Study on the friction coefficient between eggshells and powders with various chosen surfaces

Badania współczynnika tarcia między skorupkami i proszkami jaj a różnymi wybranymi powierzchniami

Marek Wozniak[1], Maciej Kuchar[1], Sergiusz Zakrzewski[1], Krzysztof Siczek[1*], Andrzej Obraniak[2], Adam Rylski[3], Przemyslaw Kubiak[4]

[1] Department of Vehicles and Fundamentals of Machine Design, Lodz University of Technology, Stefanowskiego Str. 1/15, 90-537 Lodz, Poland; [2] Faculty of Process and Environmental Engineering, Lodz University of Technology, Wolczanska Str. 213, 90-924 Lodz, Poland; [3] Institute of Materials Science and Engineering, Lodz University of Technology, Stefanowskiego Str. 1/15, 90-537 Lodz, Poland; [4] Division of Ecotechnics, Lodz University of Technology, Wolczanska Str. 221, 93-005 Lodz, Poland.

Abstract

Transport of fresh or powdered chicken eggs uses conveyors with elements made of steel or plastics, and surfaces often coated by Teflon. Various forms of eggs contact with said surfaces and are subject to friction processes between them. The frictional resistances cause a load on the devices driving the conveyors and a local and temporary increase in temperature in the contact zones and allow the abrasive wear of both the surfaces of the conveyors, packages and the eggshells themselves. This study aimed to determine such the coefficient of friction and wear intensity at various contacts. The friction and wear tests were conducted on two tribotesters and the results are shown in the article.

Abstrakt

Transport świeżych lub sproszkowanych jaj kurzych wykorzystuje przenośniki z elementami wykonanymi ze stali lub tworzyw sztucznych, a powierzchnie często pokryte teflonem. Różne formy jaj stykają się ze wspomnianymi powierzchniami i podlegają procesom tarcia między nimi. Opory tarcia powodują obciążenie urządzeń napędzających przenośniki oraz lokalny i tymczasowy wzrost temperatury w strefach styku i pozwala na zużycie ścierne powierzchni przenośników, pakietów i samych skorupek jaj. Badanie to miało na celu określenie takiego współczynnika tarcia i intensywności zużycia w różnych stykach. Testy tarcia i zużycia przeprowadzono na dwóch tribotesterach, a wyniki pokazano w artykule.

Słowa kluczowe: skorupka i proszek jaj ptasich, współczynnik tarcia, zużycie, chropowatość, tribotester

Keywords: bird eggs shell and powder, friction coefficient, wear, roughness, tribotester

[*]corresponding author e – mail: ks670907@p.lodz.pl
DOI: 10.57636/68.2023.1.8

1. Introduction

Fresh or powdered eggs, mainly of chicken, are used and processed in the production processes of the food industry. They are transported either by gravity on inclined chute surfaces of fixed structures used during a specific production process, or by means of various conveyors, the elements of which are made of various materials, such as stainless steel or some plastics. The surfaces of these elements can be covered with protective coatings, such as Teflon. During transport between different devices of the production process, the different forms of eggs come into contact with said surfaces and are subject to friction processes between them. Such friction occurs with relatively small loads and displacements of various nature and size. These can be both small vibration movements, such as when transporting fresh eggs in packages, and large movements, when transporting powdered egg or shells on conveyors. The existing frictional resistance causes the load on the devices driving the conveyors and the local and transient increase in temperature in the contact zones, and allows the surface of the conveyors, packaging and the eggshells to be worn. The proper flow of egg production, processing and packaging is strongly affected by physical features of eggs and their resistance to damage via a mechanical shock. The size of an egg depends on age, breed and weight of the chicken. Eggs can belong to various strict size categories according to weight (more specifically to minimum net weight expressed in oz per dozen), including peewee (35–42 g), small (42–49 g), medium (49–56 g), large (56–65 g), extra large (65–70 g) and jumbo (70 g). The most commonly available are medium, large and extra large ones [1, 2]. Egg size and the eggshell thickness are highly correlated. The size of an egg mainly depends on the age, breed and weight of the hen. As the hen ages, her eggs increase in size. Pullets with significant underweight at sexual maturity produce small eggs. The egg weight is weakened by heat, stress, overcrowding and poor nutrition. Chicken eggs are commonly treated as packaged food. During transportation, a crucial role of the packaged egg material plays the mechanical strength of the eggshell. Eggshell quality is affected by egg size and weight. Egg shape index and eggshell thickness decide to the number of damaged eggs over handling and transport [3].

Cahya and Marfuah [4] found that eggshells of domestic chicken, chicken broiler, duck and quail had almost the same initial structure with $CaCO_3$ rhombohedra crystals. According to Athanasiadou et al. [5] eggshells create a hard, protective biomineralized chamber for embryonic growth. In the calcitic chicken eggshell, the mineral and organic phases organize hierarchically across various length scales. Variation in nanostructure across the shell thickness influences its hardness, elastic modulus, and dissolution features. The nanostructure varies during egg incubation, weakening the shell for chick hatching. The above mentioned powdered eggs are often used in the production of food products such as cakes or ice cream in order to reduce the penetration of Salmonella bacteria, sometimes present in raw eggs, into the processed raw material. Belyavin [6] stated that, there are four major headings of dried egg products available: dried egg white, dried plain whole egg and yolk, dried blends of whole egg and yolk with carbohydrates, and special types of dried egg products. A weakening of the moisture content in egg powder from around 74% to 2–4% by weight decreases weight and volume and a concentration of food value. The physical properties important for dried egg products are bulk density, dispersibility, solubility, and reconstituted viscosity

In Ref. [7] was explained that the microwave generated by the microwave drying machine of egg powder and yolk powder can penetrate the inside and outside of the object and heat it simultaneously. The friction between molecules generates heat itself to achieve the effect of rapid drying. According to [8] values of temperature above 43 °C are not recommended for the storage of egg powder.

The study aimed to determine the coefficient of friction at various contacts of eggshells and egg powder with samples made of stainless steel with and without Teflon coating, often used in various production processes. Additionally, the wear intensity in contacts between eggshells was determined.

2. Properties of egg, eggshells, egg powders and products containing eggshells

The physic-chemical properties of fresh and processed eggs and egg-related products are very important, particularly as they affect the safe conditions of storage and transport of such products and therefore have been extensively studied at various centres.

2.1. The physic-chemical properties of fresh and processed eggs and egg products

The eggshell strength is the important parameter of the egg quality [9-17]. Eggshell strength is affected by the thickness of eggshell, shell stiffness and rupture force and energy [18-20]. The highest correlation existed between the physical and the mechanical features of chicken eggs [21, 22]. Several studies were carried out on the properties of chicken and Japanese quail eggs under various compression loads [18, 22-24]. The eggshell strength was strongly affected by the compression speed [18, 19]. There were significant correlations between egg palisade length and breaking strength, shell thickness and stiffness [25]. Kumbar et al. [26] determined weight, weight loss, shape index, yolk height, albumen height, yolk index, albumen index, and Haugh units of the geese eggs. They also studied the rheological behavior of liquid egg products (egg yolk, albumen, and whole liquid egg) using a concentric cylinder viscometer. Flow curves of all liquid egg products exhibited non-Newtonian shear thinning behavior well described by the Herschel-Bulkley model or the Ostwald-de Waele model. The storage duration affected the rheological behavior of various liquid egg products in a different manner. Except the very low shear rates, the viscosity of the egg yolk as well as of the whole liquid egg weakened with storage time. At lower shear rates the albumen viscosity enhanced with storage duration. The ultimate tensile strength, fracture strain, and fracture toughness of the eggshell membrane enhanced with the loading rate but decreased during the egg storage.

Mahmoodi et al. [27] found that the exposition of egg samples to the magnetic field enhanced the shell's resistance to failure. Additionally, samples immersed in sunflower oil had a lower failure force than those not immersed in such an oil. Eggshells are more and more utilized in the form of nano powders, particularly in medicine [28] and biomedicine [29-33]. There are various experimental techniques used for the eggshell strength measurement [34-48], both destructive and non-destructive. The shell strength of a chicken egg is usually determined by the quasi-static, non-destructive compression of an egg betwixt two parallel steel plates [21].

Interestingly, Severa et al. [44] discussed the suitability and applicability of a Berkovich indentation for determination of mechanical properties of hen's eggshell tested in the area surrounding equator line. Nanoindentation was found as a suitable tool for determining local variations of mechanical properties of eggshells. The very important problem for the food industry is the occurrence of various contaminations in eggs and their shells [45-48] such as Salmonella, antibiotics, dioxins and others.

The presented literature reports show that the physical and the mechanical properties of eggs, particularly of chicken ones are strongly corelated. A number of parameters characterizing the properties of eggs have been distinguished, such as i.e., weight of eggs and shells, protein content, crude fat, crude fiber, ash content, total and essential amino acids. The eggshell strength and its possible brittle cracking strongly affect the wear of a whole egg. Various methods allowing measuring eggshell strength can be useful for determining the model parameters of the egg mechanical wear, however, no model even partially described wear of the whole egg has been found in the literature so far. Additionally, no model describing the effect of contamination in egg and in eggshell on the wear of the whole egg or on the friction between eggshell and other eggshell or other surfaces has been found in the literature so far.

2.2. The properties of egg powders

According to [49], the powdered eggs have an advantage over the fresh ones that their contamination from the breakage of shells is impossible. Daramola [50] reported that whole egg powders produced by spray, freeze or dehydrator methods are generally accepted and serve as good alternatives to fresh eggs in addition to their use in the confectionery industry not compromising the final product quality. Huda et al. [51] compared the physicochemical characteristics of egg white powder from eggs of various types of bird (local kampung chicken, local fighting chicken, local serama chicken, leghorn chicken, turkey, and guineafowl). The mentioned characteristics of egg white powder varied noticeably among eggs from various types of bird. Koç et al. [52] studied the effect of moisture on the glass transition temperature (Tg), flow properties, color, and morphology of spray-dried powdered egg. They found that the glass transition temperature of powdered egg weakened with an enhancement of water activity. At low water activity values, the powder exhibited poor flowability and high cohesiveness. Koç et al. [53] studied physical properties and oxidative stability of egg powder microencapsulated by spray drying. They reported that the use gelatin as wall material highly enhanced the moisture content and water activity of egg powder over storage and it increases flowability. Egg powders comprising pullulan as wall material had a fibrous structure and the lowest bulk density. Insertion of lactose as wall material improved the oxidative stability. Lai [54] studied water sorption and flow characteristics of whole egg powder with and without flow conditioners. Flow conditioner silica and sodium silico-aluminate enhanced the egg powder's flowability due to particle surface modification. Insertion of the conditioners eliminated the hysteresis loop and increased the moisture uptake by powders. Ndife et al. [55] reported that egg yolk powder exhibited higher emulsification capacity and stability in comparison to whole egg and egg white powder. The egg white powder exhibited higher foam stability and capacity compared to whole egg and egg yolk powders. The highest coagulation temperature was for egg yolk, followed by whole egg and egg white. The highest solubility occurred in egg white, followed by whole egg and egg yolk powders, while the inverted tendency occurred for the water and oil absorption properties. The total solids were high in all powders studied. Kudre et al. [56] studied physicochemical and functional features of freeze-dried egg powders from Japanese quail and white Leghorn chicken. The β-sheet showed to be the major secondary structure of all egg powders. The quail egg powders exhibited higher protein solubility than corresponding chicken egg powders at all pH tested. Quail egg powders exhibited higher emulsion activity index and emulsion stability index with higher foam expansion and stability than the corresponding chicken egg powders. Asghar and Abbas [57] studied the effect of utilization of whole egg powder with the replacement of fresh eggs in the bakery products. Chemical analysis of whole egg powdered cake at different doses showed the mean values of 29% moisture content, 1.5% ash, 8% fat, 5.8% protein, 2% fiber and 1.4% water activity. The sensory evaluation of cakes having 100% substitution showed the high results' significance.

Using the conductivity technique [58] studied emulsifying properties of oil in water emulsions using quail egg white protein as an emulsifying agent. They investigated the effect of various salt concentrations (NaCl) when mixed with carious egg white concentrations for corn and soybean vegetable oils. They found that emulsifying activity and emulsion stability enhanced with the increase of salt concentration. The increase of the egg white concentration weakly influenced emulsifying activity, increasing only the emulsion stability. It is clearly visible that the egg powder is a moisture of different egg components and varying amount of water, which can strongly affect the friction inside such a moisture or between the moisture and various surfaces. No model describing the effect of composition of egg powder and particularly a water amount therein on the friction inside egg powder or between egg powder and the other surfaces has been found in the literature so far.

2.3. Friction behavior of egg and egg-related product

Some authors investigated friction between egg and different surfaces. Altuntas and Sekeroglu [24] studied the effect of chicken egg weight on static coefficient of friction on various surfaces. The static coefficients of friction on glass, plywood, galvanized metal, rubber and chipboard, enhanced proportionally to an increase of egg weight tested. The rubber surface exhibited the maximum friction followed by plywood, chipboard, galvanized metal and glass. Polat et al. [23] reported that for Japanese quail eggs the values of the friction coefficient for quail eggs on the surfaces of plywood, glass, galvanized steel and fibreglass were equal to 0.301, 0.282, 0.274 and 0.266, respectively. Salawu et al. [59] studied the effect of pulverized organic carbon (Palm kernel shell and eggshell) on the mechanical properties of grey cast iron material with a chemical composition (wt.%) of 2.68C, 1.42 Si, 0.63 Mn, 0.13 S, 0.28 P. A mixture of 70 (wt.%) of pulverized palm kernel shell and 30 (wt.%) of pulverized egg shell was used for carburization of grey cast iron samples conducted at 900 □C for 60 minutes. There occurred the variation of force with time during sliding wear test carried out. The frictional force exhibited values of 0.0000796, 0.0000438 and later increased to a 0.086 and 0.10. The low friction observed at the initial stage of sliding was due to presence of oxide films and moisture at the interface of the material tested. The low friction was traceable to the high hardness value obtained from the mixture used during carburization. No information has been found about values of friction inside egg powder or eggshell powder and between eggshell and the other eggshell and also between egg powder or eggshell powder and other surfaces so far.

2.4. Wear of eggs end egg-related products

Some authors investigated wear properties of various egg-related products. Oladele et al. [60] studied the effects of calcined and uncalcined eggshell particles (ESP) and sisal fiber (SF) on the mechanical and wear characteristics of eggshell particles/sisal fiber reinforced epoxy composites. They found that calcination decreased the content of Ca and enhanced that of O in eggshells. The strong $CaCO_3$ occurred in uncalcined eggshell while Fe and $Ca_2Fe_7O_{11}$ in calcined one. Flexural features, tensile modulus and hardness increased for uncalcined eggshell particle-based composites while impact and wear resistance enhanced for the calcined eggshell particles based one. Using a pin-on-disk operating under nominally non-abrasive conditions of samples investigated, Venkatesh et al. [61] studied the wear and friction of implants coated by naturally derived powders like Seashell powder, Eggshell powder and Aluminium Oxide (Al_2O_3). Such coating materials were used to protect the surface of the implant material and interface with biological system. The polymers namely Nylon and Teflon were used as substrate and coated with above powder by using thermal spray method. Wear test was carried out to determine the wear resistance of the coated specimen, to assure the wear properties which is essential requirements of implants. They found that plasma spray deposition provided proper coating thickness and phase purity of powder samples after deposition. The powders derived from natural sources like Aluminium oxide, eggshells and sea shell were naturally bio-active and biocompatible. Eggshell coated Teflon and Al_2O_3 coated Nylon exhibited the better wear properties compared to other specimens. Dwiwedi et al. [62] carried out wear test on Al6061/eggshell composites under controlled load, reinforcement and sliding distance. They found that reinforcement of eggshell particles increased the wear resistance of matrix noticeably. Parivendan and Ramesh [63] studied the mechanical, tribological and thermal characteristics of hemp fibre reinforced eggshell epoxy polymer composites. Particularly, they investigated the effect of fiber and filler amounts on the mentioned characteristics of epoxy-based polymer composites. They conducted mechanical test on hardness, tensile, impact and flexural strength. They also studied abrasive wear of the specimen using pin-on-disc machine. The thermal stability was evaluated using a thermo gravimetric analyzer. The effect of hemp fibre and filler were studied under various mechanical and thermal conditions. They found that the insertion of fibre enhanced the load bearing ability of epoxy resin. Whereas insertion of eggshell filler enhanced thermal stability of composite. No information about values of wear of whole egg or eggshell and egg powder and no methods for their determination have been found in literature so far.

3. Properties of egg, eggshells, egg powders and products containing eggshells

3.1. The physic-chemical properties of fresh and processed eggs and egg products

3.1.1. The bulk density of the egg powder.

During the research, the bulk density was determined by weighing the samples on a digital balance and measuring their bulk volumes using a 250 cm3 glass measuring cylinder.

Bulk density values were calculated from equation *(1)*:

$$\rho_{egg-powder} = \frac{m_{ep+c} - m_c}{V_c} \tag{1}$$

where:

m_{ep+c} - mass of the sample together with the measuring cylinder,

m_c - mass of the measuring cylinder,

V_c - volume of granules in the measuring cylinder.

It is necessary to differ between the loose volume and the compacted one of granulate.

The loose volume of granulate is obtained by gravity filling the measuring cylinder with the granulate to the nominal value of its volume.

The compacted volume of granulate is obtained by placing the cylinder with the granulate on a laboratory shaker, subjecting it to vibrations and adding granules by gravity until the maximum organoleptically observed compacting of the granulate mass in the cylinder at the nominal value of its volume.

3.1.2. Natural repose angle

The angle β of natural repose is calculated from equation *(2)*:

$$\beta = \cot^{-1}\left(\frac{2h}{D}\right) \tag{2}$$

where:
h - height of a cone of a granulate heaped on shedding plate,
D - diameter of the shedding plate.

The device for measuring the natural angle of repose of loose granulate is shown in Figure 1. It comprises a container (1), from which the granulate is poured, a shedding plate (2), on which a material cone forms, and a measuring plate (3), which is used to measure the height of the heap, and before emptying the container, it closes the discharge opening. These elements are attached to the frame (4) ensuring their proper position. The container is ended with a flange for mounting with the screws (6) of the discharge funnel (5). Due to the mounting on the support (7), the sheathed plate is tilting. The support leg is attached to the frame with wing bolts (8). The measuring plate with the slider (9) is lifted by the screw (10) fixed in the slide bearings (11) cooperating with it. The rotation of the screw is carried out by the knob (12). The entire device is leveled by means of four height-adjustable feet (13). There is a drawer (14) under the shedding plate, in which loose granulate is collected that is not stuck on the plate. The height of the poured cone is read on the scale (15).

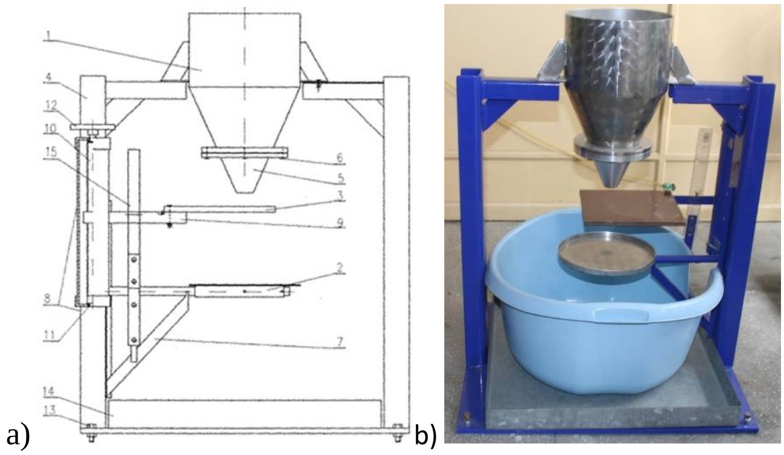

Fig. 1. A device for measuring the angle of repose (description in the text) designed in the Department of Process Apparatus of the Lodz University of Technology; a) scheme of the tester, b) view of the tester.

3.1.3. The coefficient of friction between the egg powder and the metal surface

To measure the friction angle between the egg powder and the surface of the apparatus plate, a test stand was used (Fig. 2). It comprised the measuring tabletop (1), measuring plate (2) made of the same material as the granulator disc and mounted on a hinge to the tabletop, on which the layer of the tested granulate (3) was placed, screw jack (4), which enables smooth lifting or lowering of the measuring plate, protractor (5) which measures the friction angle. The sample of the granulate was poured on the measuring plate in a designated place. Then, using a screw jack, the plate was lifted, and the behavior of the tested material was observed. The lifted plate was stopped as the material moved over the plate. In this state, the angle of the plate inclination relative to the horizontal was measured. Three measurements were made for each sample, and their average value was registered as the value of the angle γ of friction between the granulate and the plate surface. The value of the coefficient of friction μ was equal to tangent of the friction angle γ.

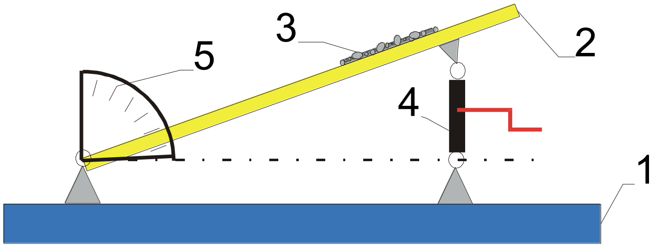

Fig. 2. The tester for measuring the friction angle between the granulate and the granulator disc built for this purpose at the Department of Process Apparatus of the Lodz University of Technology.

3.2. Measurement of eggshell roughness

Using the VHX Keyence digital microscope, the roughness parameters in 4 points chosen on the eggshell was measured before and after boiling of egg tested presented in Fig. 3.

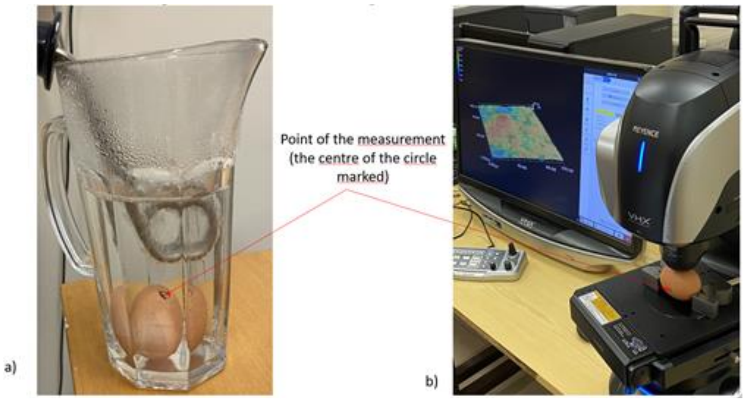

Fig. 3. Measurement of roughness in the 4 points chosen on the surface of eggshell before and after boiling. a) boiling of the egg studied, b) measurement of roughness via the digital microscope VHX KEYENCE.

3.3. Measurement of the friction coefficient between eggshell and surfaces of various base materials.

3.3.1. Preparation of the shell layer for the measurement of the friction coefficient in the shell contacts - metal surface and shells - Teflon coated surface.

The shredded eggshells of a defined medium size distribution were glued to the bottom surface of the paper box by means of starch. The average size of the shells was checked with a fine screen first and then a thin screen to fall within the range of 3mm to 6mm. The gluing process was as follows: a measured dose of crushed shells, sufficient to cover the area of 20 cm^2, was initially sprinkled on the metal surface of the auxiliary plate. The shredded shells had their outer side facing that surface of the plate. It was checked whether all the scattered shell particles met this condition, possibly using tweezers to correct the position of individual shells. The bottom part of the paper box, 53 mm x 35 mm in size, was covered with a thin layer of starch about 0.5 mm thick and at a temperature of about 40 ° C, local irregularities in the layer were smoothed out with a plastic tooth comb with dense distribution. After 5 minutes, the box was placed on a layer of shells and loaded with a metal cuboid weighing 200 g in order to exert a normal force forcing the shells to settle well in the starch layer. After the load was removed, the box was rotated to a position ensuring that the lightened shell layer was placed on its top surface. The resulting combination of the box surface, the starch layer and the shell surface were left for 1 hour for the starch to set. Excess dried starch particles protruding above the height of the lightened shell layer and possibly overlapping the shell surfaces were carefully removed with a razor blade.

3.3.2. Tribotester for determining the friction coefficient between eggshell and surfaces of various base materials.

The simple tribotester used for determining the friction coefficient between eggshell and surfaces of various base materials studied is presented in Figure 4. Such base material can be made of uncoated stainless steel or of the same steel coated by various protective layer such as the Teflon one. The tribotester comprises the fixed part 1 and the tilting part 2 of the tribotester inclined plane connected by two hinges 4. In the pocket of the tilting part 2, replaceable thin cuboidal insole 3 made of the tested material is placed. The angle of inclination α of the tilting part 2 with respect to the fixed part 1 is measured with a protractor 5. The fixed part and the tilting one 2 cooperate with the leader 6 during measurement. The fixed part 1 and the tilting one 2, with a hinge 4, a leader 6, a swivel yoke 7 and a slider 8 form together the kinematic mechanism of the tribotester. A leader 6 is rigidly connected to the swivel yoke 7, which is rotationally connected with the fixed part 1 via its pin loosely seated therein. During small rotations of the tilting part 2 around the axis of hinges 4, the slider 8 with an eyelet with enlarged hole moves along the leader 6. Such a slider 8 is fixed to the tilting part 2. The motion of the slider 8 can be blocked by the thumbscrew retainer 9 in the needed position relative to the leader 6.

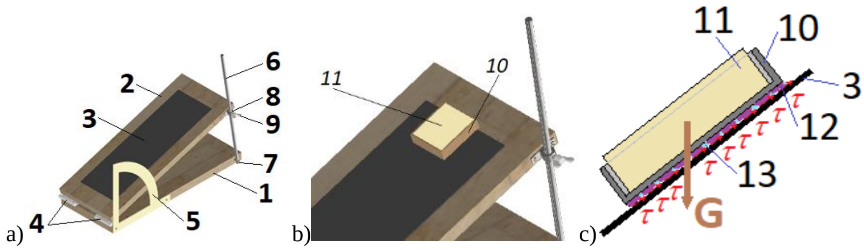

Fig. 4. Tribotester for determining the friction coefficient between eggshell and surfaces of various base materials. general view, b) initial position of paper box with eggshells glued to its bottom plane, c) the model of its contact with the replaceable insert loaded during tests on the tribotester. 1 – the fixed part of the tribotester inclined plane, 2 – the tilting part of the tribotester inclined plane, 3 - replaceable insole made of tested material, 4 – hinge, 5 – protractor, 6 – leader, 7 - swivel yoke, 8 - fixed slider with an eyelet with enlarged hole, 9 – thumbscrew retainer, 10 - paper box with eggshells glued to its bottom plane, 11 – loading metal box, 12- shredded eggshells, 13 – starch.

In the initial state the tilting part 2 with an insole 3 is situated parallel to the fixed part 1 of the tribotester. Then, the paper box 10 with the layer of shredded eggshells 12 glued via starch 13 to the bottom wall of the paper box 10 is placed on the top surface of the insole 3 near the movable end of the tilting part 2. Next, the paper box 10 is loaded by the weight of the metal cuboid 11 to create a contact pressure in the contact zone between shredded eggshells 12 and the surface of the insole 3. The weight of metal cuboid 11 can vary but is fixed during a single measurement. The movable end of the tilting part 4 is raised until the paper box 10 starts moving relative to the surfaces of an insole 3. Next, the thumbscrew retainer 9 is tightened in the threaded hole of the slider 8 until the contact pressure is generated on the retainer's front surface in the area of its contact with the leader 6 and, due to the frictional force resulted, the slider is immobilized against the guide. This allows reading a value of the measured angle α on the protractor 5 and estimating of the friction coefficient μ between eggshell and the surface of an insole 3 from equation *(3)*.

$$\mu(p_c) \approx \tan\alpha \qquad (3)$$

where:

p_c – average contact pressure between eggshell and the surface of an insole,

v – average sliding speed of paper box 10 relative to the surface of an insole 3.

The average contact pressure p_c is estimated from equation (4).

$$p_c \approx \frac{(m_{pb}+m_{mc})\cdot g\cdot\cos\alpha}{k\cdot a\cdot b} \qquad (4)$$

where:

m_{pb} – mass of paper box with a layer of mixture of shredded eggshells 12 and starch 13,

m_{mc} – mass of metal cuboid 11,

g= 9.81 m/s^2 – gravitational acceleration,

a= 53 mm, *b*= 35 mm – dimensions of rectangular bottom wall of the paper box 10,
k - the factor of filling the surface of the bottom wall of the box by projections of the projecting surfaces of shells. It can be estimated using one of the methods described:

- moisten the surfaces of the eggshells with a colored liquid, e.g., ink, and imprint them on graph paper, and then count the number of colored unit areas (1 mm^2),
- place a transparent glass plate with a mesh scale applied to an inverted box with a group of shells glued to it and count the number of unit areas that overlap with the translucent areas of the shells - this method may, however, give much lower accuracy,
- take a photo of the surface of an inverted box with a group of eggshells glued on it, perpendicularly to this surface, scan the photo, apply a grid scale to the scanned photo and count the number of unit areas overlapping with the areas covered by the protruding eggshell surfaces,
- place the paper box 10 with the layer of shredded eggshells 12 glued, on the Surface Contact Pressure Sensitive Paper [64] placed on the top surface of the insole 3; than determine the area of contact between eggshell and insole surface from the measured values according to the standardized scale that exceeds the assumed minimum level of 5 Pa. It is the most exact method but also the most expensive.

During the present study the method utilizing moisten the surfaces of the eggshells with a colored liquid of the surface of an inverted box with a group of eggshells glued on it has been applied. However, this surface was photographed and placed on graph paper allowing the counting of colored unit areas (1 mm^2).

3.4. The friction torque between the rotating egg and the stationary eggs

3.4.1. Tribotester for determining the friction torque between the rotating egg and the stationary eggs

The friction torque between the rotating egg and the stationary eggs was estimated using the home-made 5-eggs tribotester presented in Figure 5. The measurement principle similar to that utilized in the popular four-ball tribotester was applied in the present tribotester. The four eggs 6 were placed in the recesses made in the plastic bottom holder 5 fixed to the basis 1 and axial-symmetrically arranged about the axis of the rotating screw joint 9. One egg was glued with carpentry glue to the recess in replaceable wooden holder 8 connected with the steel screw joint 9. The shaft integrated with the screw joint 9 is supported in radial plain bearing with the Teflon shell, placed in the bracket fixed to the middle holder 2. The upper end of that shaft was integrated with the rotating disc 10. The disc was also fixed with a vertical mandrel. On the upper surface of the disc 10 was placed the spring stop pin 12 mating with the one arm of the torsional spring 11. This spring was guided on the mentioned vertical mandrel. The second arm of the torsional spring 11 mated with the drive lever pin 13 fixed to the drive lever 14. Such lever was fixed to the rotating shaft integrated also with the pointed arrow 16 and the knob 17. The mentioned shaft with the knob 17 was supported in a radial plain bearing with the Teflon shell relative to the vertical mandrel and to the bracket fixed to the top holder 3. The pointed arrow 16 mates with the measuring scale 15 fixed to the top holder 3. The basis 1, the middle holder 2 and the top one 3 are connected to the vertical support 4. Rotation the knob 17 by hand allowed exerting a twisting torque in the torsional spring 11 able to overcome the sum of the resistance torque in the Teflon bearings and the frictional torque between the shells of the tested eggs 6 and 7. As the resistance torque in Teflon bearings was much lower than the friction torque between the shells of the tested eggs, it was neglected during the measurement. The 5-eggs tester was calibrated with the screw joint 9 immobilized, applying a known torque to the knob 17 and reading the twist angle α of the spring 11 on the scale. The dependency $M(\alpha)$ of the torsional torque M as a function of the torsion angle α of the spring 11 were obtained. After attaching the rotated egg 7 to the holder 8, and this in turn to the screw joint 9 and releasing the screw joint 9, first the torque of the internal resistance M_{int} was measured, resulting, inter alia, from the bearing resistance of the screw joint 9. After reaching the contact between the rotating egg 7 and the stationary eggs 6, the total torque M_{tot} was measured which is the sum of the torque of internal resistance M_{int} and the friction torque M_T between the eggs. Subtracting from the torque M_{tot} the torque M_{int}, the estimated value of the torque M_T was obtained. The load between the eggs resulted practically only from the weight of the egg 7 rotated, due to the structurally introduced axial clearance between the tip of screw joint 9 with the glued egg 7 and the part connected to the rotating disc 10. Based on the value of the R reaction between the eggs obtained from the model and knowing the radius r from this model on which the friction force between the eggs acted the friction coefficient between them was determined from the formula *(5)*.

$$\mu_T = M_T/(R \cdot r) \tag{5}$$

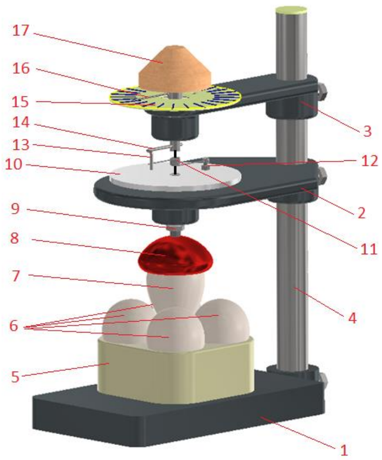

Fig. 5. The 5-eggs tribotester for determining of the friction torque between rotating egg and

the stationary eggs. 1 – basis, 2 – the middle holder, 3 – the top holder, 4 – support, 5 – fixed holder for stationary egg, 6 – stationary eggs, 7 – rotated egg, 8 – replaceable holder glued to the rotated egg, 9 supported via bearing the screw joint of the replaceable holder, 10 – rotating disc connected with the screw joint, 11 – torsion spring, 12 - spring stop pin, 13 - drive lever pin, 14 – drive lever, 15 - measuring scale, 16 - pointer arrow, 17 – knob

3.4.2. The model of 5-eggs tribotester

The normal force and contact pressure in contacts between eggs were obtained using the model of the 5-eggs tribotester elaborated using the Finite Element Method (FEM) and presented in Fig. 6. The material for 5 modelled eggs was assumed to be concrete. The bottom holder was assumed to be made of Polybutylene Terephthalate (PBT). During analysis the friction forces between eggshells were omitted as the relatively small ones. The grid of the tetrahedral finite elements was shown in Figure 7. Four options of average element size were utilized to conduct convergence evaluation in term of the effect of the average element size on the maximum values of calculated von-Mises stresses. The modelled eggs were connected each to other by contact elements with the option of 3D planar triangles and the option of their sliding/no separation while eggs with bottom holed were connected by the analogous contact element but with option of their bond behavior. The boundary conditions in the model were shown in Figure 8.

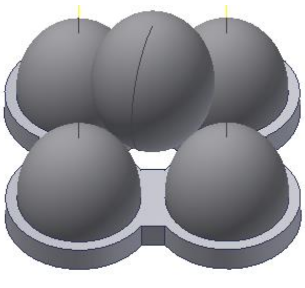

Fig. 6. The model of 5-eggs tribotester comprising a holder with 4 tested bottom eggs and 1 egg fixed to the loading head

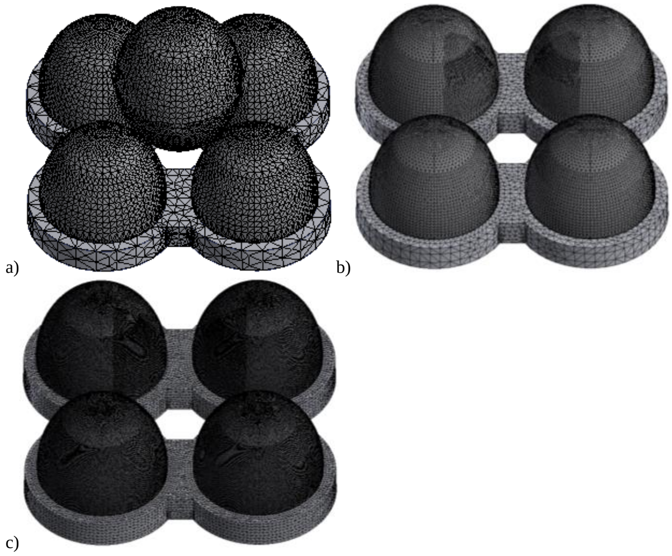

Fig. 7. The grid of tetrahedral finite elements for the model of 5-eggs tribotester. Average Element Size (as a fraction of bounding box length): (a) 0.1 – 61987 elements, 123043 nodes; (b) 0.05 – 218773 elements, 437969 nodes; (c) 0.02 – 1790257 elements, 3243643 nodes.

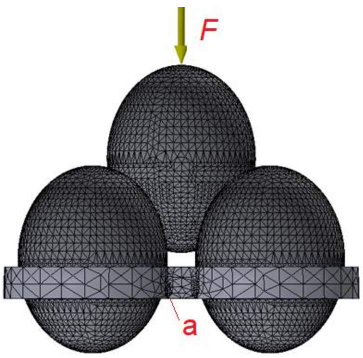

Fig. 8. The boundary conditions in the model of 5-eggs tribotester; F – loading force equal to the weight of the top egg, a – fixed bottom plain of holder with 4 tested bottom eggs.

3.5. Abrasive wear in the contact zones between the rotating egg and the stationary eggs

The abrasive wear in the contact zones between the rotating egg and the stationary eggs was determined using the other home-made 5-eggs tribotester presented in Figure 9. The vertical force F (Fig. 9) loading rotating egg 1 was determined by initial measurement of force between screw joint 3 (without egg glued) connected to the head 6 and piezoelectric weight positioned on the bench drill table while the drill feed lever was loaded by successively increasing the predetermined values of the weight suspended from the arm with the fixed value and thus producing a known driving torque. It allowed introducing the driving torque relating to the vertical force F equal to 2 ± 0.5 N. The rotational speed n (Fig. 9) of the bench drill head 6 was equal to 500 rpm. The time t of the abrasive wear process was equal to 5 s.

The volumetric abrasive wear of rotating egg was determined from equation *(6)*:

$$V_{abrasion} = \pi \cdot d \cdot s \cdot h_{aver} \tag{6}$$

where:

d= 33 mm – average diameter of the trace of abrasion, s= 1.5 mm – average width of the trace of abrasion,

h_{aver}= 0.02 mm – average depth of the trace of abrasion, obtained from measurements via the digital microscope VHX KEYENCE

To obtain values of the wear coefficient K the Archard model (7) [65] was utilized.

$$K = \frac{H \cdot V_{abrasion}}{S \cdot F_{egg-egg}} \tag{7}$$

where:

H [MPa] – Hardness of eggshell. It was estimated that the average value a such a hardness was equal to the average value of Brinell hardness of various limestones presented in [66], which varied in range (13.9-36.2) MPa. Therefore, the average value of Brinner hardness of eggshell was equal to 25 MPa.

$F_{egg-egg}$ [N] – normal force in contact zone between eggs obtained from the model of the 5-eggs tribotester described in the subchapter 3.4.2. It was determined from equation *(8)*.

$$F_{egg-egg} = \sum_e p_{aver}(e) \cdot A_e(e) \approx p \cdot A = p \cdot \pi \cdot r_e^2 \quad (8)$$

where:

r_e – radius of area A comprising loaded contact elements e,

p – average value of contact pressure in contact zone between eggs,

$p_{aver}(e)$ – average contact pressure for the finite element e,

$A_e(e)$ – area of 3D triangle contact element e ,

S [mm] - the distance of the abrasive wear process was obtained from equation (9).

$$S = \frac{\pi \cdot n}{30} \cdot \frac{d}{2} \cdot t \quad (9)$$

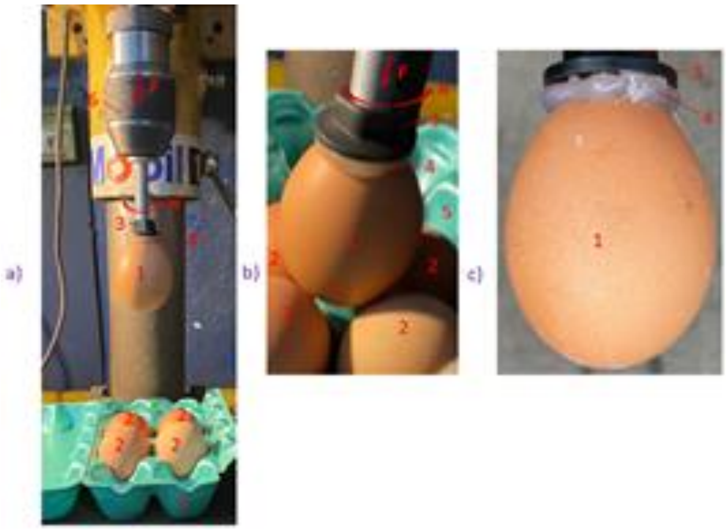

Fig. 9. The home-made device for studies of abrasion wear between rotating egg 1 driven by

the head 6 and contacted with four stationary eggs 2 fixed by glue to the support 5; a) general view of device, b) detailed view of rotating egg 1 mating with stationary eggs 2 fixed to the bottom support 5, c) detail view of rotating egg 1 connected to the screw joint 3 via a layer 4 of two-composite glue.

4. Results and Discussion

4.1. Physical properties of egg powder

The values of the density of egg powder in the loose and the compact state are presented in Table 1. Such density in the latter state is greater by 34 % than in the former one. The density of loose egg powder is higher by 42% compared to that reported in [67].

Tab. 1. Measured density of egg powder in the loose and the compact state.

State of egg powder	Density $\rho_{egg-powder}$, [g/dm^3]
Loose	320
Compact	430

The measured angle β of natural repose (maximum) for egg powder is given by eq. *(10)*:

$$\beta = 56° \qquad (10)$$

It was higher by 24.4% compared to that for chalk (of the chemical composition close to eggshell powder) and for malt or wheat flour [68]. It was also higher by 27 % compared to that of spray-dried skim milk powder [69].

The values of parameters characterising the friction between egg powder and stainless-steel plate with and without Teflon coating are shown in Table 2. These values of static coefficient of friction were eight-fold higher than in case of contact zone between UHMWPE polymer and stainless steel under egg albumen lubrication conditions and two order higher loading [70]. The wall friction angle for the whey protein powder on the stainless steel can vary in range 17°-22° [71]. As the coefficient of wall friction is the tangent of the wall friction angle [72] the wall friction coefficient in contact whey protein powder on the stainless-steel varies in range 0.3-04 which can be twice lower than static coefficient of friction in contact between egg-powder and stainless steel.

Tab. 2. The measured friction angle γ and calculated coefficient of friction in contact between egg powder and stainless-steel plate with and without Teflon coating

Contact type	Friction angle γ, [deg]	Static coefficient of friction μ, [-]
Egg powder - pure stainless steel	39° ± 7°	0.81 ± 0.12
Egg powder - stainless steel coated by Teflon	35° ± 6°	0.70 ± 0.11

4.2. Friction between eggshell and pure stainless steel and between eggshell and stainless steel covered by Teflon

The values of the static coefficient of friction between eggshell and pure stainless steel and between eggshell and stainless steel covered by Teflon under various loads were presented in Table 3. The calculated values of coefficient of friction was by an order higher than that obtained for contact between whole egg and galvanized metal surface [18]. The tendency to increase the friction coefficient with increase of loading the contact zone between eggshell and stainless-steel bot uncoated and coated by Teflon was in an agreement with the one to linear increase of the friction coefficient in contact between whole egg and galvanized metal surface with respect to egg weight [18].

Tab. 3. Static coefficient of friction μ between eggshell and stainless steel and between eggshell and stainless steel covered by Teflon under various loads determined using the tribotester based on the inclined plane.

Loading of contact zone	**Loaded by box made of AZ63 (47 g)**		**Loaded by box made of Al alloy 2014 (69 g)**	
Contact zone type	**Measured tilt angle α, [deg]**	**Calculated coefficient of friction μ, [-]**	**Measured tilt angle α, [deg]**	**Calculated coefficient of friction μ, [-]**
Eggshell-Stainless steel without coating	27°±11°	0.510±0.194	38°±7°	0.781±0.123
Eggshell-Stainless steel coated by Teflon	13°±9°	0.231±0.158	21°±11°	0.384±0.194

The example view of contact areas of eggshell glued to the bottom wall of paper box loaded by metal box with mass of 47 g was presented in Figure 10.

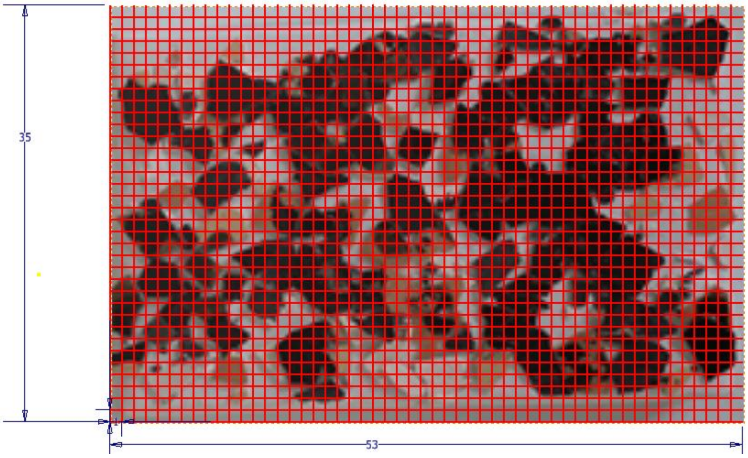

Fig. 10. The example view of contact areas of eggshell glued to the bottom wall of paper box loaded by metal box made of AZ63 with a mass of 47 g. The red lines – lines of measuring grid; black areas – eggshells covered with ink (being in contact with the core; beige areas – eggshell without coating by ink (not in contact with the core); grey areas – bottom wall of paper box covered by glue.

The values of parameter k in equation (4), calculated as the ratio of the number of black unit areas (1 mm^2) and the total number of the unit areas equal to 1855 (Fig. 11) for two mases loading the paper box with pieces of eggshells glued to its bottom wall were presented in Table 4. Also the calculated values of average contact pressure p between eggshells and the core were included. Such values were below 0.62 kPa for the case of the loading box made of AZ63 (47 g) and below 0.79 kPa for the case of the loading box made of Al alloy 2014 (69 g). The obtained values average contact pressure were by three orders lower than these caused formation of microcracks at the inner surface of the eggshell [73, 74].

Tab. 4. The values of parameter k being the ratio of the number of black unit areas (1 mm^2) and the total number of the unit areas equal to 1855 (Fig. 10) for two mases loading the paper box with pieces of eggshells glued to its bottom wall.

Loading of contact zone	**K,** **[-]**	**Average contact pressure p_c ,** **[kPa]**
by box made of AZ63 (47 g)	0.52±0.11	0.51±0.11
by box made of Al alloy 2014 (69 g)	0.63±0.16	0.63±0.16

4.3. Roughness of eggshell before boiling of the egg tested

The measured roughness parameters in the 4 point chosen on the egg shell for the egg before boiling were shown in Figure 11 and in Figure 12 after boiling. In the latter case they are rather lower. The values of obtained roughness parameters Sa and Sq were by an order higher than these of roughness parameter Rq varying in range 0.1-0.5 μm [75].

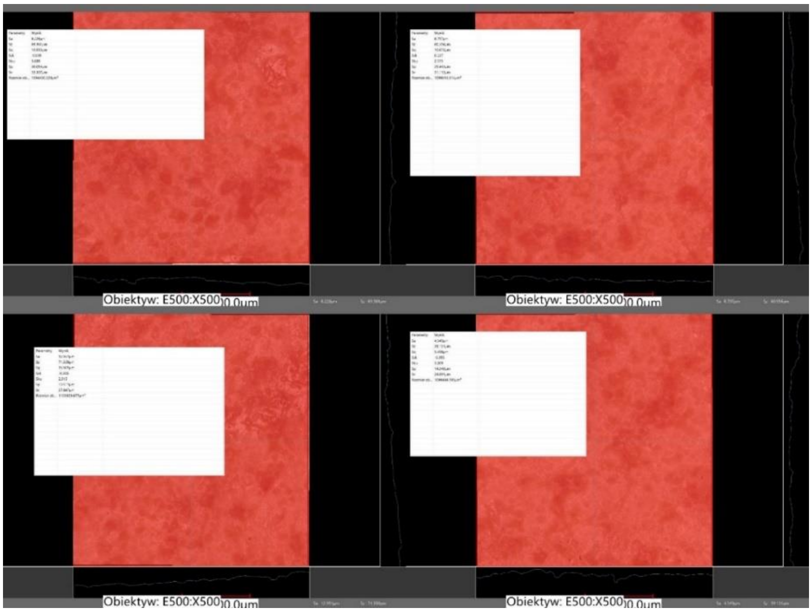

Fig. 11. The measured roughness parameter in the 4 point chosen on the eggshell before boiling.

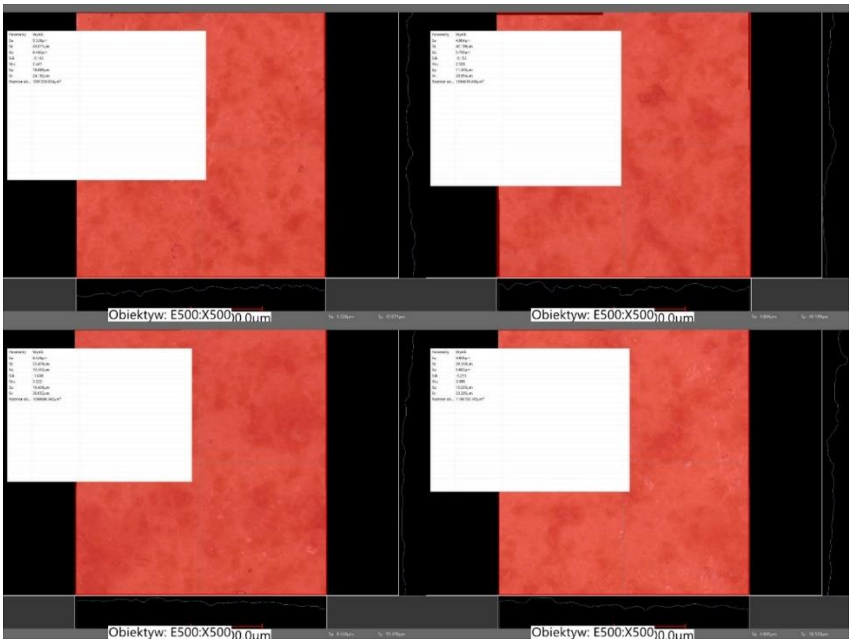

Fig. 12. The measured roughness parameter in the 4 point chosen on the eggshell after boiling.

4.4. Abrasive wear of eggshell

The shapes of abrasive wear of eggshells are shown in Figure 13.

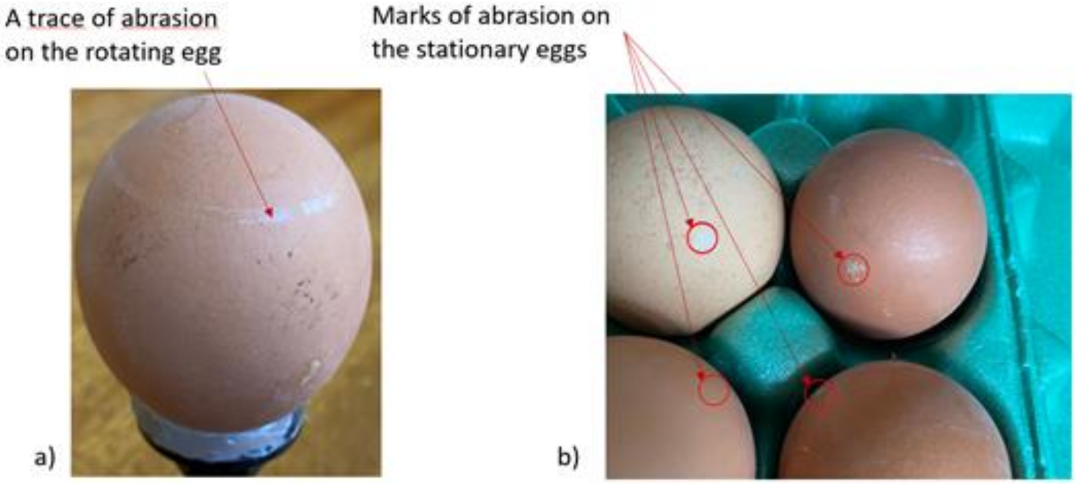

Fig. 13. Abrasive wear of eggshell obtained on the 5-eggs wear device; a) for rotating egg, b) for stationary eggs.

The average values of geometrical parameters characterizing the volumetric abrasive wear of the rotating egg was presented in Table 5. The average measured values of the diameter d, the width s and the depth h_{aver} of the trace of abrasion were equal to 33 mm, 1.5 mm and to 0.02 mm, respectively. Based of these values the calculated value of the volumetric abrasive wear $V_{abrasion}$ was equal to 3.1 mm^3.

Tab. 5. The average values of geometrical parameters characterizing the volumetric abrasive wear of the rotating egg.

Measured diameter of the trace of abrasion d, [mm]	**Measured width of the trace of abrasion s, [mm]**	**Measured depth of the trace of abrasion h_{aver}, [mm]**	**The calculated volumetric abrasive wear $V_{abrasion}$, [mm^3]**
33	1.5	0.02	3.1

The value of the distance S was equal to 4 318 mm. For the value of the force F equal to 2.5 N the estimated value of the force $F_{egg-egg}$ was equal to 1.4 N. The obtained value of the wear coefficient K between eggs was equal to 0.007. The wear studies conducted using rotary shear apparatus for the contact zone between Dover limestones was reported in [76]. During such studies for the slip velocity in range 0.1-0.15 m/s, normal stress 0.5 MPa, slip distance 1 m, the average wear rate was equal to 20 μm/m. Assuming that the hardness of Dover limestone was equal to 25 MPa, the estimated value of wear coefficient K utilized in the Archard model (7) was equal to 0.001, which was the seven-fold lower than that of the contact between eggs.

4.5. Stresses and contact pressure in the model of the 5-eggs tribotester

The obtained values of the von-Mises stresses σ_{red} in the model of 5-eggs tribotester were shown in Figure 14. They were below 0.56 MPa. The values of the contact pressure were presented in Figure 15. They did not exceed 0.32 MPa. The obtained values of the average contact pressure were eight-fold lower than these caused formation of microcracks at the inner surface of the eggshell [73, 74].

The effect of the average element size on the maximum value of von Mises stresses σ_{red} was shown in Table 6.

Tab. 6. The effect of the average element size on the maximum value of von Mises stresses.

Average Element Size (as a fraction of bounding box length), [%]	**von Mises stresses σ_{red}, [MPa]**
10	0.51
5	0.55
2	0.56

It was assumed that the case with Average Element Size as a 2% fraction of bounding box length was the optimal choose for the comparative analysis under the small costs of computation time and involvement of the computer RAM.

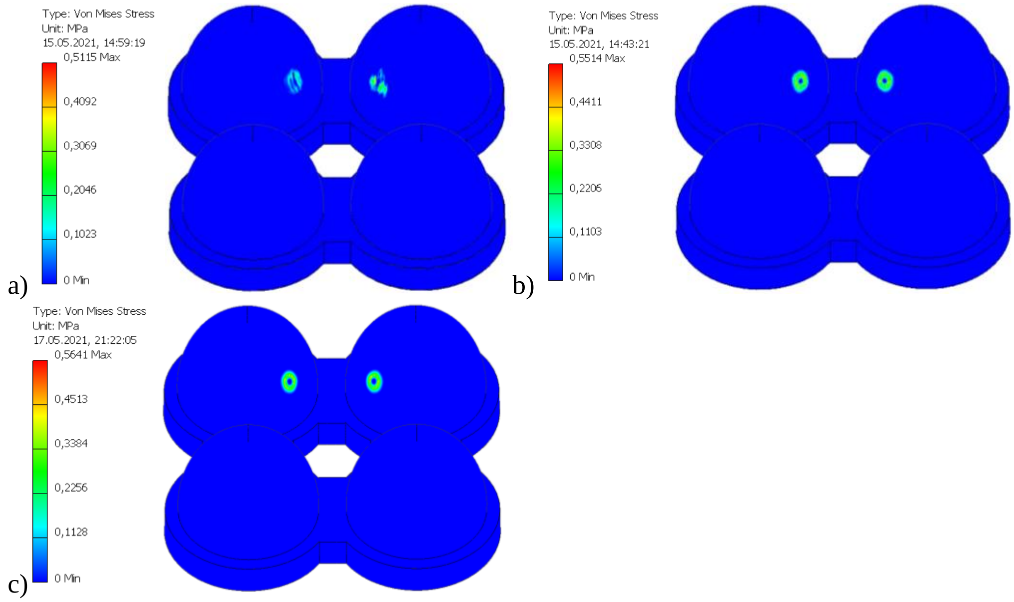

Fig. 14. The von-Mises stresses σ_{red} in the model of 5-eggs tribotester with the hidden egg fixed to the measuring head. Average Element Size (as a fraction of bounding box length): (a) 0.1; (b); (c) 0.02.

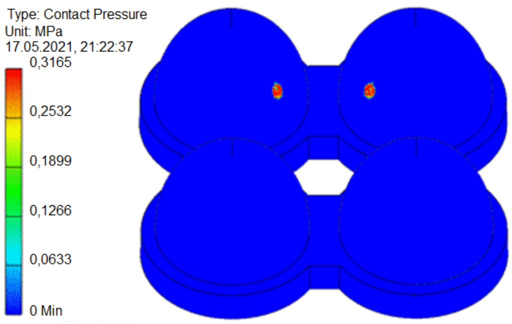

Fig. 15. The contact pressure p_c in the model of 5-eggs tribotester with the hidden egg fixed to the measuring head.

4.6. Friction between eggshells

The values of the measured friction torque and the calculated coefficient of friction between eggshells under various loads were presented in Table 7. It was clearly visible that for heavier egg the friction coefficient was higher. The obtained values of coefficient of friction between eggshells were close to lower ones from the range 0.15-0.55 obtained in contact between limestones sliding at the average speed equal to 0.25 mm/s under loading of 0.75 MPa [77].

Tab. 7. The friction torque and the coefficient of friction between eggshells under various loads determined using the 5-egg tribotester.

Loading of contact zone	**Loaded Medium egg 52.0 ± 1.5 g**		**Loaded by Jumbo egg 71.5 ± 2.5 g**	
Contact zone type	Measured friction torque M_T [Nmm]	Calculated coefficient of friction μ [-]	Measured friction torque M_T [Nmm]	Calculated coefficient of friction μ [-]
Eggshell-Eggshell	2.01±0.08	0.1±0.004	2.67±0.08	0.12±0.003

5. Conclusions

In this study the following quantities were determined: density and natural repose angle of egg powder, the coefficient of friction for the contact zones between egg powder and stainless steel with and without Teflon coating, between eggshell and stainless steel with and without Teflon coatings, and between eggshells. What is more, the wear coefficient utilized in the Archard model applied for the contact between eggs was also estimated. The measured density of egg powder in the compact state exceeds by 34 % that in the loose one. The coefficient of friction in contact between egg powder and stainless-steel plate with Teflon coating is lower by 16 % than in case of lack of such a coating. When transporting egg powder, the conveyor belts should be inclined at an angle of less than 32° for stainless steel belts and less than 29° for Teflon-coated stainless steel belts to avoid self-falling off of the powder. When moving egg powder with chutes, they should be tilted more than 46° for stainless steel surfaces and more than 41° for Teflon-coated stainless steel surfaces to avoid unnecessary accumulation of powder deposits on the chutes.

The static coefficient of friction between eggshell and pure stainless steel is above twice higher, compared to that between eggshell and stainless steel covered by Teflon. In all cases studied, for about 30 % higher load the friction coefficient was also about 30% higher. When transporting eggshells, the conveyor belts should be inclined at an angle of less than 16° for stainless steel belts and less than 4° for Teflon-coated stainless steel belts to avoid self-falling off of the eggshells. When moving eggshells with chutes, they should be tilted more than 45° for stainless steel surfaces and more than 32° for Teflon-coated stainless steel surfaces to avoid unnecessary accumulation of eggshell deposits on the chutes. Boiling of an egg can result in a decrease in roughness parameters on the eggshell surface compared to these for the fresh egg. The home-made 5-eggs tester allowed determining value of the eggshell volumetric abrasive wear equal to 3.1 mm^3. The values of the von-Mises stresses in the model of the 5-eggs tribotester were below 0.56 MPa. The relating values of the contact pressure did not exceed 0.32 MPa and was eight-fold lower than these caused formation of microcracks at the inner surface of the eggshell. The obtained value of the abrasive wear coefficient K in contact zone between eggshells was equal to 0.007, being seven fold higher than one between limestones. The coefficient of friction between eggshells in the contact assembly applied in the 5-eggs tester for the case of the Jumbo eggs was higher by 20% than the one for the case of the Medium eggs. The further studies will be focused on the effect of temperature, humidity and slip velocity on the friction coefficient and wear coefficient in contact zones between eggshells and eggshell and various metallic surfaces with and without various coatings.

References

[1] United States, U. States, & Agricultural Marketing Service, A. Marketing Service. Egg-grading manual, Agriculture handbook (United States. Dept. of Agriculture), no. 75, 2000.

[2] Egg Marketing. A Guide for the Production and Sale of Eggs, Food and Agriculture Organization of the United Nations, Rome, Italy, 2003.

[3] Anderson, K.E., Tharrington, J.B., Curtis, P.A., Jones, F.T.: *Shell characteristics of eggs from historic strains of single comb white leghorn chickens and relationship of egg shape to shell strength*, Int. J. Poult. Sci., 3, 2004, 17–19.

[4] Cahya, M., Marfuah, N.: *Identification of Calcium Carbonate ($CaCO_3$) Characteristics from Different Kinds of Poultry Eggshells Using X-Ray Diffraction (XRD) and Fourier Transformation Infra-Red (FTIR),* Proceedings of the 2014 International Conference on Physics and its Applications, 9, 2014, 138-142.

[5] Athanasiadou, D., Jiang, W., Goldbaum, D., Saleem, A., Basu, K., Pacella, M.S., Böhm, C.F., Chromik, R.R., Hincke, M.T., Rodríguez-Navarro, A.B., Vali, H., Wolf, S.E., Gray, J.J., Bui, K.H., McKee, M.D.: *Nanostructure, osteopontin, and mechanical properties of calcitic avian eggshell*, Science Advances, 4(3), 2018. eaar3219.

[6] Belyavin, C.G.: *Eggs: Use in the Food Industry*, Editor(s): Caballero, B., Finglas, P.M., Toldrá, F., *Encyclopedia of Food and Health*, Academic Press, 2016, 476-479.

[7] *Industrial microwave machine*, Microwave drying equipment for egg powder and yolk powder. https://industrialmicrowavemachine.com/microwave-drying-equipment-for-egg-powder-and-yolk-powder/ (accessed on 03 November 2023).

[8] Salinas Gonzalez, F.P.: *The Effect of Storage Temperature and Time on The Quality of Spray Dried Egg Powder*, LSU Master's Theses, 2017, 4583.

[9] Lin, J., Puri, V.M., Anantheswaran, R.C.: *Measurement of eggshell thermal - mechanical properties*, Transaction of the ASAE, 38, 1995, 1769–1776.

[10] Carnarius, K.M., Conrad, K.M., Mast, M.G., Mac Neill, J.H.: *Relationship of eggshell ultrastructure and Shell Strength to the Soudness of Shell Eggs*, Poultry

Science, 75, 1996, 656-663.

[11] El-Boushy, A.R., Raterink, R.: *Egg shell strength: The cases of egg breakage in relation to nutrition, management and environment*. Poult. Advis., 26(11), 1993, 47-55.

[12] Rezac, P., Poschel, M., Havlicek, Z.: *Relationship of plasma oestradiol - 17 beta and cholesterol levels to eggshell strength in laying hens*, Czech Journal of Animal Science, 45, 2000, 313–318.

[13] Nirasawa, K., Takahashi, H., Takeda, H., Furukawa, T., Takeda, T., Nagamine, Y.: *Restricted maximum likelihood estimates of genetic parameters and genetic trends of chickens divergently selected for eggshell strength*, J. Anim. Breed. Genet., 115, 1998, 375-381.

[14] Nirasawa, K., Takahashi, H., Takeda, H., Furukawa, T., Picman, J., Pripil, S.: *Is greater eggshell density an alternative mechanism by which parasitic cuckoos increase the strength of their eggs?* Journal for Ornitologie, 138, 1997, 531–541.

[15] Hincke, M., Nys, Y., Gautron, J., Mann, K., Rodriguez-Navarro, A., McKee, M. *The eggshell: structure, composition and mineralization*, Frontiers in bioscience, 17, 2012, 1266-80.

[16] Adeyeye, E.I.: *Comparative study on the characteristics of eggshells of some bird species*, Bull. Chem. Soc. Ethiop., 23(2), 2009, 159-166.

[17] Tsai, W.T., Yang, J.M., Lai, C.W., Cheng, Y.H., Lin, C.C., Yeh, C.W.: *Characterization and adsorption properties of eggshells and eggshell membrane*, Bioresource Technology, 97(3), 2006, 488-493.

[18] Altunas, E., Sekeroglu, A.: *Effect of shape index on mechanical properties of chicken eggs*, J. Food Eng. 85 (2008) 606-612.

[19] Voisey, P.W., Hunt, J.R.: *Effect of compression speed on the behaviour of eggshells*, J. Agric. Eng. Res., 14, 1969, 40–46.

[20] Abdallah, A.G., Harms, R.H., El-Husseiny, O.: *Various methods of measuring shell quality in relation to percentage of cracked eggs,* Poult. Sci., 72, 1993, 2038-2043.

[21] de Ketelaere, B., Govaerts, T., Couke, P., Dewil, E., Visseher, T., Decuypere, L., de Baerdemaeker, J.: *Measuring the eggshell strength of 6 different strains of*

laying hens: techniques and comparison, Br. Poult. Sci., 43, 2002, 238-244.

[22] Narushin, V.G., van Kepmen, T.A., Wineland, M.T., Christensen, V.L.: *Comparing infrared spectroscopy and egg size measurements for predicting eggshell quality*, Biosyst. Eng., 87, 2004, 367-373.

[23] Polat, R., Tarhan, S., Çetin, M., Atay, U.: *Mechanical behaviour under compression loading and some physical parameters of Japanese quail (Coturnix coturnix japonica) eggs*, Czech. J. Anim. Sci., 52, 2007, 50-56.

[24] Altuntas, E., Sekeroglu, A.: *Mechanical behavior and physical properties of chicken egg as affected by different egg weights*, Journal of Food Process Engineering, 33, 2010, 115-127.

[25] Radwan, L.M.: *Eggshell quality: a comparison between Fayoumi, Gimieizah and Brown Hy-Line strains for mechanical properties and ultrastructure of their eggshells*, Animal Production Science, 56, 2015, 908-912.

[26] Kumbar, V., Nedomova, S., Trnka, J., Buchar, J., Pytel, R.: *Effect of storage duration on the rheological properties of goose liquid egg products and eggshell membranes*, Poultry Science, 95(7), 2016, 1693-1701.

[27] Mahmoodi, M.J., Azadbakht, M., Asghari, A., Dastar, B.: *Investigating the Amount of Resistance to Break the Eggshell Under the Influence of a Strong Magnetic Field (MRI)*, Poultry Science Journal, 7(2), 2019, 101-108.

[28] Apalangya, V.A., Rangari, V.K., Tiimob, B.J., Jeelani, S., Temesgen, S.: *Eggshell Based Nano-Engineered Hydroxyapatite and Poly(lactic) Acid Electrospun Fibers as Potential Tissue Scaffold*, International Journal of Biomaterials, 2019, 6762575.

[29] Mijan, M.A., Kim, D.-H., Kwak, H.-S.: *Physicochemical properties of nanopowdered eggshell*, International Journal of Food Science and Technology, 49, 2014, 1751-1757.

[30] El-Shibiny, S., Abd El-Gawad, M.A.M., Assem, F., El-Sayed, S.: *The use of nano-sized eggshell powder for calcium fortification of cow's and buffalo's milk yogurts*, Acta scientiarum polonorum. Technologia alimentaria, 17, 2018, 37-49.

[31] Azis, Y., Adrian, M., Alfarisi, C.D., Khairatand, Sri, R.M. Synthesis of hydroxyapatite nanoparticles from eggshells by sol-gel method. IOP Conf. Series: Materials Science and Engineering 345 (2018) 012040. doi: 10.1088/1757-

899X/345/1/012040.

[32] Puspitasari, P., Yuwanda, V., Sukarni, Dika, J.W.: *The Properties of Eggshell Powders with the Variation of Sintering Duration*, IOP Conf. Series: Materials Science and Engineering, 515, 2019, 012104.

[33] Krittirash Yorseng, Suchart Siengchin, Basa Ashok, Anumakonda Varada Rajulu, *Nanocomposite eggshell powder with in situ generated silver nanoparticles using inherent collagen as reducing agent*, Journal of Bioresources and Bioproducts, 5(2), 2020, 101-107.

[34] Bain, M.: *A reinterpretation of eggshell strength*. In: Solomon S.E. (ed.): *Egg and Eggshell Quality*. Manson Publishing Ltd., London, UK, 1997, 131–141.

[35] Bain, M.: *Recent advances in the assessment of eggshell quality and their future application*, World's Poultry Science Journal, 61(2), 2005, 268-277.

[36] Voisey, P.W., Hunt, J.R.: *Measurement of eggshell strength*, Journal of Texture Studies, 5, 2007, 135-182.

[37] Snapir, N., Perek, M.: *Evaluation of Various Methods of Measuring Eggshell Quality*, Annales de zootechnie, INRA/EDP Sciences, 18(4), 1969, 399-405.

[38] Hamilton, R.M.G.: *Methods and Factors that affect the Measurement of Egg Shell Quality*, Poultry Science, 61, 1982, 2022-2039.

[39] Mehdizadeh, S.A., Nadi, F.: *Experimental and Numerical Analysis for Prediction of Mechanical Properties of Eggshell*, nt. J. Food Eng. 12(3), 2016, 287–293.

[40] Voisey, P.W., Hunt, J.R.: *Physical properties of eggshells*, British Poultry Science, 8(4), 1967, 263-271.

[41] Hunt, J.R., Voisey, P.W., Thompson, B.K.: *Physical Properties of Eggshels: a Comparison of the Puncture and Compression Tests for Estimating Shell Strength*, Canadian Journal of Animal Science, 57(2), 1977.

[42] Ketta, M., Tůmová, E.: *Eggshell structure, measurements, and quality-affecting factors in laying hens: a review*, Czech J. Anim. Sci., 61(7), 2016, 299-309.

[43] Montenegro, A.T., Garcia, E.A., Molino, A.B., Cruvinel, J.M., Ouros, C.C., Alves, K.S.: *Methods to Evaluate the Eggshell Quality of Table Eggs*, Brazilian Journal of Poultry Science, 21(3), 2019, eRBCA-2019-1046.

[44] Severa, L., Buchar, J., Votava, J.: *New approach of eggshell mechanical properties*

determination, Acta Universitatis Agriculturae et Silviculturae Mendelianae Brunensis, 58, 2010, 161-166.

[45] Kan, C.A. (Kees): *Contaminants in eggs: effects of feed and environment*, Proceedings of XII European Symposium on the Quality of Eggs and Egg Products At: Prague, 2007.

[46] Spitzer, H.: *An Analysis of Bacterial Contamination of Chicken Eggs and Antimicrobial Resistance,* All College Thesis Program 2016-2019, 2016, 27.

[47] de Freitas Neto, O.C., Penha Filho, R.A.C., Barrow, P., Berchieri Jr., A.: *Sources of human non-typhoid salmonellosis: a review*, Brazilian Journal of Poultry Science, 12(1), 2010, 01-11.

[48] Whiley, H., Ross, K.: *Salmonella and eggs: from production to plate*, International journal of environmental research and public health, 12(3), 2015, 2543-2556.

[49] Hosoglu, M.I., Guneser, O., Yuceer, Y.K.: Chapter 2 - *Different Bioengineering Approaches on Production of Bioflavor Compounds*, Editor(s): Grumezescu, A.M., Holban, A.M., In: *Role of Materials Science in Food Bioengineering, Handbook of Food Bioengineering*, Academic Press (2018) 37-71. https://doi.org/10.1016/B978-0-12-811448-3.00002-4.

[50] Daramola, E.I.: *Comparative Evaluation of Differently Processed Whole Eggpowder*, Ahmadu Bello University, Zaria, Nigeria, 2018.

[51] Huda, N., Tze, W., Dewi, M., Hashim, H.: *Physicochemical Properties of Egg White Powder from Eggs of Different Types of Bird*, International Journal on Advanced Science, Engineering and Information Technology, 8(2), 2018, 4087.

[52] Koç, M., Koç, B., Güngör, Ö., Kaymak-Ertekin, F.: *The Effects of Moisture on Physical Properties of Spray-Dried Egg Powder*, Drying Technology, 30, 2012, 567-573.

[53] Koç, M., Koç, B., Sakin-Yilmazer, M., Kaymak-Ertekin, F., Susyal, G., Bağdatlıoğlu, N.: *Physicochemical Characterization of Whole Egg Powder Microencapsulated by Spray Drying*, Drying Technology, 29, 2011, 780-788.

[54] Lai, C.C., Gilbert, S.G., Mannheim, C.H.: *Effect of flow conditioners on water sorption and flow properties of egg powder*, Journal of Food Engineering, 5(4), 1986, 321-333.

[55] Ndife, J., Udobi, C.E., Amaechi, N.C.: *Effect of oven drying on the functional and nutritional properties of whole egg and its components*, African Journal of Food Science, 4(5), 2010, 254- 257.

[56] Kudre, T.G., Bejjanki, S.K., Kanwate, B.W., Sakhare, P.Z.: *Comparative study on physicochemical and functional properties of egg powders from Japanese quail and white Leghorn chicken*, International Journal of Food Properties, 21(1), 2018, 957-972.

[57] Asghar, A., Abbas, M.: *Effect of spray dried whole egg powder on physicochemical and sensory properties of cake*, Am. J. Sci. Ind. Res., 6(5), 2015, 97-102.

[58] Lafetá Jr., J.A.Q., de Oliveira, M.J., de Oliveira, D.R.B., Santos, I.J.B., Saldaña, M.D.A., dos Reis Coimbra, J.S.: *Emulsifying properties of quail egg white proteins in different vegetable oil emulsions*, Acta Scientiarum. Technology, 43, 2021, e50067.

[59] Salawu, E.Y., Ajayi, O.O., Inegbenebor, A., Akinlabi, S., Akinlabi, E.: *Influence of pulverized palm kernel and eggshell additives on the hardness, coefficient of friction and microstructure of grey cast iron material for advance applications*, Results in Engineering, 3, 2019, 100025.

[60] Oladele, I.O., Makinde-Isola, B.A., Adediran, A.A., Oladejo, M.O., Owa, A.F., Olayanju, T.M.A.: *Mechanical and wear behaviour of pulverised poultry eggshell/sisal fiber hybrid reinforced epoxy composites*, IOP Publishing Ltd. Materials Research Express, 7(4), 2020, 045304.

[61] Venkatesh, N., Hanumanthraju, H.G., Aravinda, Rachappa: *A Wear Study on Bio-Active Coating of Al2o3, Egg and Sea Shell Powder on Teflon and Nylon, elucidated*, IAETSD Journal for Advanced Research in Applied Sciences, 5(4), 2018, 583-595.

[62] Dwiwedi, S.K., Srivastava, A.K., Chopkar, M.K.: *Wear Study of Chicken Eggshell-Reinforced Al6061 Matrix Composites*, Trans Indian Inst Met, 72, 2019, 73–84.

[63] Parivendan, J., Ramesh, S.: *Mechanical, wear & thermal behaviour of Hemp fibre/eggshell particles reinforced epoxy resin bio composite*, Transactions - Canadian Society for Mechanical Engineering, 42(3), 2018, 280-285.

[64] *Surface Contact Pressure Sensitive Paper Reveals Distribution and Magnitude*.

Available on: https://www.sensorprod.com/campaign/pressure-sensitive-paper/index.php?mcode=gc-pressure (accessed on 03 November 2023).

[65] Karaca, Z., Günes Yilmaz, N., Goktan, R.M.: *Abrasion wear characterization of some selected stone flooring materials with respect to contact load*, Constr. Build. Mater., 36, 2012, 520–526.

[66] Anikoh, G.A., Adesida, P.A., Afolabi, O.C.: *Investigation of Physical and Mechanical Properties of Selected Rock Types in Kogi State Using Hardness Tests*, Journal of Mining World Express (MWE), 4, 2015, 37-51.

[67] Chapter 2: *Conveyor Chain Designer Guide*. In *Conveyor chain. Installation, maintenance & designer guide*. Renold Superior Chain Technology 21-61. Available on: https://www.renold.com/media/165388/conveyor-ins-main-ren16-eng-10-10.pdf (accessed on 03 November 2023).

[68] Al-Hashemi, H.M.B., Al-Amoudi, O.S.B.: *A review on the angle of repose of granular materials*, Powder Technology, 330, 2018, 397–417.

[69] Ilari, J.-L., Mekkaoui, L.: *Physical properties of constitutive size classes of spray-dried skimmilk powder and their mixtures*, Le Lait, INRA Editions, 85(4-5), 2005, 279-294.

[70] Kahyaoglu, O.K., Unal, H.: *Friction and wear behaviours of medical grade UHMWPE at dry and lubricated conditions*, International Journal of Physical Sciences, 7(16), 2012, 2478-2485.

[71] *Protein Powder Rheology*, Centre of Industrial Rheology. Available on: https://www.rheologylab.com/articles/food/protein-powder-rheology/ (accessed on 03 November 2023).

[72] Hancock, B.C.: *The Wall Friction Properties of Pharmaceutical Powders, Blends, and Granulations*, Journal of Pharmaceutical Sciences, 108, 2019, 457-463.

[73] Bain, M.M., MacLeod, N., Thomson, R., Hancock, J.W.: *Microcracks in Eggs*, Poultry Science, 85, 2006, 2001–2008.

[74] MacLeod, N., Bain, M.M., Hancock, J.W.: *The mechanics and mechanisms of failure of hens' eggs*, Int J Fract, 142, 2006, 29-41.

[75] Li, Q., Wang, K., Zheng, J., Sun, C., Ge, C., Yang, N., Xu, G.: *Nanostructural basis for the gloss of chicken eggshells*, Poultry Science, 98(11), 2019, 5446-5451.

[76] Boneh, Y., Sagy, A., Reches, Z.: *Frictional strength and wear-rate of carbonate faults duringhigh-velocity, steady-state sliding*, Earth and Planetary Science Letters, 381, 2013, 127–137.

[77] Drennon, C.B. III: *Stick-slip friction of lightly loaded rock*. Retrospective Theses and Dissertations 1972, 5903.