Effect of the loading rate on compressive properties of goose eggs

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Abstract The resistance of goose (*Anser anser f. domestica*) eggs to damage was determined by measuring the average rupture force, specific deformation and rupture energy during their compression at different compression speeds (0.0167, 0.167, 0.334, 1.67, 6.68 and 13.36 mm/s). Eggs have been loaded between their poles (along *X* axis) and in the equator plane (*Z* axis). The greatest amount of force required to break the eggs was required when eggs were loaded along the *X* axis and the least compression force was required along the *Z* axis. This effect of the loading orientation can be described in terms of the eggshell contour curvature. The rate sensitivity of the eggshell rupture force is higher than that observed for the Japanese quail's eggs.

Keywords Goose egg · Compression · Rupture force · Deformation · Loading rate · Eggshell curvature

1 Introduction

Eggs can be regarded as naturally packaged food. When examining the quality of the packaging, one primarily considers the strength of the eggshell. For table eggs, shells must be strong enough to prevent failure during packing and/or transportation. For hatching eggs,

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shells have to be also thick and strong for preservation of the embryo as well as thin for gas exchange and weak enough to allow the chick to crack the shell when hatching [1].

Eggshell strength consists of both structural and material components. The material strength of the eggshell depends on its microstructure and chemical composition, both of which vary through the shell thickness. The main factors which affect the material strength have been studied primarily in hen's eggs, see e.g. [2–4]. Structural strength, on the other hand, is related to the interaction among the building units and depends on several variables, namely egg dimensions, egg shape, eggshell thickness, and distribution of the shell components. The resistance of eggshell to mechanical loading can be characterized by measures such as rupture force, specific deformation, rupture energy and firmness [5–8].

It was found that eggshell strength is also significantly dependent on the compression rate. The first data were obtained in papers [7–9] for hen's eggs. The effect of loading rate on the eggshell rupture force has been also found for Japanese quails's eggs [10, 11].

The aim of this study was to determine the mechanical behaviour of the goose's eggs such as the rupture force, eggshell deformation at the rupture and the energy absorbed during the loading process at different loading rates. This research extends our preliminary results obtained in [12]. In order to interpret the obtained results, some basic physical properties such as dimensional properties, description of the eggshell contour, sphericity, unit mass, egg surface, volume and eggshell thickness have been also evaluated.

2 Materials and methods

Exactly 226 eggs (3 days old) from goose (*Anser anser f. domestica*) were chosen for the experiment. Temperature of short storage was 6 °C and measuring temperature was 18 °C. Geese were kept in free-range technology at a commercial breeding farm in the Czech Republic (region South Moravia). Eggs were collected from 3 years old geese.

Length L and width B of eggs were measured with a digital calliper to the nearest 0.01 mm. The unit mass of each egg was weighed with an electronic balance to the nearest 0.001 g. The eggshell thickness was determined according to [13]. Shape index SI was determined using the following equation [14]:

$$SI = \frac{L}{B} 100\%. \quad (1)$$

The knowledge of the egg dimensions enables to evaluate the geometric mean diameter D , sphericity Φ , volume V , surface area S of eggs using the following equations [15]:

$$D = (LB^2)^{\frac{1}{3}}, \quad (2)$$

$$\Phi = \frac{D}{L} 100\%, \quad (3)$$

$$S = \pi D^2, \quad (4)$$

$$V = \frac{\pi}{6} LB^2. \quad (5)$$

In the second step the digital photos of the eggs were obtained. The image analysis was performed using Matlab software has been used for the evaluation of the coordinates x_i and y_i of the egg contour [16]. Instead of Cartesian coordinates the shape the eggshell contour can be described using the polar coordinates r and ϕ :

$$x = r \cos \phi, \quad y = r \sin \phi.$$

The experimental points r_i and ϕ_i have been fitted by the Fourier series

$$r = a_0 + \sum_{i=1}^{i=\infty} [a_i \cos(i\omega\phi) + b_i \sin(i\omega\phi)].$$

The values of the radius of the curvature R , egg surface S and the egg volume V are given by the well-known equations of differential geometry – see e.g. [16]:

$$R = \frac{\left[\left(\frac{dx}{d\Phi} \right)^2 + \left(\frac{dy}{d\Phi} \right)^2 \right]^{\frac{3}{2}}}{\left| \frac{dx}{d\Phi} \frac{d^2y}{d\Phi^2} - \frac{dy}{d\Phi} \frac{d^2x}{d\Phi^2} \right|}, \quad (6)$$

$$S = 2\pi \int_0^\pi r \sin \Phi \sqrt{\left(\frac{dx}{d\Phi} \right)^2 + \left(\frac{dy}{d\Phi} \right)^2} d\Phi, \quad (7)$$

$$V = \pi \int_{\Phi_1}^{\Phi_2} r^2(\Phi) \sin^2 \Phi \frac{dx(\Phi)}{d\Phi} d\Phi. \quad (8)$$

The eggs have been compressed between the two plates using the testing device TIRAT-EST. The egg sample was placed on the fixed plate and loaded at the compression velocities 0.0167, 0.167, 0.334, 1.67, 6.68 and 13.36 mm/s until the egg ruptured. Two mutually perpendicular compression axes (X , Z) corresponding to the main geometrical axes were used, see Fig. 1. On the left side the loading along the X axis is shown. Two more orientations were considered in the case of the X axis. If the egg sharp end is in contact with the moving plate the symbol X_s is used. The symbol X_b corresponds to the orientation where egg's blunt end is in contact with the moving plate.

Response of the egg to compression loading between two parallel plates is characterized by a nearly linear increase in the loading force F with moving plate displacement p . At the moment of eggshell break the loading force rapidly decreases. The maximum of the loading

Fig. 1 Schematic of the egg compression

Table 1 Mass and main dimensional properties of the tested eggs (Std. denotes standard deviation)

Parameter	Minimum	Average	Maximum	Std.
L [mm]	70.77	89.57	100.29	3.94
B [mm]	50.97	58.16	95.32	3.12
D [mm]	60.56	67.14	92.73	2.65
SI [%]	55.75	65.03	108.63	4.13
Φ	0.6774	0.7503	1.0567	0.0305
S [mm ²] – (4)	11521.44	14117.21	16749.26	854.50
V [mm ³] – (5)	116438.70	172178.46	222377.64	17431.78
S [mm ²] – (7)	11414.77	13798.07	16129.59	755.36
V [mm ³] – (8)	112126.90	169166.27	218562.40	19404.04
m [g]	126.15	163.69	215.35	14.44

force is then defined as the rupture force F_m . The next parameter describing the eggshell rupture is the displacement (deformation) at the point of rupture of the eggshell p_m [mm]. The specific deformation was obtained from the following equation:

$$\varepsilon = \frac{p_m}{L_0}, \quad (9)$$

where L_0 is the undeformed egg length measured in the direction of the compression axis (X or Y), see [17].

Energy W absorbed by an egg at the moment of rupture was determined by calculating the area under the force F –deformation p curve:

$$W = \int_0^p F(p) dp. \quad (10)$$

The egg resistance to the fracture is also characterized by the firmness Q , defined as a ratio of compressive force to deformation at the rupture point of an egg:

$$Q = \frac{F_m}{p_m}. \quad (11)$$

The use of this parameter is effective if the force linearly increases with the displacement up to the fracture. Because this is not typical for goose eggs this parameter has not been used in the given paper [12].

Analysis of variance (ANOVA) was applied to all variables studied. Mean values obtained in the different measurements were compared by one-way ANOVA. Statistical analysis was performed with the statistical toolbox of Matlab version R2011a (MathWorks, USA).

Table 2 Radii of the curvature (Std. denotes standard deviation)

	Minimum	Average	Maximum	Std.
R_1 [mm]	12.57	15.71	21.68	1.387
R_2 [mm]	14.64	21.10	26.84	1.844
R_3 [mm]	41.15	61.25	125.20	9.624

Table 3 Eggshell thickness (Std. denotes standard deviation)

	Minimum	Mean	Maximum	Std.
Sharp end [mm]	0.248	0.505	0.722	0.0838
Blunt end [mm]	0.267	0.460	0.659	0.0821
Equator [mm]	0.321	0.511	0.681	0.0681
Average [mm]	0.313	0.492	0.642	0.0698

3 Experimental results and discussion

The mass of eggs and main geometrical properties of the goose eggs are presented in Table 1.

The radii of the egg counter curvature were evaluated at the sharp end R_1 , blunt end R_2 , and at the equator circumference R_3 . Their values are given in Table 2.

The knowledge of these radii is very useful, namely for the solution of contact problems [18].

Eggshell thicknesses are given in Table 3.

Examples of the experimental recording of the force F – displacement p curves are displayed in the Fig. 2. The force increases to a maximum, which corresponds to the rupture force F_m at which fracture of the eggshell occurs. The increase of the force is not strictly a linear function of the displacement (p).

Example shown in the Fig. 2 indicates that the value of the rupture force depends on the loading orientation and on the loading rate v . The orientation of the loading as well as the loading rate exhibits an influence on all the parameters describing the mechanical behaviour of eggs as shown in Figs. 3, 4 and 5.

The data on the fracture behaviour of the eggshell are given in Tables 4, 5 and 6. All results in these tables are presented as means $\pm$ Std. ($n = 10$). For each column in Tables 4–6 any two values not followed by the same letter were significantly different ($p < 0.05$).

The rupture force increases with the compression velocity. The loading orientation with the least resistance to the rupture is the Z axis. The highest rupture are forces required when

Fig. 2 Examples of experimental records of force–displacement (deformation)

Fig. 3 Effect of the loading rate on the egg fracture parameters – X_b orientation of the loading

loading along the X_s axis. The deformation p_m increases with the compression rate. The effect of compression axes on rupture force was also significant. The analysis of experimental data shown that the effect of the compression velocity, v , on rupture force (F_m), deformation (p_m) and rupture energy (W) can be described by the functions:

$$F_m = av^n + b, \quad (12)$$

$$p_m = av^n + b, \quad (Z \text{ and } X_s \text{ axes}) \quad (13)$$

$$p_m = a_2v^2 + a_1v + b. \quad (X_b \text{ axis}) \quad (14)$$

and

$$W = av^n + b \quad (15)$$

Respectively parameters of (12)–(15) are given in Table 7.

Fig. 4 Effect of the loading rate on the egg fracture parameters – X_s orientation of the loading

Fig. 5 Effect of the loading rate on the egg fracture parameters – Z orientation of the loading

Table 4 Fracture parameters of eggs compressed along X_b axis

Loading rate v [mm/s]	F_m [N]	p_m [mm]	W [N•mm]	p_m/L [1]
0.0166	42.75 ± 2.712^a	0.276 ± 0.0327^a	5.365 ± 0.733^a	0.003076 ± 0.00044^a
0.1666	53.67 ± 2.131^b	0.295 ± 0.0381^b	7.185 ± 0.911^b	0.003291 ± 0.00049^a
0.3333	72.82 ± 1.303^c	0.319 ± 0.0238^c	10.555 ± 0.742^c	0.003583 ± 0.00029^a
1.6666	84.97 ± 2.439^d	0.318 ± 0.0220^c	12.295 ± 1.112^d	0.003564 ± 0.00031^a
6.6666	111.08 ± 2.926^e	0.326 ± 0.01838^d	16.530 ± 1.312^e	0.003622 ± 0.00067^a
13.333	119.91 ± 1.777^f	0.400 ± 0.0226^e	19.757 ± 0.657^f	0.004593 ± 0.00035^b

Table 5 Fracture parameters of eggs compressed along X_s axis

Loading rate v [mm/s]	F_m [N]	p_m [mm]	W [N•mm]	p_m/L [1]
0.0166	63.72 ± 1.80^a	0.249 ± 0.015^a	7.21 ± 0.51^a	0.00286 ± 0.00019^a
0.1666	83.81 ± 2.97^b	0.306 ± 0.046^b	11.69 ± 2.04^b	0.00344 ± 0.00050^b
0.3333	92.97 ± 2.08^c	0.431 ± 0.019^c	19.92 ± 1.41^c	0.00487 ± 0.00021^c
1.6666	121.89 ± 2.58^c	0.471 ± 0.056^c	26.14 ± 3.57^d	0.00523 ± 0.00066^c
6.6666	135.28 ± 1.98^d	0.531 ± 0.017^d	32.66 ± 1.43^e	0.00591 ± 0.00051^d
13.333	141.32 ± 2.63^d	0.552 ± 0.019^d	36.86 ± 1.75^f	0.00599 ± 0.00024^d

Table 6 Fracture parameters of eggs compressed along Z axis

Loading rate v [mm/s]	F_m [N]	p_m [mm]	W [N•mm]	p_m/L [1]
0.0166	63.72 ± 1.799^a	0.249 ± 0.015^a	7.2132 ± 0.506^a	0.00285 ± 0.0002^a
0.1666	83.81 ± 2.968^b	0.306 ± 0.046^{ab}	11.692 ± 2.045^b	0.00343 ± 0.0005^b
0.3333	92.80 ± 2.907^c	0.431 ± 0.019^{ab}	19.918 ± 1.413^b	0.00487 ± 0.0002^{ab}
1.6666	121.89 ± 2.575^d	0.471 ± 0.055^c	26.141 ± 3.565^c	0.00522 ± 0.0006^c
6.6666	135.28 ± 1.892^e	0.531 ± 0.018^c	32.6628 ± 1.435^d	0.005914 ± 0.0005^c
13.333	141.32 ± 2.629^f	0.552 ± 0.016^c	36.860 ± 1.752^e	0.005990 ± 0.0002^c

Table 7 Parameters of Eqs. (12–15). R^2 is the coefficient of determination

	Loading orientation	a [$\text{N}\bullet\text{mm}^{-n}\bullet\text{s}^n$]	n [–]	b [N]	R^2
(12)	X_s axis (sharp end)	280.3	0.04519	-171.1	0.9854
	X_b axis (blunt end)	78.4	0.16410	1.487	0.9816
	Z axis (equator)	2347	0.003407	-2227.8	0.9832
(13)	Loading orientation	a [$\text{mm}\bullet\text{mm}^{-n}\bullet\text{s}^n$]	n [–]	b [mm]	R^2
	X_s axis (sharp end)	-1.8570	-0.02516	2.2980	0.9770
	Z axis (equator)	0.6524	0.08750	-0.2303	0.9361
(14)	Loading orientation	a_2 [$\text{mm}^{-1}\bullet\text{s}^2$]	a_1 [s]	b [mm]	R^2
	X_b axis (blunt end)	0.0003403	0.002931	0.2987	0.8722
	Loading orientation	a [$\text{N}\bullet\text{mm}\bullet\text{mm}^{-n}\bullet\text{s}^n$]	n [–]	b [$\text{N}\bullet\text{mm}$]	R^2
(13)	X_s axis (sharp end)	49.46	0.0977	-26.65	0.9766
	X_b axis (blunt end)	9.91	0.2299	1.510	0.9807
	Z axis (equator)	19.02	0.1779	-5.653	0.9904

The effect of the loading rate on the specific deformation (9) is not too significant. The sensitivity of the rupture force to the compression velocity can be characterized by the parameter:

$$\frac{\partial F_m}{\partial v} = anv^{(n-1)}. \quad (16)$$

In Fig. 6 the dependence of the rupture force sensitivity to the loading rate is displayed.

This sensitivity decreases with the loading rate. The highest decrease occurs for the loading along the Z axis and the lowest decrease is observed for the loading along the X_b axis. The effect of the loading orientation on the rupture force sensitivity depends on the loading rate.

The dependence of the eggshell fracture parameters on the loading orientation can be partially explained by the egg shape. In the ASAE method [19] for compression tests of food materials of convex shape are described. According to this theory the loading force depends on the main curvature of the eggshell. If we denote the radii of the curvature at the

Fig. 6 Sensitivity of the eggshell rupture force to the loading rate

Table 8 Curvatures of the tested eggs. All results are presented as means $\pm$ Std. ($n = 10$). For each column any two values not followed by the same letter were significantly different ($p < 0.05$)

Loading rate v [m/s]	Sharp end k [1/mm]	Blunt end k [1/mm]	Equator k [1/mm]
0.0166	0.125 $\pm$ 0.012 ^a	0.097827 $\pm$ 0.0076 ^a	0.1252 $\pm$ 0.012 ^a
0.1666	0.129 $\pm$ 0.012 ^a	0.100096 $\pm$ 0.0098 ^a	0.1285 $\pm$ 0.012 ^a
0.3333	0.123 $\pm$ 0.014 ^a	0.089732 $\pm$ 0.0071 ^a	0.1225 $\pm$ 0.013 ^a
1.6666	0.131 $\pm$ 0.010 ^a	0.095602 $\pm$ 0.0089 ^a	0.1307 $\pm$ 0.011 ^a
6.6666	0.131 $\pm$ 0.012 ^a	0.096052 $\pm$ 0.0089 ^a	0.1314 $\pm$ 0.012 ^a
13.333	0.123 $\pm$ 0.014 ^a	0.098698 $\pm$ 0.0076 ^a	0.1227 $\pm$ 0.014 ^a

sharp end as R_1 , at the blunt end as R_2 and at the equator as R_3 then for the loading in the X_s , X_b and Z axes we obtain the curvatures k_1, k_2, k_3 :

$$X_s : k_1 = \frac{2}{R_1}, \quad X_b : k_2 = \frac{2}{R_2}, \quad Z : k_3 = \frac{1}{R_3} + \frac{2}{W}$$

The values of the curvatures are given in Table 8. It is obvious that the curvatures are the same for all tested eggs the same. The same conclusion is valid also for the eggshell thickness.

In Fig. 7 the dependence of the rupture force on the curvature is displayed. It is evident that the rupture force increases with the main eggshell curvature.

The increase of the rupture force with the compression velocity has been also observed for the hen's eggs e.g. [9] and for the quail eggs, by [11, 20]. As is shown in Fig. 8 the rupture force is highest for the goose eggs and smallest for the quail eggs. Similar results are valid also for the deformation and absorbed energy.

The increase of the rupture force with compression rate has been observed for many different materials, e.g. [21]. The physical interpretation of this phenomenon is known for metallic materials, polymers and for some ceramics. The first explanation of the mechanism of the eggshell strength dependence on the loading rate (e.g. on the compression velocity) was probably given by Carter [22]. Carter considered the effect of loading rate as the period of time over which a load is applied. The decrease in strength of an eggshell which accompanies an increasing of the period mentioned above might come about by either of two

Fig. 7 Effect of the eggshell curvature on the rate dependence of the rupture force

Fig. 8 Effect of the loading rate on the rupture force of the eggs of different domestic fowls

mechanisms: a decrease in the strength of the material constituting the strong, outer layer of the mineral shell, or a decrease in the thickness of this layer brought about by deepening of the crevices that are normally present between adjacent crystal columns in the weak, inner layer of the shell. The experiments described in the cited paper indicate the dominant role of the second mechanism. This mechanism explains many phenomena like delayed fracture, etc. The use of this model in the interpretation of our results was not successful. In order to obtain some insight on this problem it is reasonable to take into account the behaviour of the outer layer of the mineral shell under mechanical loading. This layer exhibits similar features to many ceramics. The effect of the loading rate on the fracture of ceramics and generally brittle materials is described in many papers, e.g. [23]. In our previous paper [11] a procedure for the design of the corresponding constitutive equations for the description of the eggshell behaviour has been outlined.

4 Conclusions

The results indicated that the mechanical properties of the goose eggshell are highly dependent on compression velocities. Rupture force increases with the compression velocities for all main orientations of egg loading. The rupture force observed for eggs compressed along the X_s axis were higher than the values obtained for the X_b and Z orientation. The effect of the loading orientation can be quantitatively described using of the main eggshell curvature at the point of contact between egg and moving plate. The displacements at the eggshell fracture (deformation) and rupture energy values observed for eggs compressed along the X_s axis were also higher than the values obtained when testing eggs in the X_b and Z orientations. The sensitivity of the rupture force to the compression velocity decreases with this velocity. This decrease is highest for the eggs loaded along the Z axis. Comparison with the behaviour of the eggshells of hen and quail eggs show that the highest strength of the eggshell occurs in goose eggs and the lowest strength is typical for the quail eggs.

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