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The fracture toughness of eggshell

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A R T I C L E I N F O

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A B S T R A C T

The shells of avian eggs are very brittle, but how brittle? Fracture toughness, K_c is a standard measure used widely to characterise engineering materials. We devised a novel way to measure K_c and applied it to commercial hens' eggs, obtaining a value of 0.3 MPa$\sqrt{m}$. This value is much lower than previous published values, which we argue are incorrect and misleading. We discuss how this exceptionally low toughness value (in comparison to that of other natural materials made from calcium carbonate) has been achieved by prevention of toughening mechanisms. Eggshell has an unusual combination of mechanical properties (low fracture toughness combined with high Young's modulus), making it ideally suited as a container for the developing chick, which must be stiff and rigid but also brittle enough to be broken when required. Further testing and analysis using the Theory of Critical Distances and Weibull probability theory allowed us to describe the effects of defects of various types: cracks, holes and notches, on the strength of whole eggs. These results are of commercial importance because many eggs break prematurely as a result of microscopic defects.

Statement of Significance

This paper presents the first accurate measurements of the fracture toughness of eggshell. These results are important because eggshell is a brittle material which fails from microscopic defects, so knowledge of the fracture toughness is essential to understand its mechanical performance.
The toughness value obtained is discussed in the context of other mechanical properties, of eggshell and other natural materials. This is useful for understanding how eggshell's stiffness and toughness make it ideally suited to its purpose, and the mechanisms by which toughness is achieved.
The paper also contains analysis of the effect of defect type, including cracks, notches and holes, to provide a fuller picture of defect tolerance which will be useful in the egg producing industry.

1. Introduction

Avian eggshell is an extremely common biological material, which performs an important structural function. The egg must be sufficiently stiff and strong to protect the developing embryo, but during hatching the chick must be able to break out using its beak. The mechanical properties of eggshell are also of considerable commercial importance. Tens of millions of tonnes of eggs are produced annually, of which an estimated 8–10% suffer damage during routine handling [1]; damaged eggs represent a considerable financial loss as well as a health hazard [2]. As a result, there has been a considerable body of work on the determination of eggshell structure and mechanical properties (for a recent review see [3]).

The sensitivity of a material to the presence of small cracks can be described using a mechanical property known as fracture toughness, which is commonly expressed in one of two different ways: (i) the energy required to propagate a crack by a given amount, G_c, given in units of energy per unit increase in the cracked area, and; (ii) a parameter K_c, which is related to the stress σ_f needed to propagate a crack of given length, a, according to the following Eq. (4):

$$K_c = F\sigma_f\sqrt{\pi a} \tag{1}$$

The constant F in this equation depends on the geometry of the crack and the body containing it, and the type of loading applied. These two toughness parameters are related to each other via the material's stiffness (Young's modulus, E), as follows [4]:

$$K_c = \sqrt{G_c E} \tag{2}$$

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Classic brittle materials, such as glass and most ceramics, are relatively strong in compression but weak in tension, owing to low fracture toughness. When exposed to tensile stress, such a material is highly sensitive to cracks, and almost invariably fails at a stress lower than its inherent strength as a result of microscopic defects. Eggshell would appear to be such a material, and if so its K_c value will be crucial in determining its mechanical performance.

Values of K_c and G_c for eggshell have been reported in three previous papers. Mabe et al. reported K_c values of the order of 350 $Nmm^{-3/2}$, which, when converted into SI units, gives 11.1 $MPa\sqrt{m}$ [5] (Note: the unusual conversion factor is due to the square root of length in the units for this quantity). They tested whole hens' eggs, compressing them between rigid, parallel platens, which caused failure by propagation of cracks from the contact points. They calculated K_c using a formula previously devised by one of the authors [6]. More recently Xiao et al. reported similar values, of the order of 12.6 $MPa\sqrt{m}$, in a paper investigating the effect of dietary supplements on hen egg properties [7]. Assuming a value of Young's modulus E = 55 GPa [1] gives values of G_c (using Eq. (2) above) of 2.2 kJm^{-2} and 2.6 kJm^{-2} respectively for Mabe et al. and Xiao et al. Gosler et al. used a different method, obtaining G_c by measuring the force needed to cut eggshell samples using scissors [8]. Their results, for Great Tit eggshells, show a lot of variability, but fall within the same order of magnitude as the results from the above workers, with values in the range 0.5–17 kJm^{-2}.

All of these values are much too high to be credible. For comparison, Table 1 lists some typical values of K_c for a range of natural and manmade materials. Eggshell is a ceramic material, made largely from calcium carbonate in the form of calcite. There are almost no ceramic materials which have toughness values higher than 10 $MPa\sqrt{m}$. Pure mineral calcite has values in the range 0.2–1.8 $MPa\sqrt{m}$ [9,10]. Some biological materials based on calcite (or the related mineral aragonite) have achieved higher toughness by evolving specialised microstructures (see below) but even these only reach values in the range 3–5 $MPa\sqrt{m}$. A further illustration of the impossibility of such high K_c values comes from estimating the critical crack length, which can be done using Eq. (1) above and substituting the material's tensile strength for σ_f. Using a typical strength value of 15 MPa [1,11] and the K_c value from Mabe et al. we find a critical crack length of 0.34 m. Since this is much larger than the size of an egg, it implies that the strength of eggs will never be reduced as a result of having cracks, which is contrary to all experience.

The aim of the present work was to devise a method to measure the fracture toughness of eggshell and, more generally, to assess the effect of small cracks and other defects such as holes on the strength of eggs.

Table 1
Typical values of Fracture Toughness K_c and Young's Modulus E for Various Materials Data from [27] except the following: mussel shells [28]; nacre [17]; bone [18]; temporomandibular joint disc [29]; cartilage [30]; stratum corneum [31].

Material	E (GPa)	K_c ($MPa\sqrt{m}$)	E/K_c ($m^{-1/2} \times 10^3$)
Ceramics (natural and manmade)			
Granite	60	3	20.0
Ice	9.1	0.2	45.5
Alumina	390	4	97.5
Silicon carbide	440	3	146.7
Concrete	40	0.2	200.0
Glass	69	0.75	92.0
Polymers and metals			
Perspex	3.4	1.1	3.1
Epoxy	3	0.4	7.5
Steel	200	50	4.0
Aluminium	69	30	2.3
Stiff biological materials			
Mussel shell	80	3	26.7
Nacre	70	4.3	16.3
Wood	12	10	1.2
Bone	17	4	4.3
Soft biological materials			
Temporomandibular joint disc	0.0022	0.11	0.02
Cartilage	0.0075	0.08	0.04
Stratum corneum	0.013	0.007	1.86

2. Methods and materials

We used hens' eggs obtained from a retail outlet, described as "free range, size large". In total, 46 tests were carried out, of which 4 were discarded owing to errors (misalignment etc), giving 42 valid results. All eggs were used on the day of purchase. They were tested at room temperature (18–21 °C), after being kept for a minimum of one hour to equilibrate to the temperature of the laboratory. External dimensions were measured before testing: height H in the long-axis direction and width W defined as the maximum diameter normal to the long axis. Shell thickness t was measured after testing, on a part of the fracture surface close to the crack initiation site. The contents were removed before testing by drilling a small hole in each end and blowing with compressed air. A hole of radius a was drilled at half height using a high speed, low torque drill. Four different hole radii were used, varying from 0.25 mm to 2.5 mm. The larger holes were created using successive drills of gradually increasing size; microscopic examination revealed no signs of cracking or damage caused by the drilling operation. In addition to these circular holes, sharp notches were created by first drilling holes and then extending them in the long-axis direction using either a file or a scalpel. This allowed us to create notches with lengths varying from 0.84 mm to 3.25 mm and root radii varying from 0.01 mm to 0.23 mm (see Fig. 1).

We devised a novel testing procedure which relies on the fact that, if a thin-walled sphere is loaded in axial compression, a simple biaxial stress state arises near its equator. A test rig was designed with the aim of applying axial compression in such a way as to avoid failure occurring at the loading points (see Fig. 2). Loading between flat metal plates, as carried out by other workers [5,7] creates high local stresses at the contact points. To

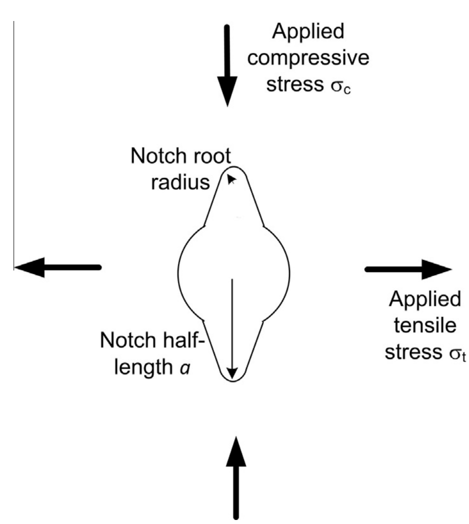

Fig. 1. Holes (of radius a) were drilled into whole eggs. Some holes were extended by machining to produce sharp notches (of half-length a and root radius ρ). Under an applied remote compressive load the local stress field in the vicinity of the hole/notch is biaxial, consisting of equal tensile and compressive stresses.