. elongations, max. tensile forces, tensile strengths, tensile indexes and strain at breaks of the longitudinal and transversal specimens were evaluated.

MATERIAL AND METHODS

Butter and curd aluminium paper foil Radaflex (Radaflex s.r.o., Trnava, Slovak Republic) is a composite foil which consists of four layers. Aluminium layer has the thickness of 9 μm and the surface mass 23 g/m^2, wax layer with the surface mass 13 g/m^2, paper layer with the surface mass 45 g/m^2 and sub paint layer with the surface mass 1 g/m^2. Total surface mass is 83 g/m^2. Thickness of the foil is 80 mm.

Tensile test. Examinations were realized by means of the standard STN EN ISO 1924-2 (2009). Samples were cut in the longitudinal and transversal direction on the dimensions 150 × 15 mm. Initial length of samples was 150 mm and initial cross section area was 1.2 mm^2. Thickness of the samples was 80 mm. Ten specimens of the foils were used of each sort. In this test, a load was applied along the longitudinal axis of a test specimen. The applied load and the resulting elongation of the member were measured. The process was repeated with increased load until the desired load levels were reached or the specimen breaks. The tensile behaviour was monitored on the motorized test stand Andilog Stentor 1000 (Andilog Technologies, Vitrolles, France) with max. reached force about 37 N for longitudinal samples and about 42 N for transversal samples (Fig. 1). The force F (N) and elongation δ (mm) were measured when the speed of flat grip fixtures was 20 mm/min and data were stored in the xls format in the computer by means of analogue to digital converter and software RSIC v 4.06 (Andilog Technologies, Vitrolles, France). The force and elongation were transformed by means of the software Microsoft Office Excel 2003 (Microsoft, Redmont, USA) on the tensile stress σ (MPa) and the strain ε (mm/mm). The tensile stresses σ (MPa) were determined from the equation:

$$\sigma = \frac{F}{S} \quad (1)$$

where:
F – force (N)
S – initial cross section area of the foils (mm^2)

The strains ε (mm/mm) were determined as a change in the specimen's gage length from the equation:

$$\varepsilon = \frac{\delta}{l} \quad (2)$$

where:
δ – elongation (mm)
l – initial length (mm)

Tensile modulus of elasticity E (MPa) was defined from the equation:

$$E = \frac{S_{max} l}{bt} \quad (3)$$

where:
S_{max} – max. slope of the curve of force versus elongation (N/mm)
l – initial length of the specimen (mm)
b – initial width of the specimen (mm)
t – thickness of the paper (mm)

Tensile strength σ_T^b (kN/m) is max. tensile force referring on the unit of the width, which paper suffers before the breaking. The max. tensile force of each specimen was determined. The average max. tensile force was calculated and then the tensile strength was evaluated from the equation:

Fig. 1. Test stand Andilog Stentor 1000 with the foil specimen

$$\sigma_T^b = \frac{\overline{F_t}}{b} \tag{4}$$

where:
$\bar{F}_t$ – average max. tensile force (N)
b – initial width of the specimen (mm)

Tensile index σ_T^W (kNm/kg) was defined from the equation:

$$\sigma_T^w = \frac{1,000\ \sigma_T^b}{w} \tag{5}$$

where:
w – surface mass (g/m^2)

Max. strain at break ε_T (%) was defined as the percent of the initial length of the specimen from the equation:

$$\varepsilon_T = \frac{\delta_b}{l} \times 100 \tag{6}$$

where:
δ_b – max. elongation (mm)
l – initial length (mm)

The max. elongation was measured at the moment of breaking of the sample.

Oxygen permeability test. Methods of detection and measurement of parameters of permeability of packaging materials of gases are specified in the Standard STN EN 77 0333 (1987). The method was modified for the conditions of our test. Basis of the test of the isobaric method is the determination of the concentration of the testing gas, which diffused through the tested material from the chamber filled with pure testing gas to the chamber with the air. The samples have to be planar, pure and without mechanical damage. The temperature and the moisture are continually controlled. The dimensions of volumes V_1, V_2 and area S were determined before the test, where V_1 is the volume of the upper chamber of the testing vessel measured with the precision of ± 5%, V_2 is the volume of bottom chamber of the testing vessel with the precision of ± 5% and S is the testing area of the sample.

The upper chamber was perfused with the testing gas and the bottom chamber with the air before the measurement as long as the homogenous environs was reached in the each of the both chambers. The suitable flow of the both gases was about 600 cm^3/min. The time of the perfusion had to be at least 30 min and it was prolonged if the material was less permeable. The supply of the testing gas was stopped after the perfusion and all valves of the both chambers were closed. The time of the permeation of the testing gas through the sample was started at the moment. The diffusion of the gas between both chambers was in the progress for a period of 24 hours. The digital oxygen meters Mesura (Pierron, Sarrguemines, France) were applied for measurement of the amount of diffused oxygen.

The coefficient of permeability P was obtained from the increasing concentration $\Delta\rho_p$ of the gas permeated through the foil to the calibrated volume V in the time Δt because the oxygen probes measured the relative concentration of the oxygen and the absolute values of concentration had to be calculated from the tabulated values of the air and oxygen at the real conditions. Zeman and Kubík (2012) declared basic permeability parameters. Coefficient of permeability P can obtain from the equation:

$$P = \frac{\Delta\rho_p}{\Delta t} \times \frac{V\,h}{S\,\rho_i} \times \frac{1}{R\,T} \tag{7}$$

where:
ρ_i – density of the gas in the initial volume (kg/m^3)
$\Delta\rho_p$ – increase of the density of the gas transferred into calibrated volume (kg/m^3)
V – calibrated volume (m^3)
h – thickness of the foil (m)
Δt – time of the duration of the diffusion (days)
S – area of the foil (m^2)
R – universal gas constant, R = 8,314 J/kmol·K
T – temperature (K)

We can also obtain permeability of the membrane P_x (m^3/m^2·s·Pa) from the equation:

$$P_x = \frac{\Delta\rho_p\,V\,M}{\Delta t\,S\,\rho_i^2\,R\,T} \tag{8}$$

where:
M – molecular mass (kg/mol)

The solubility coefficient S_p (mol/m^3·Pa) can be calculated from the equation (Pauly 1999):

$$S_p = \frac{P}{D} \tag{9}$$

where:
P – coefficient of permeability (mol/m·s·Pa)
D – diffusion coefficient (m^2/s)

RESULTS AND DISCUSSION

Tensile diagram of butter and curd aluminium paper foil Radaflex for one longitudinal specimen is presented on the Fig. 2. Max. tensile force obtained from diagram was 36.061 N and max. elongation was 0.349 mm. Determination of modulus of elasticity of the specimen was provided on the basis of Eq. (3) and the stress-strain dependence on the Fig. 3a. Modulus of elasticity was the slope of the linear dependence. Tensile diagram of butter and curd aluminium paper foil Radaflex for one transversal specimen is presented on the Fig. 3b. Max. tensile force obtained from diagram was 42.50 N and max. elongation was 10.739 mm. Determination of modulus of elasticity of the specimen was provided on the basis of Eq. (3) and the stress-strain dependence on the Fig. 4. Tensile properties as: modulus of elasticity of longitudinal specimens maximal elongations, maximal tensile forces, tensile strengths, tensile indexes and strain at breaks of the longitudinal and transversal specimens were evaluated on the basis of Eqs (3–6) and they are presented in the Tables 1 and 2. Standard deviations of the longitudinal quantities were about 5.6% only elongation and strain at break had the standard deviation about 12.1%. Standard deviations of the transversal quantities were about 3.5% only elongation and strain at break had the standard deviation about 27.1%. Bigger values of the standard deviations were caused by the dispersion of the measurement of the elongation on the tensile stand. Average value of modulus of elasticity of longitudinal specimens was 35.662 GPa and modulus of elasticity of transversal specimens was 1.726 GPa. Schröder and Bensarsa (2002) present the values of the moduli of elasticity 3.680 GPa for dry paper and 19.370 GPa for dry paper fibres. We can see from the Fig. 5 that the correlation dependence was not obtained between moduli of elasticity in the longitudinal and transversal directions. The foil has different elastic properties in the longitudinal and transversal directions. Holik (2013) presents the tensile indexes of the pulp from 30 to 40 kNm/kg, which is in good agreement with our measurements in Tables 1 and 2. Kataja-Aho et al. (2011) present the values of the tensile strength of the wet paper from 0.1 to 0.4 kN/m and the strain at break of the wet paper from 2 to 4% in dependence of the dry solids content. The results of our measurement for the tensile strength of our

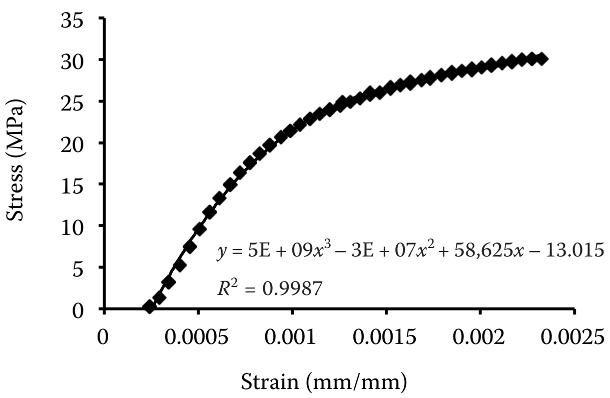

Fig. 2. Tensile diagram of butter and curd aluminium paper foil Radaflex, longitudinal specimen 1: stress in the foil and strain in the foil during loading

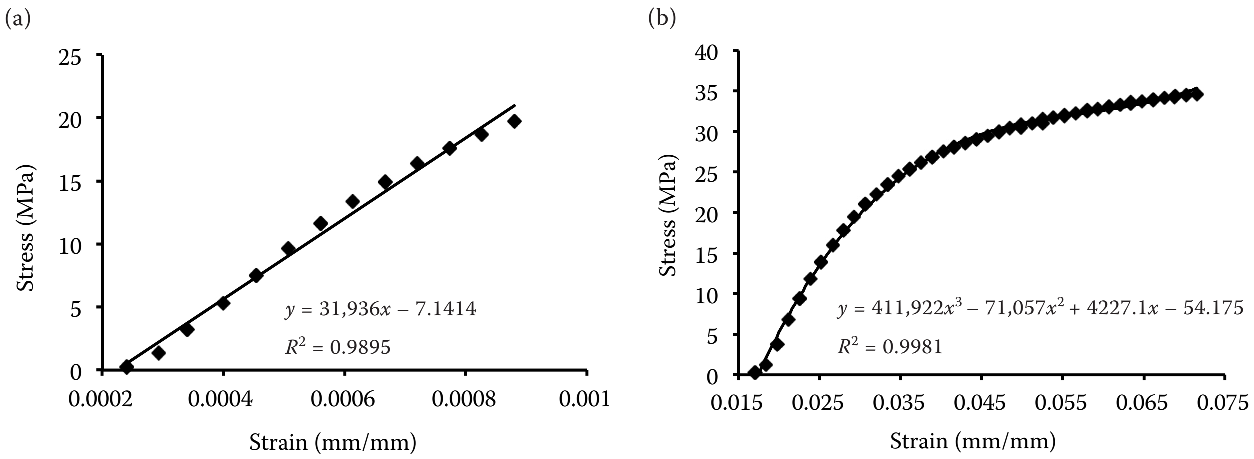

Fig. 3. Determination of modulus of elasticity of butter and curd aluminium paper foil Radaflex from linear part of dependence stress on the strain and (a) longitudinal specimen 1 (modulus of elasticity E = 31.936 GPa) and (b) transversal specimen 1

Table 1. Results of tensile properties of longitudinal specimens

No. of sample	E_L (GPa)	δ (mm)	F_t (N)	σ_T^b (kN/m)	σ_T^W (kNm/kg)	ε_T (%)
1	31.936	0.349	36.061	2.404	28.860	0.233
2	33.568	0.337	35.880	2.392	28.715	0.225
3	34.749	0.353	30.429	2.029	24.353	0.235
4	37.784	0.436	36.787	2.452	29.144	0.291
5	35.186	0.407	36.515	2.434	29.224	0.271
6	38.882	0.313	35.381	2.359	28.316	0.209
7	36.133	0.336	34.746	2.316	27.808	0.224
8	36.465	0.325	33.612	2.241	26.900	0.217
9	35.140	0.385	37.059	2.471	29.659	0.257
10	36.779	0.301	35.335	2.356	28.279	0.200
Average	35.662	0.354	35.181	2.345	28.126	0.236
s	2.016	0.043	1.956	0.130	1.541	0.029
s (%)	5.654	12.075	5.561	5.561	5.480	12.110

E_L – modulus of elasticity of longitudinal specimens; δ – max. elongation; F_t – max. tensile force; σ_T^b – tensile strength; σ_T^W – tensile index; ε_T – strain at break; *s* – standard deviation

Table 2. Results of tensile properties of transversal specimens

No. of sample	E_T (GPa)	δ (mm)	F_t (N)	σ_T^b (kN/m)	σ_T^W (kNm/kg)	ε_T (%)
1	1.709	10.739	42.550	2.770	33.253	7.159
2	1.748	8.319	40.416	2.699	32.346	5.546
3	1.722	7.139	39.236	2.616	31.401	4.759
4	1.727	12.639	39.327	2.622	31.474	8.426
5	1.820	10.729	41.550	2.770	33.253	7.153
6	1.747	11.300	38.919	2.595	31.150	7.533
7	1.679	7.009	39.554	2.637	31.656	4.673
8	1.663	14.059	37.921	2.528	30.349	9.373
9	1.651	15.769	38.738	2.583	31.003	10.513
10	1.791	14.200	40.643	2.710	32.527	9.467
Average	1.726	11.190	39.885	2.653	31.841	7.460
s	0.054	3.035	1.402	0.081	0.971	2.024
s (%)	3.122	27.125	3.514	3.061	3.049	27.125

E_T – modulus of elasticity of transversal specimens; δ – max. elongation; F_t – max. tensile force; σ_T^b – tensile strength; σ_T^W – tensile index; ε_T – strain at break; *s* – standard deviation

samples were from 2.4 to 2.7 kN/m. Our results of the strain at break were from 0.2% for longitudinal samples and 7.5% for transversal samples. Differences were caused by the moisture in the samples.

The permeability of pure oxygen (99.5%) through aluminium paper foils was also studied. Thickness of the samples was 80 mm. The conditions of measurement are described in the Table 3. The

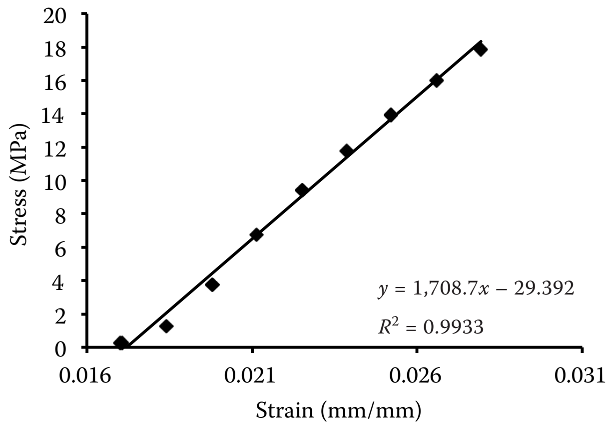

Fig. 4. Determination of modulus of elasticity of butter and curd aluminium paper foil Radaflex from linear part of dependence stress on the strain, transversal specimen 1 (modulus of elasticity E =1.7087 GPa)

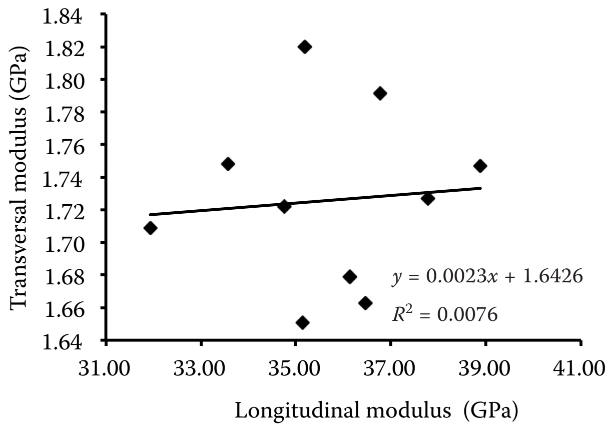

Fig. 5. Determination of correlation dependence between moduli of elasticity in longitudinal direction and transversal direction of butter and curd aluminium paper foil Radaflex

measurements were realized at the temperature 22°C, 30% of the air moisture and the barometric pressure 102 400 Pa. Measured quantities needed of calculating of the result quantities are presented in the Table 4. The basic absolute values of the volume concentration of the oxygen at the temperature 295 K were used 1.1965 kg/m^3 of the air and 1.3386 kg/m^3 of the oxygen. These values were calculated and extrapoled by means of the equation of state for ideal gas. The absolute values of the measured densities were calculated from the basis absolute values and the relative values measured by the oxygen probes. The oxygen probes were calibrated on the value of 20.9% of oxygen in the air at the beginning of the test. The perfusion of the equipment by the air and oxygen during 30 min at the beginning of the test caused the increase of the initial values of the oxygen probes from the 20.9% to the 21.3% in the bottom chamber and to the 94.9% in the upper chamber. Dependence of the volume concentration of the oxygen on the time in the upper vessel during the test is presented in the Fig. 6a. Dependence of the volume concentration of the oxygen on the time in the bottom vessel during the test is presented in the Fig. 6b. We can see that dependency on the Fig. 8 is linear and constant. Change of the volume concentration of the oxygen during 24 h was only 0.9% of the initial volume concentration. Aluminium paper was not permeable for the oxygen. Permeability parameters such as the permeability and the solubility coefficient were not determined.

Table 3. Conditions of oxygen permeability measurement

Symbol	Unit	Quantity	Description
V_1	m^3	0.0011283	volume of upper chamber
V_2	m^3	0.0011283	volume of bottom chamber
d_s	m	0.07	diameter of the foil sample
S	m^2	0.0038465	area of the foil sample
h	mm	80	thickness of the foil
b	Pa	102 400	barometric pressure of the air
T	K	295	temperature of the air
j	%	30	relative moisture of the air
M	kg/kmol	32	molar mass of the O_2
R	J/kmol·K	8314	universal gas constant

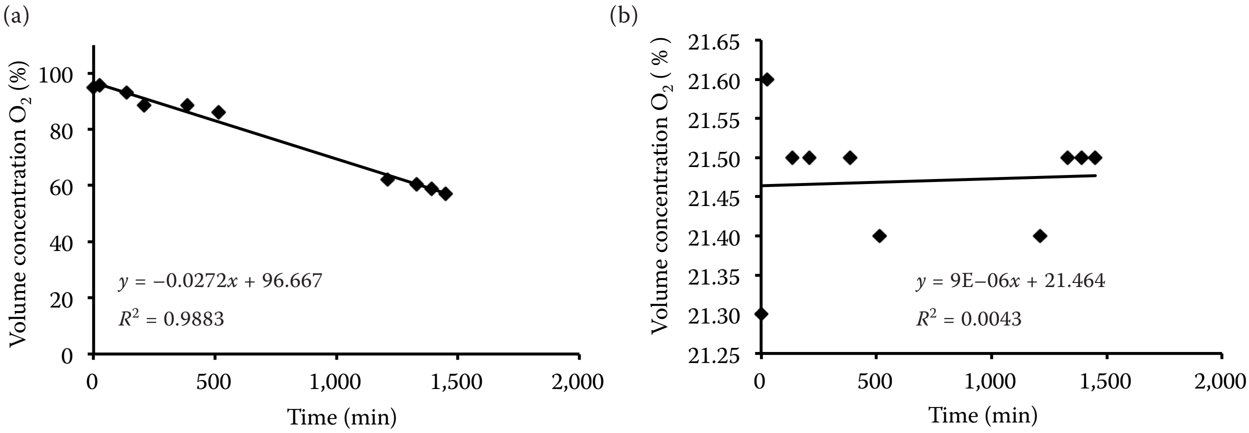

Fig. 6. Dependence of the volume concentration of O_2 on the time in (a) the upper and (b) bottom chamber during the test of butter and curd aluminium paper foil Radaflex

Table 4. Measured quantities of oxygen permeability of the butter and curd aluminium paper foil Radaflex

Symbol	Unit	Quantity	Description
Δt	day	1.007	duration of the permeation
ρ	kg/m^3	1.1965	density of the air at the temperature 295 K
ρ_{O2}	kg/m^3	1.3386	density of the O_2 at the temperature 295 K
ϕ_{1O2i}	% vol.	94.9	initial relative concentration of O_2 at the temperature 295 K measured by the oxygen probe in the upper chamber
ρ_{1O2i}	kg/m^3	1.2703	initial density of O_2 at the temperature 295 K measured by the oxygen probe in the upper chamber
ϕ_{2O21}	% vol.	21.3	initial relative concentration of the O_2 at the temperature 295 K measured by the oxygen probe in the bottom chamber
ρ_{2O21}	kg/m^3	0.2851	initial density of O_2 at the temperature 295 K measured by the oxygen probe in the bottom chamber
ϕ_{2O22}	% vol.	21.5	final relative concentration of the O_2 at the temperature 295 K measured by the oxygen probe in the bottom chamber
ρ_{2O22}	kg/m^3	0.2878	final density of the O_2 at the temperature 295 K measured by the oxygen probe in the bottom chamber
$\Delta\rho_{O2p}$	kg/m^3	0.0027	increase of the density of the O_2 at the temperature 295 K in the bottom chamber

CONCLUSION

The measurement of the permeability of the oxygen and mechanical properties of the butter and curd aluminium paper foils Radaflex were realized. Determination of moduli of elasticity in the longitudinal and transversal direction were provided and tensile properties as maximal elongations, max. tensile forces, tensile strengths, tensile indexes and strain at breaks of the longitudinal and transversal specimens were evaluated. Standard deviations of the longitudinal quantities were about 5.6% only elongation and strain at break had the standard deviation about 12.1%. Standard deviations of the transversal quantities were about 3.5% only elongation and strain at break had the standard deviation about 27.1%. Average value of modulus of elasticity of longitudinal specimens was 35.662 GPa and modulus of elasticity of transversal specimens was 1.726 GPa. The foil had the different elastic properties in the longitudinal and transversal directions. The permeability of pure oxygen through aluminium paper foils was also studied. Aluminium paper foil was not permeable for the oxygen. The foil is suitable for food packaging and packaging butter and curd.

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