ACTA UNIVERSITATIS AGRICULTURAE ET SILVICULTURAE MENDELIANAE BRUNENSIS

Volume 64 18 Number 1, 2016
http://dx.doi.org/10.11118/actaun201664010159

TENSILE STRENGTH OF THE EGGSHELL MEMBRANES

Jana Strnková[1], Šárka Nedomová[1], Vojtěch Kumbár[2], Jan Trnka[3]

[1] Department of Food Technology, Faculty of AgriSciences, Mendel University in Brno, Zemědělská 1, 613 00 Brno, Czech Republic
[2] Department of Technology and Automobile Transport, Faculty of AgriSciences, Mendel University in Brno, Zemědělská 1, 613 00 Brno, Czech Republic
[3] Institute of Thermomechanics, Czech Academy of Science, Dolejškova 5, 182 00 Praha, Czech Republic

Abstract

STRNKOVÁ JANA, NEDOMOVÁ ŠÁRKA, KUMBÁR VOJTĚCH, TRNKA JAN. 2016. Tensile Strength of the Eggshell Membranes. *Acta Universitatis Agriculturae et Silviculturae Mendelianae Brunensis,* 64(1): 159–164.

The mechanical behaviour of eggshell membranes under tensile loading has been studied. Samples from different bird species (hen, goose and Japanese quail) have been used. Samples were cut out of the membrane in latitudinal direction. TIRAtest 27025 tensile testing machine equipped with a 200 N load-cell was used. Tensile deformation exhibits both non-linear as well as linear region. The experiments were performed at five loading velocities 1, 10, 100, 400 and 800 mm.min^{-1}. The main parameters describing the eggshell strength increase with the loading rate. This dependence exhibits the same qualitative features as the rate dependence of the eggshell strength.

Keywords: eggshell membrane, tensile test, loading rate, tensile strength, fracture strain

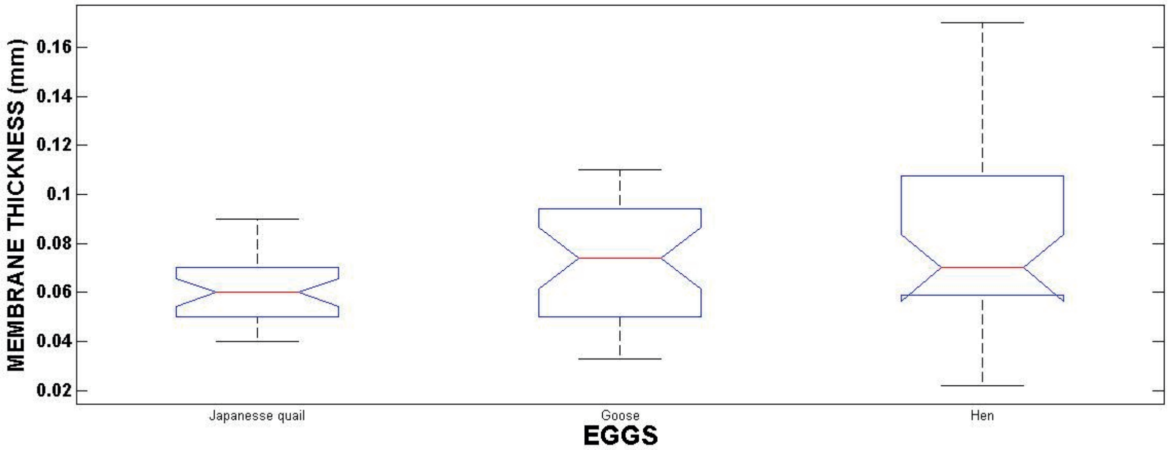
INTRODUCTION

Eggshell membrane is a part of egg which adheres to eggshell, but its effect on eggshell strength is still not clear because there is not any way to research eggshell membrane with intact eggshell and it is often considered as an unimportant impact factor on eggshell strength. Only limited number of information is known about its physical and structural properties, such as the pore and mechanical characteristics of the membrane. The only exception represents the paper of Torres *et al.* (2010) which is focused on the study of hen's egg membranes under tensile loading and nanoindentation.

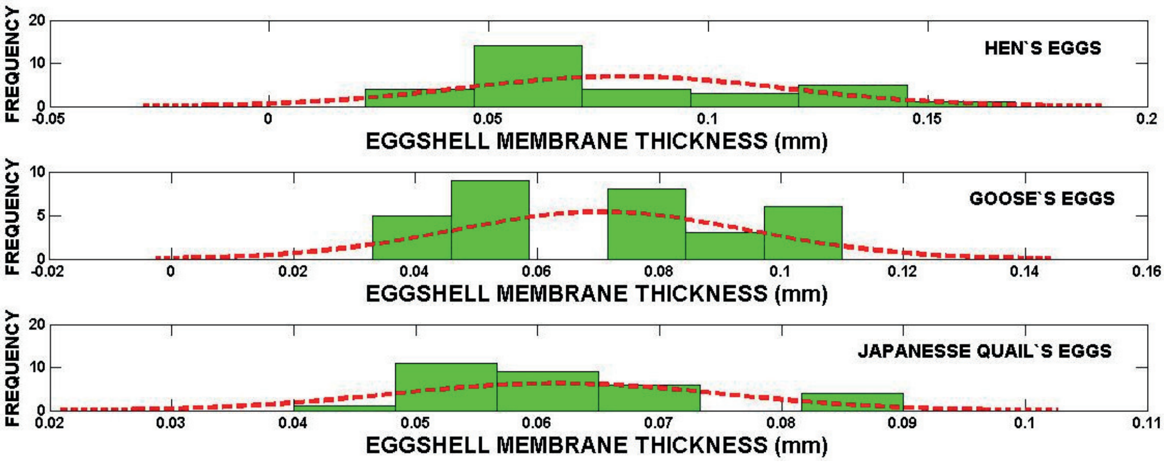
The given paper is focused on the research of the eggshell membranes behaviour under tensile loading. The results on the fracture strength of the whole eggshell show that this parameter is more or less dependent on the loading rate (Carter, 1979; Trnka *et al.*, 2012; Nedomová *et al.*, 2014). The same dependence may occur also for the eggshell membranes. In the given paper this dependence has been studied on the eggshell membranes of three domestic fowls (hen, goose and Japanese quail). The knowledge of these characteristics is meaningful e.g. in design of the numerical model of egg. These models are than used in numerical simulation of the egg behaviour under different loads (Song *et al.*, 2006; Perianu *et al.*, 2010).

MATERIALS AND METHODS

Eggshell membranes were obtained from commercial breeding lines of hens, gooses and Japanese quails. The eggs were sawn up around the meridian using a special cutting machine. The outer membranes were carefully removed using clamps. Samples for the measurement were sawn out at the equator of the shell where the eggshell curvature was minimal. The membranes were washed thoroughly with distilled water to remove any egg white sticking onto the surface of the membrane. The membranes were then stored in physiologic saline solution in order to avoid dehydration. Samples were cut out of the membrane in latitudinal direction. In order to measure membrane thickness the membranes were placed between two aluminium plates of known thickness. The total thickness of this sandwich can be easily measured using of digital micrometer. TIRAtest



1: *Membrane thickness (On each box, the central mark is the median, the edges of the box are the 25th and 75th percentiles, the whiskers extend to the most extreme data points not considered outliers, and outliers are plotted individually)*



2: *Histogram of the membrane thickness (broken lines denote a fitted normal distribution)*

I: *Membrane thickness*

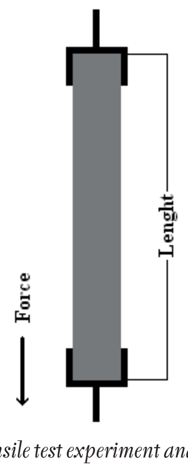
Thickness [mm]	Minimum	Mean	Maximum	Standard deviation
Hen's egg	0.022	0.080	0.170	0.037
Goose's egg	0.033	0.070	0.110	0.025
Quail's egg	0.040	0.062	0.090	0.014

27025 tensile testing machine equipped with a 200 N load-cell was used. Rectangular samples (15 mm × 15 mm) were used for the measurements. The results obtained were statistically analyzed using the statistical package UNISTAT. Evaluated were the means and standard deviations using ANOVA with subsequent Tukey's test at significance level of $P > 0.95$. Thickness of the membranes exhibits a scatter as shown in the Fig. 1.

The statistical analysis shows that statistically significant difference occurs between thickness of goose and quail eggshell membranes. Histogram of this quantity is displayed in the Fig. 2.

Statistical data are given in the Tab. I.

Specimens were glued to thin metallic plates – see Fig. 3.



3: *Schematic of tensile test experiment and attached specimen*

The deformation of the sample was assumed to be equal to the separation of the crossheads. The force F and the deformation $\Delta l = l - l_o$, where l is the instantaneous specimen length at the time t, are measured during tension and both quantities are recorded. The force-deformation data may easily be transformed into normalized quantities such as stress and strain. The Cauchy strain and Hencky's natural or true strain are of common use in representing compression curves. The evaluation of these quantities as well as the values of stress, σ, and/or true stress, respectively is described e.g. by Mehnet Ak and Gunasekaran (1997).

The specimen deformation is also described using the stretching parameter, λ, which is defined as

$$\lambda = \frac{l}{l_o} = 1 + \varepsilon_C . \quad (1)$$

The transformation force-deformation data into quantities given above have been performed using of MATLAB software. Five speeds, v, were used: 1, 10, 100, 400 and 800 mm.min^{-1}. Loading rate can be converted to the strain rate:

$$\frac{d\varepsilon}{dt} \equiv \dot{\varepsilon} = \frac{v}{l_o} . \quad (2)$$

The corresponding values of strain rates are: 0.00111; 0.0111; 0.111; 0.444 and 0.888 s^{-1}. Experiments were performed at the room temperature. Experimental data for Japanese quails were published independently in (Strnková *et al.*, 2015).

RESULTS AND DISCUSSION

In the Fig. 4 an example of the experimental record force-displacements is shown.

The loading force increases up to some value corresponding to the membrane fracture. In this moment the force nearly immediately falls to zero. The only exceptions were observed for the membranes of quail eggs. The force decreases gradually in this case. This is probably a consequence of relatively low crack velocity in the membrane.

Experimental records force-displacement were converted to the dependence of stress, σ, on the strain, ε, using of Eqs. in Mehnet Ak and Gunasekaran (1997). The maximum of the stress corresponds to the moment of eggshell membrane fracture. This quantity is denoted as the ultimate tensile strength (UTS). The corresponding strain represents the fracture strain ε_f. The next parameter which describes the fracture behaviour of the eggshell membrane is the fracture toughness. This quantity is expressed as the energy absorbed by the eggshell membrane up to rupture point per unit volume of the membrane and was determined using the following formula (Polat *et al.*, 2007):

$$W = \int_0^{\varepsilon_f} \sigma d\varepsilon . \quad (3)$$

Experimental data describing the eggshell membrane fracture behaviour are given in the Tabs. II–IV.

These data show that all fracture parameters increase with the loading velocity. These dependences are shown in the Fig. 5.

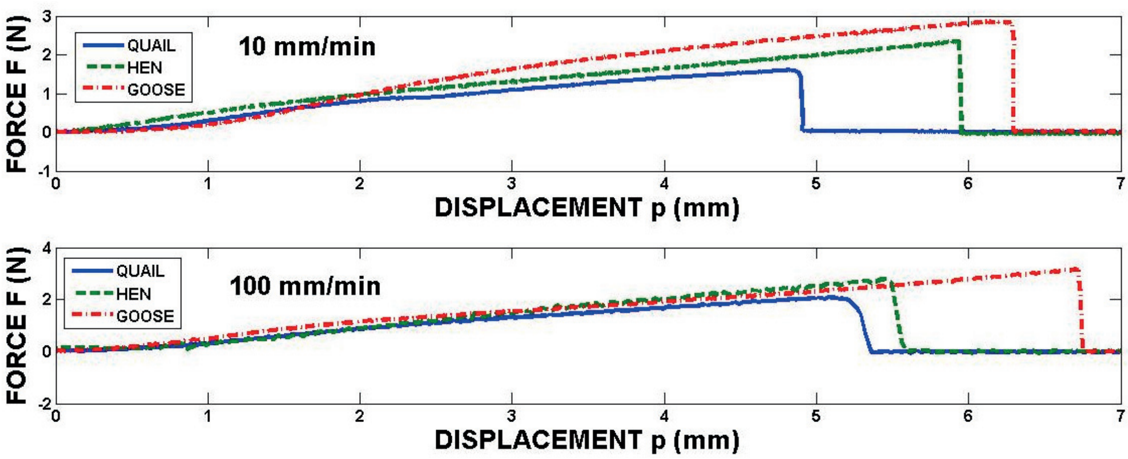
The dependence of the ultimate tensile strength on the loading velocity v can be fitted by the power function:

$$UTS = a + bv^c . \quad (4)$$

The parameters of Eq. 4 are given in the Tab. V.

The same function can be used for the fitting of experimental data on the fracture toughness. The corresponding coefficients are given in the Tab. VI.

The power function (4) can be also used for the fitting of data on the fracture strain ε_f for quail and hen eggs. The coefficients are given in the Tab. VII.



4: *Experimental records of force-displacement for two different loading rates*

II: *Fracture parameters of the eggshell membranes (Japanese quail eggs)*

Loading rate	Ultimate tensile strength [MPa]			
	Minimum	**Mean**	**Maximum**	**Standard deviation**
1 mm.min^{-1}	1.05	1.11	1.15	0.04
10 mm.min^{-1}	2.09	2.16	2.24	0.06
100 mm.min^{-1}	2.80	2.95	3.08	0.11
800 mm.min^{-1}	3.57	3.74	3.91	0.14
	Fracture strain [1]			
	Minimum	**Mean**	**Maximum**	**Standard deviation**
1 mm.min^{-1}	0.184	0.204	0.247	0.025
10 mm.min^{-1}	0.242	0.281	0.311	0.026
100 mm.min^{-1}	0.339	0.352	0.373	0.014
800 mm.min^{-1}	0.387	0.408	0.421	0.013
	Fracture toughness [J/m^3]			
	Minimum	**Mean**	**Maximum**	**Standard deviation**
1 mm.min^{-1}	76874.22	91869.40	128544.59	20844.65
10 mm.min^{-1}	340874.07	362883.64	376454.47	13293.23
100 mm.min^{-1}	389065.19	462359.97	486152.42	41308.33
800 mm.min^{-1}	664204.87	686757.33	704406.12	15044.17

III: *Fracture parameters of the eggshell membranes (goose eggs)*

Loading rate	Ultimate tensile strength [MPa]			
	Minimum	**Mean**	**Maximum**	**Standard deviation**
1 mm.min^{-1}	1.920071	1.971661	2.014312	0.034015
10 mm.min^{-1}	2.529502	2.583293	2.624702	0.035093
100 mm.min^{-1}	2.634261	2.788316	2.920022	0.103276
400 mm.min^{-1}	3.766396	3.839524	3.910143	0.053282
800 mm.min^{-1}	4.313467	5.041023	5.751289	0.528752
	Fracture strain [1]			
	Minimum	**Mean**	**Maximum**	**Standard deviation**
1 mm.min^{-1}	0.244090	0.250444	0.256095	0.005268
10 mm.min^{-1}	0.319801	0.326091	0.329823	0.004730
100 mm.min^{-1}	0.322989	0.339340	0.357237	0.013624
400 mm.min^{-1}	0.411308	0.419686	0.428123	0.006762
800 mm.min^{-1}	0.525468	0.531089	0.537910	0.005045
	Fracture toughness [J/m^3]			
	Minimum	**Mean**	**Maximum**	**Standard deviation**
1 mm.min^{-1}	347362	351519	354109	2743
10 mm.min^{-1}	693398	710578	747518	21783
100 mm.min^{-1}	1184200	1223068	1245695	23050
400 mm.min^{-1}	2120673	2160572	2284200	69764
800 mm.min^{-1}	2593815	2704937	2867523	102252

For the goose eggs the influence of loading rate on the fracture strain can be described by a linear function:

$$\varepsilon_f = a + bv, \quad (5)$$

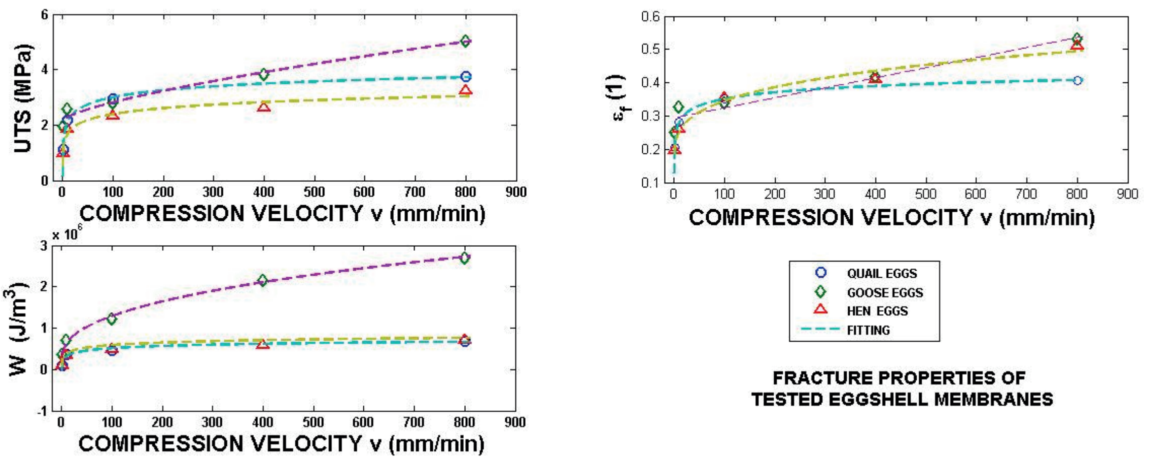
where a = 0.2942, b = 0.0003018 min.mm^{-1} and R^2 = 0.9332.

The statistical analysis of the obtained data was performed at loading rates 1, 10, 100 and 800 mm.min^{-1}. The results are presented in the Tabs. VIII–X.

With exception of the smallest loading velocity, v = 1 mm.min^{-1}, the fracture parameters UTS, ε_f and W increase from quail eggshell membranes towards to the goose eggshell membranes. The same tendency has been observed for the fracture parameters of the eggshells in our previous papers.

IV: *Fracture parameters of the eggshell membranes (hen eggs)*

Loading rate	Ultimate tensile strength [MPa]			
	Minimum	Mean	Maximum	Standard deviation
1 mm.min^{-1}	0.870474	0.973065	1.088092	0.087483
10 mm.min^{-1}	1.826440	1.848202	1.888617	0.027697
100 mm.min^{-1}	2.176184	2.340416	2.455979	0.102541
400 mm.min^{-1}	2.549244	2.603649	2.681369	0.056045
800 mm.min^{-1}	3.093290	3.223861	3.380857	0.124523
	Fracture strain [1]			
	Minimum	Mean	Maximum	Standard deviation
1 mm.min^{-1}	0.293602	0.303027	0.317544	0.010220
10 mm.min^{-1}	0.220139	0.231636	0.246372	0.010196
100 mm.min^{-1}	0.167102	0.279578	0.189587	0.008846
400 mm.min^{-1}	0.335579	0.344040	0.358985	0.009004
800 mm.min^{-1}	0.400034	0.411178	0.419943	0.007172
	Fracture toughness [J/m^3]			
	Minimum	Mean	Maximum	Standard deviation
1 mm.min^{-1}	0.181875	0.196750	0.208750	0.010573
10 mm.min^{-1}	0.246250	0.260713	0.279375	0.012874
100 mm.min^{-1}	0.341250	0.354007	0.373750	0.013866
400 mm.min^{-1}	0.398750	0.410682	0.431875	0.012752
800 mm.min^{-1}	0.491875	0.508625	0.521875	0.010802



5: *Main fracture parameters of tested eggshell membranes*

V: *Coefficients in equation (8), UTS vs. v, (R^2 denotes the correlation)*

Eggshell membrane	a [MPa]	b [MPa]	c [1]	R^2
Quail	10.37	–9.239	–0.0493	0.9957
Goose	2.17	0.025	0.7088	0.9764
Hen	–20.55	21.580	0.0133	0.9617

VII: *Coefficients in equation (8), ε_f vs. v, (R^2 denotes the correlation)*

Eggshell membrane	a [MPa]	b [MPa]	c [1]	R^2
Quail	0.9398	–0.7358	–0.0486	0.9999
Hen	0.2658	0.001836	1	0.8528
Goose	0.2942	0.0003018	1	0.9332

VI: *Coefficients in equation (8), W vs. v, (R^2 denotes the correlation)*

Eggshell membrane	a [MPa]	b [MPa]	c [1]	R^2
Quail	1.163×10^6	-2.058×10^6	–0.04779	0.9735
Goose	2.159×10^5	1.672×10^5	0.40510	0.9927
Hen	1.170×10^7	-1.161×10^7	0.00763	0.9915

VIII: *Results of ANOVA analysis of the results on UTS, (+ denotes statistically significant difference, n.s denotes no significant difference)*

Loading rate [mm.min^{-1}]	1	10	100	800
Quail – Hen	n.s	+	+	+
Hen – Goose	n.s	+	+	+
Quail – Goose	n.s	+	+	+

IX: *Results of ANOVA analysis of the results on the fracture strain, (+ denotes statistically significant difference, n.s denotes no significant difference)*

Loading rate [mm.min^{-1}]	1	10	100	800
Quail – Hen	n.s	+	n.s	+
Hen – Goose	+	+	+	+
Quail – Goose	+	+	+	+

X: *Results of ANOVA analysis of the results on the fracture toughness, (+ denotes statistically significant difference, n.s denotes no significant difference)*

Loading rate [mm.min^{-1}]	1	10	100	800
Quail – Hen	n.s	+	n.s	+
Hen – Goose	+	+	+	+
Quail – Goose	+	+	+	+

CONCLUSION

Fracture of eggshell membranes at tensile loading has been studied. The fracture behaviour can be described in terms of the ultimate tensile strength (UTS), fracture strain (ε_f) and fracture toughness (W). Results obtained in this paper show that these quantities increase with the loading rate. With exception of the smallest loading velocity (1 mm.min^{-1}) the values of the fracture parameters exhibit the smallest value for the eggshell membrane of the quail egg and the highest for the eggshell membrane of goose egg.

Acknowledgement

The authors would like to acknowledge the support of IP 17/2014 IGA MENDELU and of the Institute of Thermomechanics AS CR, v. v. i. of the Czech Academy of Sciences through institutional support No. RVO: 61388998.

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Contact information

Jana Strnková: jana.strnkova@ mendelu.cz
Šárka Nedomová: snedomov@mendelu.cz
Vojtěch Kumbár: vojtech.kumbar@ mendelu.cz
Jan Trnka: trnka@it.cas.cz