STUDIES ON PHYSICAL PROPERTIES OF EGG SHELLS

by

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B.S.A., University of British Columbia, 1960

A THESIS SUBMITTED IN PARTIAL FULFILMENT OF
THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE IN AGRICULTURE

in the Department
of
Agricultural Mechanics

We accept this thesis as conforming to the
required standard

THE UNIVERSITY OF BRITISH COLUMBIA

APRIL, 1967

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ABSTRACT

Physical characteristics of egg shells and their relationships to shell strength were studied in 2,733 eggs collected over thirty-two weeks from a flock of sixty Single-Comb White Leghorn pullets.

Shell strength under quasi-static loading was measured as maximum force at failure and as energy absorbed at failure when load was applied at the equator of the egg. Area under the force-deformation curve was taken as energy absorbed by the shell up to failure and the slope of the curve as shell stiffness.

Egg size was measured as egg weight, width and length. Shell weight, thickness at the equator, percent egg as shell, and shell weight per unit surface area were studied as measures of shell quantity. Shape index, roundness, and three concepts of sphericity were used to describe egg shape. Hardness in radial sections of 425 shells was tested with a micro-indentation technique. Variation in hardness across the thickness of egg shells was examined in radial and tangential sections of nine shells.

Force at failure as a measure of shell strength showed high multiple correlations with combinations of physical properties, whereas energy absorbed at failure had relatively small multiple correlations with physical characteristics.

Shell stiffness was found to be the most important

indirect measure of shell strength along with lesser effects of egg weight, shell width, shape index, and hardness.

Shell quantity characteristics, along with egg size and shape, were shown by means of theoretical and statistical analyses to be largely responsible for shell stiffness.

Shape index proved to be the most satisfactory measure of egg shape with respect to reducing residual variance of force at failure after stiffness was considered and was judged to be the most accurate of the shape measurements studied.

Shell hardness was found to vary in a parabolic manner across the shell thickness, reaching minimum values near the midpoint of the shell. Comparable hardness gradients were observed in both radial and tangential shell sections. No appreciable change in hardness or its gradient resulted from removal of shell membranes with sodium hydroxide solution.

The proportions of variation in force at failure explained by the non-destructive variables shell stiffness, egg size, and shape were 60.5, 77.7, and 86.3 percent in pooled-egg, bird average per period, and overall bird average analyses respectively.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS AND DEFINITIONS

D.P.H., Diamond pyramid hardness. - Load per unit area of surface contact in kgm./sq.mm.

Eggwt, Egg weight. - Fresh weight of the egg in gm.

Energy, Energy absorbed at failure. - Amount of energy absorbed by the egg on being crushed calculated as the area under the force-deformation curve in gm.-cm.

Length, Egg length in cm.

Load, Force at failure. - The force in grams applied to the equator of the egg that results in shell failure, in gm.

Mgmcm2, Shell weight per unit surface area - in mgm./sq.cm.

Persh, Percent shell. - The ratio of shell weight to fresh egg weight in percent.

Poisson's Ratio - The ratio of unit lateral contraction to unit longitudinal extension for a solid material.

Prasph, Practical sphericity. - The ratio formed by dividing the diameter of a circle equal in area to the projected area of a particle by the diameter of the smallest circumscribing circle, in percent.

P3dsph, Practical three-dimensional sphericity. - The ratio formed by dividing the diameter of a sphere of volume equal to that of the particle by the diameter of the smallest circumscribing sphere, in percent.

Quasi-Static Loading - The application of force to a specimen at relatively low rates.

Round, Roundness. - The maximum projected area of the egg divided by the area of the smallest circumscribing circle, in percent.

Shell Level - Position across the thickness of the egg shell from the outer edge as a fraction of shell thickness at that location.

Shelwt, Shell weight. - Weight of the dried shell without membranes, in gm.

Shindx, Shape index. - The ratio formed by dividing egg width by egg length, in percent.

Stiff, Shell stiffness. - The ratio formed by dividing force applied to the shell by deformation in the direction of applied force, in gm./micron.

Thick, Shell thickness. - Thickness of the shell taken at the egg's equator, in microns.

Totdef, Total deformation. - The overall dimensional change in the direction of applied force, in microns.

Trusph, True sphericity. - The ratio formed by dividing the surface area of a sphere of volume equal to that of the particle by the surface area of the particle, in percent.

Width, Egg width. - The diameter of the egg at its equator, in cm.

Young's Modulus - The proportionality constant between stress and strain in an elastic material.

ACKNOWLEDGEMENTS

The writer wishes to express his appreciation for assistance in this study by:

Professor L.M. Staley who directed this research, provided encouragement, and advice,

Dr. J.F. Richards, Department of Poultry Science, for counsel on aspects of egg shell strength and the supply of some materials and facilities,

Dr. C.W. Roberts and Professor E.L. Watson for serving on the research committee and reviewing this paper,

Dr. E. Teghtsoonian and the Department of Metallurgy for advice and facilities in the study of hardness,

Mr. M. Hudson, foreman, and other staff members of the Poultry Farm who collected and recorded eggs used in this study,

Mr. W. Gleave for suggestions which led to construction of shadow photography equipment.

INTRODUCTION

The proportion of cracked eggs reported by registered grading stations in Canada has increased by 140 percent since 1953 according to the Poultry Market Review (1964 and 1965). Cray (1953) found that grading stations detected only about 48 percent of all eggs cracked up to the time of grading because the remaining 52 percent were removed on the farm. Assuming comparable breakage in flocks whose eggs were not shipped to grading stations and a decrement of 10 cents per dozen, weak shells cost the Canadian egg industry approximately 4.2 million dollars in 1965. In B.C., where Raffa (1967) estimates that 65 percent of all eggs pass through registered grading stations, the loss was about 590 thousand dollars in 1965. Cracked eggs have been shown by Brown et al. (1966) to be more susceptible to bacterial spoilage than sound eggs under certain adverse conditions, thereby presenting a potential health hazard.

Reduction of damage to egg shells in mechanical handling requires a knowledge of stress levels which result in shell failure. Overall improvement of egg shell strength by either genetic or nutritional means is contingent upon selection of an appropriate measure of shell strength and identification of shell characteristics that contribute to its strength. This study was designed to examine a number of physical and mechanical properties of egg shells and their influence on two measures of egg shell strength.

REVIEW OF THE LITERATURE

Early studies on egg shell strength have been reviewed by Tyler (1961). The concept of strength has been described as resistance of the shell to crushing, impact and puncturing.

Rehkugler (1964) studied impact strength of shells using various types of cushioning materials. He observed that shells have a greater capacity to absorb energy under impact loading than static loading. Sluka et al. (1965) reported the development of an hydrostatic shell strength tester that is claimed to simulate dynamic situations involving impact deceleration of the egg. In a later paper, Sluka et al. (1966) presented an analysis of shell stresses under impact deceleration which was used to calculate ultimate shell stress. Voisey and Hunt (1967c) described a device used for measuring the maximum force imposed on egg shells by the impact of a falling steel rod.

In general, resistance of the shell to crushing is measured by quasi-static loading of the shell between two surfaces. Brooks and Hale (1955) used load at failure and also load at failure divided by shell thickness as measures of resistance to crushing. Presumably the latter concept was an attempt to evaluate the intrinsic strength of the shell material by correcting for variations in shell thickness. Rehkugler (1964) introduced the degree of energy absorption by the egg under quasi-static loading as a measure of shell strength. Energy absorbed by the shell was taken as the area under the

load-deformation curve up to the point of failure. Schoorl and Boersma (1962) suggested the use of shell deformation caused by a given load as an index of strength because shell thickness and percentage shell are more highly correlated with deformation than breaking strength. Hunt and Voisey (1966) and Richards and Staley (1967) have used maximum force at failure as a measure of crushing strength.

Shell strength measurements by puncturing are described by Lund et al. (1938), Novikoff and Gutteridge (1949), and Tyler (1961). The main advantage of puncturing methods is that several measurements may be made on a single egg.

Romanoff (1949), Brooks and Hale (1955), Brooks (1958), and Gaisford (1965) reported no significant correlation between egg size and crushing strength. In a study of over 300 eggs, Stewart (1936) found a highly significant correlation ($r = +.260$) between egg weight and crushing strength. Richards and Staley (1967) reported a small but significant simple correlation ($r = +.11$, $n = 531$) between shell strength and egg weight. Egg size as measured by egg width and egg length was shown to be highly correlated with shell strength in the work of Richards and Staley (1967).

Shell quantity measured as shell weight, percent egg as shell, and shell thickness have been shown to be very highly correlated with shell strength by several workers among whom are Shuster (1959), Hunt and Voisey (1966) and Richards and Staley (1967). An indirect method using specific gravity of

the whole egg as a measure of shell quantity has been used by Novikoff and Gutteridge (1949), Marks and Kinney (1964) and Frank et al. (1964). Tyler and Geake (1961) and Hurwitz and Griminger (1962) suggest the use of shell weight per unit surface area as a more accurate measure of shell quantity.

Stewart (1936) studied egg shape and curvature in relation to shell strength and found small but significant correlations between strength and shape measurements. Frank et al. (1964 and 1965) recognized the need to consider shell geometry in relation to strength. Richards and Swanson (1965) reported egg shape expressed as shape index to be independent of shell thickness and to account for 15 to 35 percent of the variability in crushing strength after shell thickness was considered. Hunt and Voisey (1966) found egg shape to be the most important shell strength predictor after shell stiffness was considered. Richards and Staley (1967) point out that shape index, when included with deformation per unit load increased the coefficient of determination of crushing strength by 15 and 20 percent in their pooled-egg and bird average analyses respectively.

Mechanical properties of egg shell material were first studied with micro-indentation hardness testing by Brooks and Hale (1955). They reported the average hardness of ten strong shells to be significantly higher than that of ten weak shells. A gradient of hardness was found to exist across the thickness of the shell which increased almost linearly toward the outer edge. Rehkugler (1963) developed a technique whereby

the modulus of elasticity and ultimate strength of shell material were measured.

The behavior of the egg shell under quasi-static loading has been studied by Brooks and Hale (1955), Schoorl and Boersma (1962), Rehkugler (1964), Gaisford (1965), Hunt and Voisey (1966) and Richards and Staley (1967) with simultaneous measurement of applied load and resultant deformation of the shell. Each of these investigators has observed that the load-deformation curve is approximately linear and that the slope of the curve, or its inverse, is highly correlated with load at failure. Richards and Staley point out the validity of calculating the slope of the curve directly as the ratio of maximum load and deformation.

The literature reveals that several physical characteristics of the hen's egg shell are important to its strength; however, the roles of egg size, egg shape and shell hardness in relation to other physical properties and to shell strength are not well understood. This investigation was designed to clarify relations between egg size, egg shape, shell quantity, shell hardness measurements and shell strength and to investigate the feasibility of non-destructive evaluation of egg shell strength.

EXPERIMENTAL METHODS

Sampling Procedures

A total of 2,733 eggs were collected during the second and third weeks of eight four-week periods beginning January the second, 1966, from a flock of sixty Single-Comb White Leghorn pullets in their first year of production. The flock, which consisted of equal numbers of birds from the two resultant crosses of a reciprocal mating program, was fed a commercial ration containing four percent calcium. Individual wire cages allowed identification of eggs produced by each hen. For the purpose of analysis, Group One was made up of the entire sample of 2,733 eggs, whereas a subsample of 425 eggs from ten arbitrarily selected birds of one cross was designated as Group Two for the additional testing of shell hardness.

Egg and Shell Physical Properties

Egg Size

Physical characteristics representing egg size were assumed to be egg weight, width, and length. The fresh weight of each egg was measured to the nearest centigram after which egg width and length were determined with a precision of $\pm$ .005 cm. using a vernier caliper.

Egg Shape

Shape index was calculated in the usual manner as the quotient of egg width and length multiplied by one hundred.

Roundness in a plane parallel to the major axis of

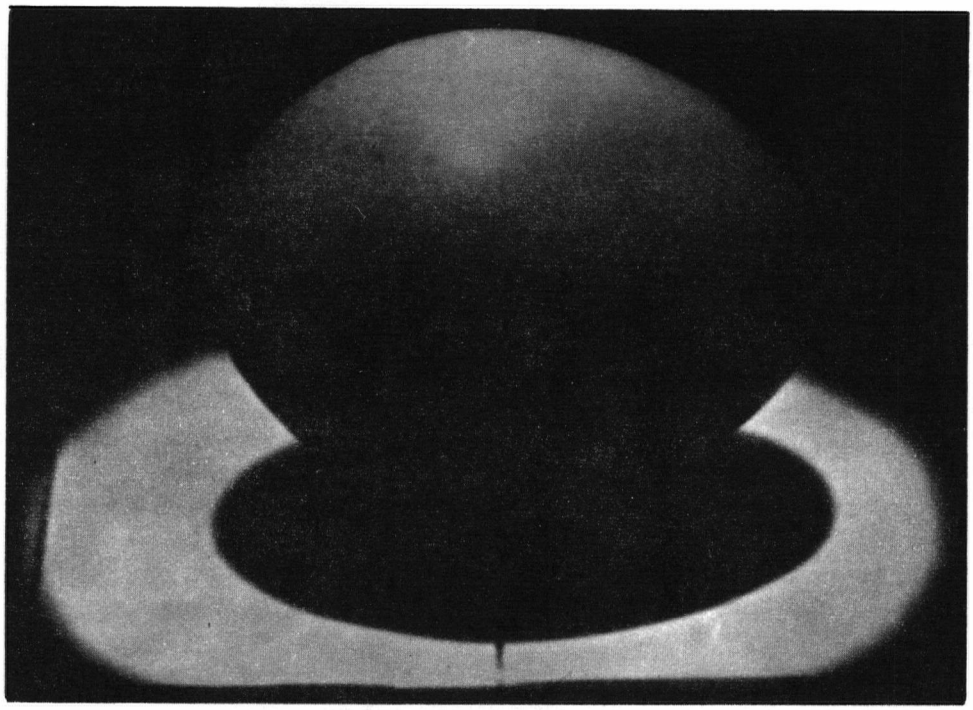

Fig. 1. Shadow Photography Method.

the egg was measured with the aid of a shadow photograph taken as shown in Fig. 1 and the formula:

$$\text{Roundness} = \frac{127\ A}{D^2} \qquad (1)$$

where A = area of the shadow cast by the egg, and

D = maximum diameter of the shadow.

This formula defines roundness as one hundred times the maximum projected area of the egg divided by the area of the smallest circumscribing circle. A roundness of 100 is approached as the shadow approaches circularity. Area of the shadow photograph was measured with a polar compensating planimeter and shadow length with dividers and a scale to precision limits of $\pm$ .01

square inch and $\pm$ .01 inch respectively.

The concepts of roundness and sphericity as applied to geology and petrography were clarified by Wadell (1933) from which three measures of sphericity were adapted for use in this study to describe egg shape.

Wadell defined true sphericity as:

$$\psi = \frac{s}{S} \tag{2}$$

where s = surface area of a sphere of volume equal to that of the particle, and

S = surface area of the particle.

The formula of Tyler and Geake (1961) was used to represent the volume of an egg, that is,

$$V = .512LB^2 - .06 \tag{3}$$

where V = volume of the egg in cm.^{3},

L = egg length in cm., and

B = egg width in cm.

For a sphere, surface area and volume are related by

$$s = 4.836V^{2/3} \tag{4}$$

where s = surface area in cm.^{2}, and

V = volume in cm.^{3}.

By substitution of equation (3) in (4), the surface area of a sphere with a volume equal to that of an egg was given by

$$s = 4.836(.512LB^2 - .06)^{2/3}. \tag{5}$$

Surface area of the egg was taken from the formula of Mueller and Scott (1940),

$$S = 4.67W^{2/3} \tag{6}$$

where S = surface area of the egg in cm.^{2}, and

W = fresh weight of the egg in gm.,

which gave true sphericity based on an index of one hundred as

$$\psi = \frac{100s}{S} = \frac{483.6(.512LB^2-.06)^{2/3}}{4.67W^{2/3}}. \tag{7}$$

That is,

$$\text{True sphericity} = 103.6\left[\frac{.512LB^2-.06}{W}\right]^{2/3} \tag{8}$$

It is noteworthy that this expression of egg shape was derived from three measures of egg size--egg weight, width, and length.

Wadell defined practical sphericity as:

$$\phi = \frac{d}{D} \tag{9}$$

where d = diameter of a circle equal in area to the area of the particle projection, and

D = diameter of the smallest circle circumscribing the particle.

The relation of the diameter of a circle to its area,

$$d = (1.27A)^{1/2}, \tag{10}$$

was substituted into equation (9) which resulted in

$$\phi = \left[\frac{1.27A}{D^2}\right]^{1/2} \tag{11}$$

as the formula for practical sphericity based on an index of one hundred. It was noted that practical sphericity was the square root of the roundness measurement previously discussed; therefore, practical sphericity of each egg was calculated from

$$\phi = 10(\text{Roundness})^{1/2} \tag{12}$$

Practical three-dimensional sphericity was suggested by Wadell to be:

$$\gamma = \frac{d'}{D'} \tag{13}$$

where d' = diameter of the sphere of volume equal to that of the particle,

D' = diameter of smallest circumscribing sphere.

Using the relation,

$$\text{diameter} = 1.24(\text{volume})^{1/3}\ , \tag{14}$$

for a sphere along with the formula of Tyler and Geake for the volume of an egg and substituting the length of the egg for D', the equation becomes:

$$\gamma = \frac{124(.512LB^2 - .06)^{1/3}}{L} \tag{15}$$

for the practical three-dimensional sphericity of an egg. It was noted that this measure of egg shape was a function of egg width and length and was therefore similar to shape index in that respect.

Shell Strength

Two concepts of shell strength under quasi-static loading were studied--force at failure, and energy absorbed up to failure. The testing machine (Figs. 2 and 3) was a Bellows Valvair Hydrocheck Compression Unit in which the piston was moved by compressed air at a rate controlled by hydraulic checking valves. This equipment was described in detail by Mohsenin (1963).

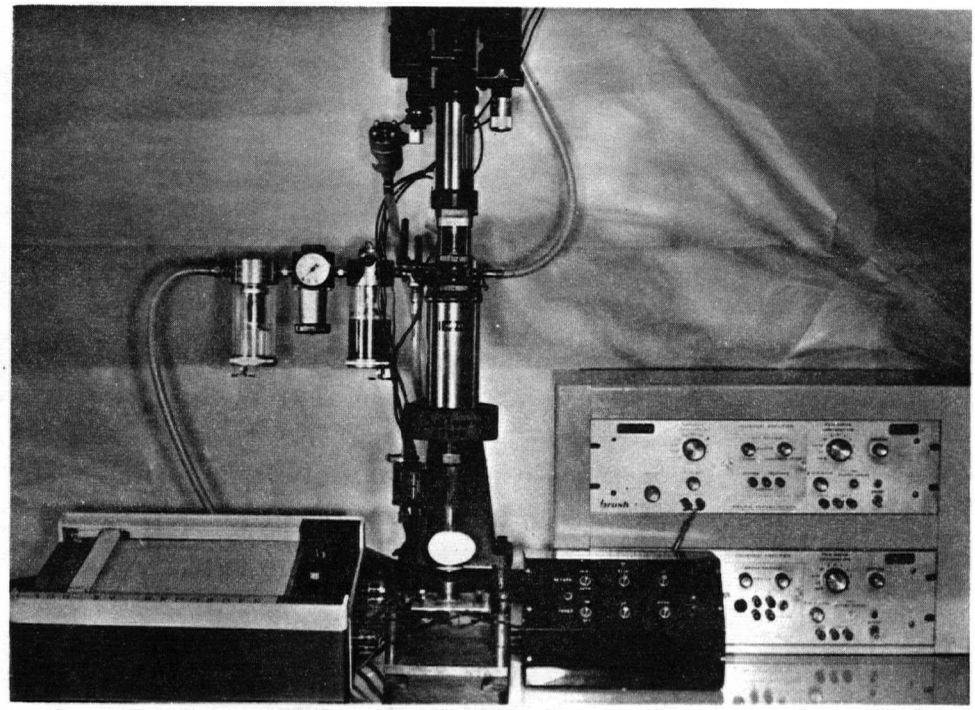

Fig. 2. Bellows Valvair Hydrocheck Compression Unit.

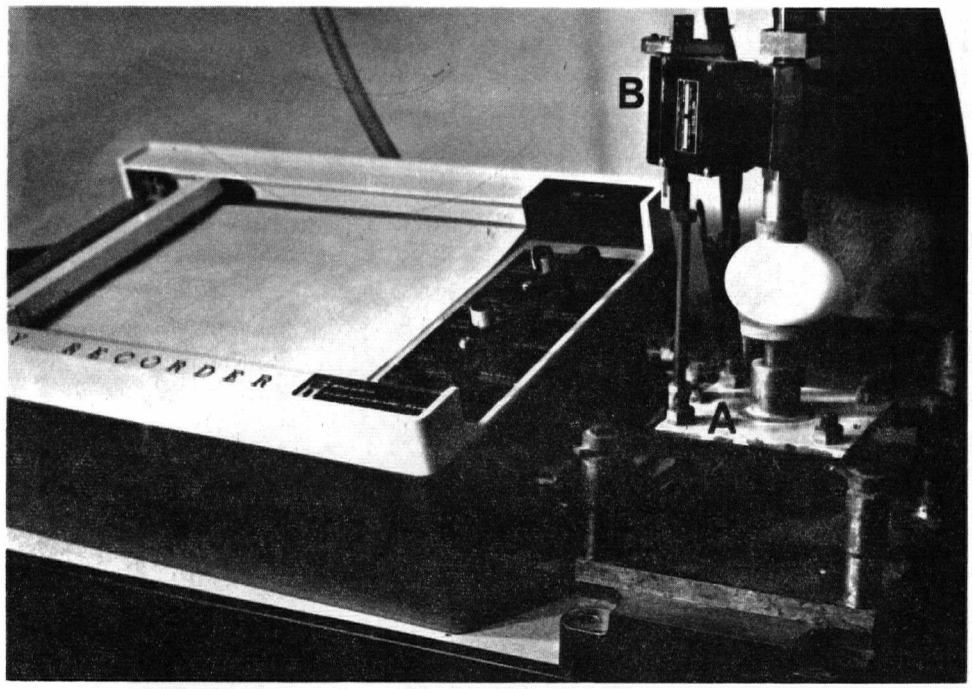

Fig. 3. Bellows Valvair Hydrocheck Compression Unit Showing Load Cell (A) and L.V.D.T. (B).

A force was applied to the egg parallel to its minor axis by two flat brass plates. The lower plate was adjustable vertically to accommodate eggs of varying size and was ridged near the outer edge to prevent eggs from rolling off the plate. Load applied to the egg was measured by supporting the lower plate on a strain gauge load cell and feeding the amplified signal to the pen drive (Y-axis) of the XY recorder. Deformation of the egg while being crushed was measured by a linear variable differential transformer (L.V.D.T.) whose amplified signal was fed to the carriage drive (X-axis) of the XY recorder. Sensitivities of 600 $\pm$ 10 grams per inch on the Y-axis and 42 $\pm$ 2 microns per inch on the X-axis were used and the deformation rate was controlled at 44 $\pm$ 2 microns per second.

Typical force-deformation curves for two different eggs appear in Fig. 4. The curves were linear, or nearly so, and the point of shell fracture was indicated by the sharp peak on the graph. Four data were obtained from each graph: force at failure (max. Y value), energy absorbed up to failure (area under the curve up to the point of failure), total deformation of the shell (max. X value), and shell stiffness (slope of the curve). The graphs were analyzed quickly by means of a modified drafting set square to which scales were glued that allowed reading force and total deformation at failure directly from the graph. Energy absorbed up to failure was taken as one-half the product of maximum force and total deformation, and shell stiffness was calculated as the quotient of maximum force and total deformation.

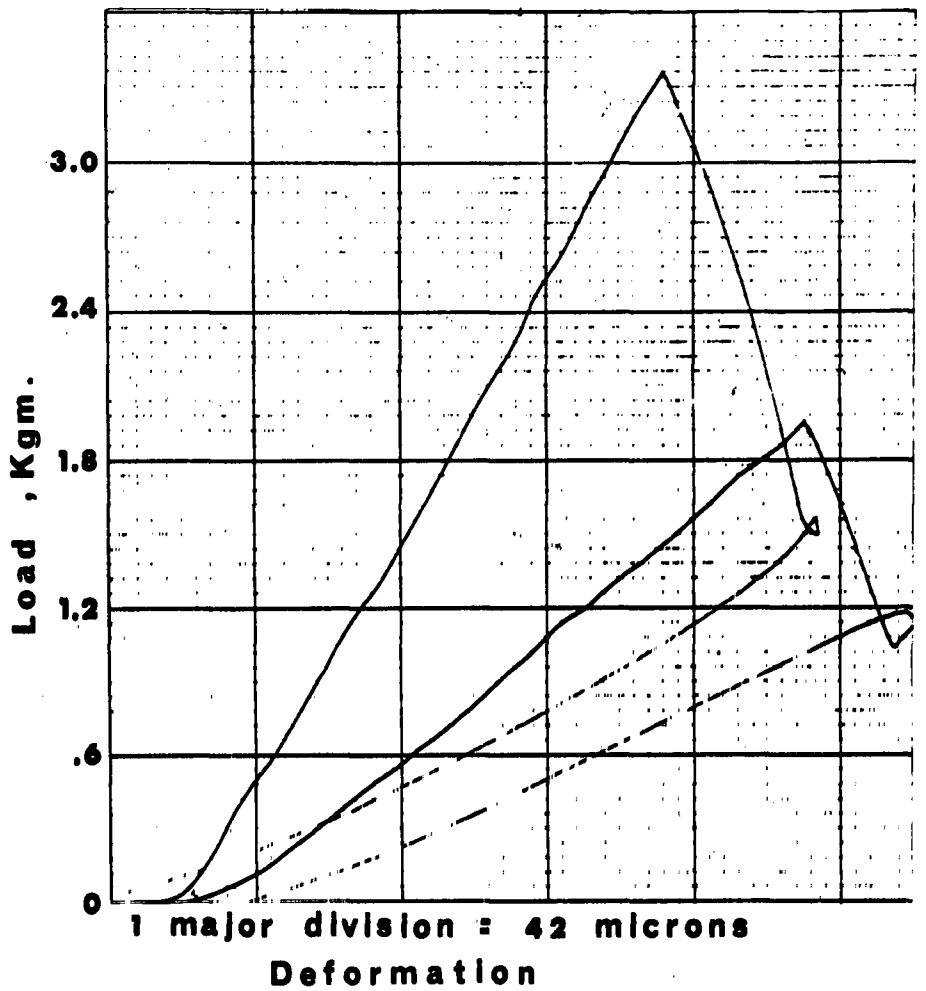

Fig. 4. Typical Force-Deformation Curves for Egg Shells.

Shell Quantity

Shell weight, shell thickness, percent egg as shell, and shell weight per unit surface area were used to express shell quantity. A line was drawn around each egg at its equator after which the egg contents were discarded and the shells boiled in .625 Molar aqueous sodium hydroxide for ten minutes to remove shell membranes and cuticle. The shells were rinsed thoroughly in tap water and dried in an oven at 80°C. for

twenty-four hours. Dried shells were weighed to the nearest centigram, and shell thickness to the nearest micron was taken as the average of three measurements at the equator using an anvil-jawed dial micrometer.

Percent egg as shell was calculated as the quotient of dried shell weight and fresh egg weight expressed in percent. Egg surface area was estimated using the formula of Mueller and Scott (Equation 6). Shell weight was divided by egg surface area and converted to milligrams per square centimeter.

Shell Hardness

Tests of Radial Sections

Hardness of shells produced by 10 birds was measured by a micro-indentation technique using the Tukon hardness tester shown in Fig. 5, and described by Mott (1956). After the shell membranes and cuticle had been removed, a small strip of shell taken from near the equator of each egg was mounted in epoxy resin as shown in Fig. 6,A. Each test block contained sections of shell from several eggs in order to minimize the number of blocks made.

The epoxy blocks were polished with a series of increasingly fine emery papers and two aluminum oxide lapidary wheels to reveal a radial section of each shell approximately in the plane of the equator (see Fig. 7). Diamond pyramid hardness was measured along a line at one-quarter the thickness of the shell from the outer edge (shell level .25) by

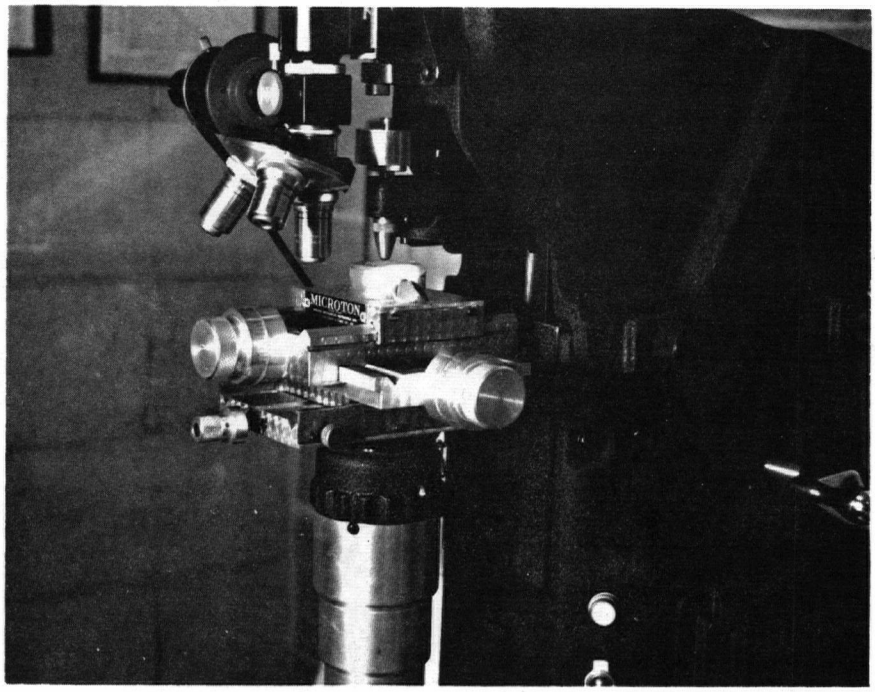

Fig. 5. Tukon Micro-Indentation Hardness Tester.

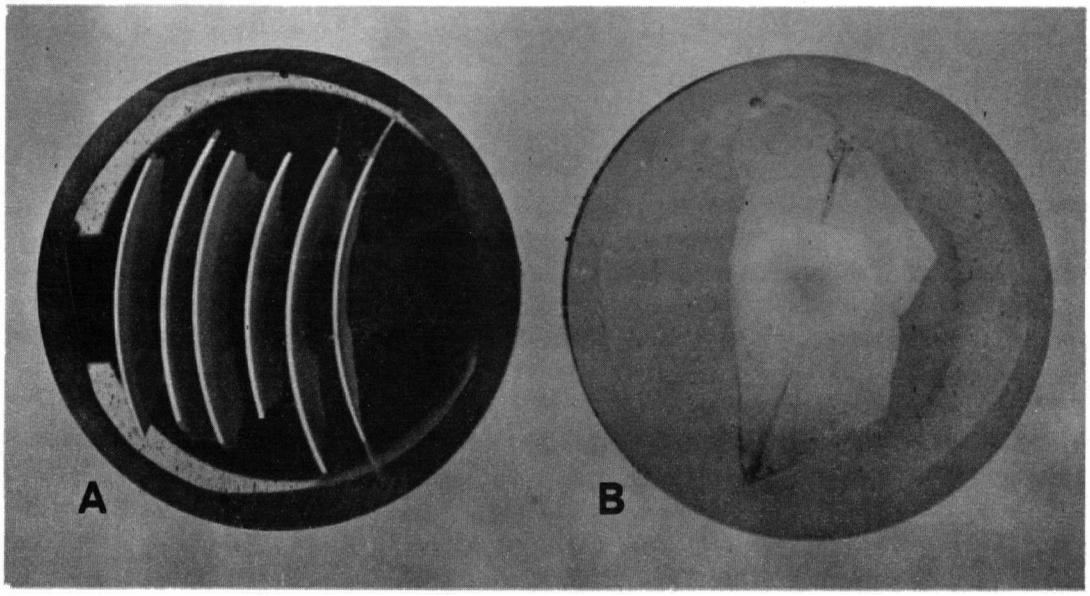

Fig. 6. Shells Mounted in Epoxy for Hardness Testing.
A - Radial Tests. B - Tangential Tests. (Mag. x 2)

Fig. 7. Photomicrograph of a Radial Section of Egg Shell Showing Indentation at Shell Level .25. (Mag. x 210)

forcing a square-based diamond pyramid into the shell and measuring the diagonals of the recovered indentations with an ocular micrometer on the Tukon tester. The diamond pyramid hardness is defined as the load per unit area of surface contact in kilograms per square millimeter calculated from the average diagonal length and the formula:

$$D.P.H. = \frac{1.8544L}{d^2} \tag{16}$$

where D.P.H. = diamond pyramid hardness

L = load in kilograms

d = average diagonal length in millimeters.

The average of the diagonal lengths of six indentations was used to calculate the hardness of each shell at its .25 shell

level. A load of 100 grams on the indenter was used and the .25 shell level was chosen because Brooks and Hale (1955) reported greater differences in hardness near the outer edge of the egg shell. Brittleness of the shell material precluded testing nearer the outer edge in radial sections.

Nine shells, produced by three different birds, were selected to measure the hardness across the shell from levels .25 to .75. Forty indentations per shell were made at randomly selected shell levels which were also recorded. The hardness data of each shell were separated into six groups for which the average hardness and shell level were calculated. These data were plotted in order to identify possible variations in hardness across the shell.

Tests of Tangential Sections

A method was developed whereby a tangential section of shell could be exposed to allow testing for hardness near the edges of the egg shell. The major difficulty presented was that of locating positions of shell levels on a tangential section as shown in Fig. 8. The principle used was that of the intersection of an arc (the shell level) and a chord (representing the exposed surface). Symbols used in the derivation are:

B = egg width at the equator,

T = shell thickness at the equator,

C = chord length,

P = distance along chord from either end,

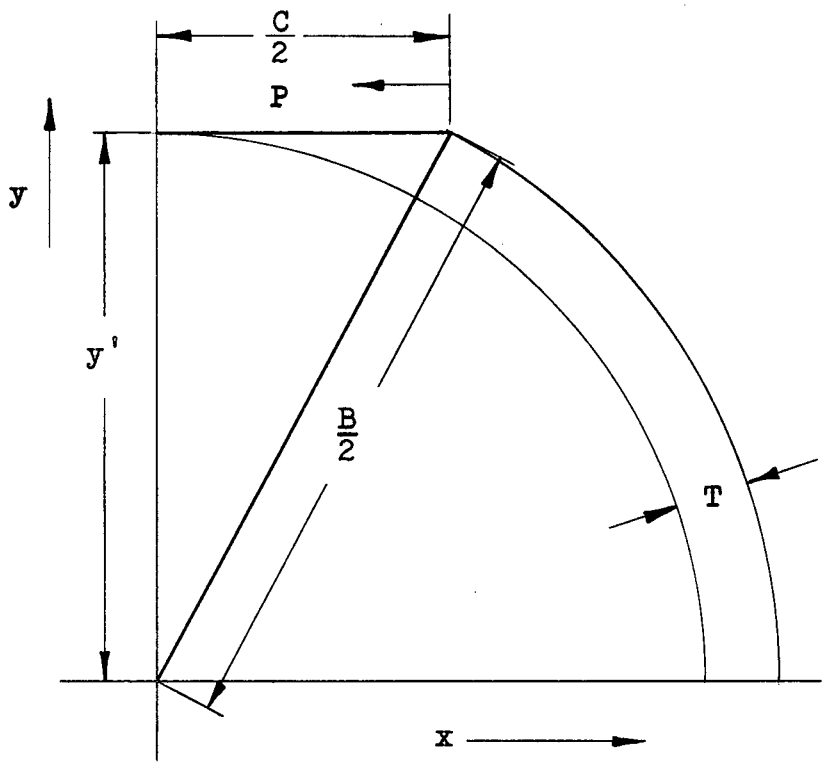

Fig. 8. Schematic Diagram of an Egg Shell in the Plane of its Equator.

j = shell level from outer edge (a decimal number), and

x, y = coordinate directions.

Intersection of the chord and the arcs will be at points,

$$P = \frac{C}{2} - x. \tag{17}$$

From the triangle,

$$(y')^2 = \frac{B^2}{4} - \frac{C^2}{4} , \tag{18}$$

and for the arcs at various shell levels

$$x^2 + y^2 = \left(\frac{B}{2} - jT\right)^2 . \tag{19}$$

At the intersections of the arcs with the chord, $y = y'$ and equation (18) may be substituted into equation (19) to give

$$x^2 + \frac{B^2}{4} - \frac{C^2}{4} = \left(\frac{B}{2} - jT\right)^2 \tag{20}$$

which may be solved for x.

$$x = (.25C^2 - jBT + j^2T^2)^{1/2} \tag{21}$$

and

$$P = .5C - (.25C^2 - jBT + j^2T^2)^{1/2} \tag{22}$$

The units of B and T were centimeters and inches respectively. The length of the chord, C, was measured with the Microton stage of the Tukon tester in units of 10 microns; therefore all other units were converted to those of the Microton stage to give the working equation:

$$P = .5C - (.25C^2 - 2.54 \times 10^6\ jBT + 6.452 \times 10^6\ j^2T^2)^{1/2} \tag{23}$$

A computer program was written to calculate the test location P for various values of j when C, B, and T were provided. The precision error limits using this method to locate shell levels on a tangential surface were estimated to be $\pm$ 1.2 percent.

Nine shells whose hardness gradients were measured in radial sections were also tested tangentially at shell levels .02, .10, .20, ..., .90. A piece of shell bearing a line corresponding to the equator of the shell was mounted in an epoxy block such that a tangential section at the equator could be exposed from the outside (see Fig. 6,B). Three indentations were made at each designated shell level starting from one edge of the exposed section along a narrow strip on either side of the equator. A duplicate set of indentations was then made starting at the opposite edge of the exposed area so that the

average of six indentations was used to calculate hardness at each shell level. After tests were made from level .02 to .50, the test block was cast in epoxy so that the original block could be ground away to expose a similar shell section from the inside on which levels .50 to .90 were tested. The duplicate testing of level .50 provided a total of twelve indentations from which the hardness at that level was calculated.

A test was conducted to determine whether the hardness gradient was affected by removing shell membranes and cuticle with boiling sodium hydroxide solution. Membranes were stripped mechanically from pieces of three shells that were then tested for hardness tangentially and compared with other samples of the same shells that had been treated with sodium hydroxide.

Analytical Methods

Facilities of the University of British Columbia Computing Center, which include an I.B.M. 7040 digital computer, were used to calculate data derived from original measurements and to analyze the results of this study. Means, standard deviations, simple and partial correlations, simple and multiple linear regressions, and stepwise multiple regressions were calculated with a method similar to that of Ralston and Wilf (1960). Snedecor (1956) and Ezekiel and Fox (1959) were used as references in the interpretation of statistical analyses. A plotting program was also employed to fit polynomial curves

by the method of least squares to the hardness gradient data.

All eggs tested in this study formed Group One which was studied on a pooled basis with each egg contributing a set of variables to the analysis. Data of individual birds for each test period were then averaged and analyzed on a bird average per period basis. Overall averages were calculated for those birds having complete records over all eight test periods to form the basis of the third analysis. Eggs tested for hardness constituted Group Two which was examined on both pooled-egg and bird average per period bases.

RESULTS AND DISCUSSION

Appendix A contains general sample data, means and standard deviations for all analyses. Results of simple and partial correlation analyses appear in Appendix B. Stepwise multiple regressions which successively eliminated non-significant independent variables were tabulated in Appendix C along with selected multiple linear regressions using only non-destructive shell measurements in relation to force at failure.

Egg and Shell Physical Properties

Shell Strength

The mean strength of eggs in this study was 3557 ± 578 grams when measured as force at failure, and 27.5 ± 6.1 gm.-cm. when taken as energy absorbed while being crushed by a quasi-static force applied at the shell equator.

Variation in force at failure was more completely accounted for by physical characteristics of the shell than was variation in energy absorbed at failure. (Table 1 and Appendix C).

TABLE 1

COEFFICIENTS OF MULTIPLE DETERMINATION (x 100) FOR REGRESSION OF ALL SHELL PROPERTIES ON SHELL STRENGTH EXPRESSED AS FORCE AND ENERGY AT FAILURE. GROUP 1.

	Pooled-Egg Basis	Bird Av. Per Period	Overall Bird Av.
Force	62.2	79.6	89.0
Energy	20.2	41.1	61.8

If physical properties were assumed to be capable of explaining variability in shell strength measured as energy absorption, the relatively large residual variance in the regressions on energy indicated that important factors had been overlooked or that the present method of analysis was unsuitable. Relationships among variables may differ from bird to bird such that strong relationships within birds were masked by analyzing samples composed of eggs from several birds. This contention was supported by the fact that Richards and Staley (1967)found inconsistent relationships between shell characteristics for different birds.

Coefficients of multiple determination were found to be consistently higher for regressions using averages rather than individual egg data (Table 1). To a certain extent this result was to be expected because the averaging process tends

to reduce the effects of random errors due to precision limits of measurement. Another major source of random variation could have been that of the measured strength of the shell which was composed primarily of the ceramic material, calcite. Ceramics characteristically show considerable variation in strength (Hayden et al. 1965; Rehkugler, 1963) which could result in an appreciable range of strengths measured for ostensibly identical egg shells. For this reason, strength of individual egg shells may well defy complete explanation in terms of physical properties. Average values for shell strength and physical properties of a small sample of eggs are therefore recommended when evaluating the strength of shells produced by individual birds.

Shell Stiffness

Egg shell stiffness was found to be the most important single predictor of shell strength measured as force at failure. Coefficients of determination were 57.1, 72.9, and 78.5 percent for Group One pooled-egg, bird average per period and overall bird average analyses respectively. These results are slightly higher than those of Richards and Staley (1967) who reported corresponding values of 49.0 and 62.4 percent for pooled-egg and bird average samples.

Stiffness alone explained only 8.4, 20.4, and 25.1 percent of the variation in energy absorbed at failure in pooled-egg, bird average per period and overall bird average data respectively.

Egg shell stiffness was highly correlated with measures of shell quantity (Table 2). The fact that each of the shell quantity characteristics was highly correlated with stiffness was not surprising in view of their strong inter-correlation.

TABLE 2

SIMPLE CORRELATIONS OF SHELL STIFFNESS WITH SHELL QUANTITY MEASUREMENTS. GROUP 1.

	Pooled-Egg Basis	Bird Av. Per Period	Overall Bird Av.
Shell weight	.701	.755	.853
Thickness	.836	.914	.956
Percent shell	.849	.921	.944
Shell wt./area	.846	.918	.958

Relationships between shell stiffness and other physical properties were examined further by stepwise multiple regression of egg size, shape, and shell quantity measurements on stiffness (Tables C3, C6, and C9). In the pooled-egg sample, egg width and roundness were important in addition to shell quantity with a coefficient of multiple determination of 76.1 percent. Bird average per period analyses revealed the importance of egg shape as roundness and true sphericity in addition to shell quantity with an R^2 of 90.2 percent. Width was included with shell quantity in the overall bird average analysis to give R^2 = 95.2 percent. Addition of all egg size and shape variables to the regression of shell quantity measures on stiffness reduced the residual variation in stiffness by

5.9, 20.5, and 34.9 percent in pooled-egg, bird average per period, and overall bird average analyses respectively (Table 3). These analyses show the existence of a strong relationship between shell stiffness and shell quantity along with minor contributions by egg size and shape.

TABLE 3

COEFFICIENTS OF MULTIPLE DETERMINATION (x 100) FOR REGRESSIONS OF SHELL QUANTITY, EGG SIZE, AND SHAPE ON STIFFNESS. GROUP 1.

	Pooled-Egg Basis	Bird Av. Per Period	Overall Bird Av.
Shell quantity*	74.6	87.8	93.7
Shell quantity, egg size** and shape***	76.1	90.3	95.9

* Shell weight, thickness, percent shell, and shell weight/area
** Egg weight, width, and length
*** Shape index, roundness, true sphericity, practical sphericity, and practical three-dimensional sphericity.

Voisey and Hunt (1967,b) developed a theoretical analysis of stresses in the egg shell under external loads. They showed that when force is applied to the poles of the egg, deformation of the shell is given by:

$$\delta = \frac{\sqrt{3(1-V^2)}PR}{2ET^2} \qquad (24)$$

where δ = deformation in the direction of applied load,

V = Poisson's ratio for shell material,

P = load applied,

R = one-half of egg width,

E = Young's modulus for shell material, and

T = thickness of shell.

Stiffness of the shell is defined as the ratio of force to deformation which is

$$\frac{P}{\delta} = \frac{2ET^2}{\sqrt{3(1-V^2)}R} \tag{25}$$

If Poisson's ratio and Young's modulus for shell material are assumed to be constant and the substitution, .5B = R where B = egg width is made, all constants may be combined to give:

$$\text{Stiffness} = \frac{kT^2}{B} \tag{26}$$

where $k = \frac{4E}{\sqrt{3(1-V^2)}}$

In the present study, force was applied at the equator of the egg; therefore, a similar analysis of factors involved in shell stiffness would be complicated by the lack of symmetry in a plane normal to the direction of applied force. Egg shape would undoubtedly be an important factor in the analysis of stiffness when force is applied to the equator.

From the previous discussions it may be concluded that theoretical and statistical analyses indicate that egg shell stiffness is largely a reflection of shell quantity along with probable effects of egg size and shape.

Egg Size

Egg size measured either as egg weight or width remained as a significant independent variable in the stepwise multiple regressions on force and energy absorbed at failure for Group One (Appendix C). In similar analyses of Group Two both egg weight and length remained in the regressions. After shell stiffness had been considered, the three measures of egg size in combination explained 7.7, 17.0, and 34.9 percent of the residual variation in force at failure for Group One pooled-egg, bird average per period, and overall bird average analyses respectively.

Egg width was found to be the most important measure of egg size in multiple regression with stiffness on force at failure. Decreases of 4.4, 5.5, and 24.2 percent in the residual variance of force at failure resulted from including egg width with stiffness in the three Group One analyses.

Egg Shape

Egg shape measured as shape index, roundness, practical sphericity, and practical three-dimensional sphericity had highly significant positive simple correlations with force and energy absorbed at failure in Group One pooled-egg and bird average per period analyses. True sphericity showed highly significant negative simple correlations with both measures of shell strength in these analyses.

Table 4 was used to compare the five egg shape measurements on the basis of their reduction of the residual variance in force at failure after shell stiffness had been considered. Shape index and practical three-dimensional sphericity showed consistently greater contributions to the regressions in each analysis than did the other measures of egg shape.

TABLE 4

PERCENT REDUCTION IN RESIDUAL VARIANCE BY ADDING EGG SHAPE MEASUREMENTS TO THE REGRESSION OF STIFFNESS ON FORCE AT FAILURE. GROUP 1.

	Pooled-Egg Basis	Bird Av. Per Period	Overall Bird Av.
Shape index	5.3	13.3	19.5
Roundness	3.5	11.1	14.4
True sphericity	3.0	6.6	15.8
Practical sphericity	3.5	10.7	14.0
Practical three-dimensional sphericity	5.3	13.3	19.5

Practical three-dimensional sphericity was highly correlated with shape index (r = .999); therefore, comparable results for these shape measurements were expected. This similarity can be examined in the formula by which practical three-dimensional sphericity was calculated:

$$P3dsph = \frac{124(.512LB^2 - .06)^{1/3}}{L} \quad . \qquad (15)$$

When cubed,

$$(P3dsph)^3 = 976{,}190 \frac{B^2}{L^2} - \frac{114{,}400}{L^3} \qquad (27)$$

Substituting shape index, $Shindx = 100\frac{B}{L}$ and noting that the second term may be omitted because it is very small compared with the first (about .1%), gives:

$$P3dsph = 4.6(Shindx)^{2/3} \quad \text{(approximately).} \qquad (28)$$

Roundness proved to be the most important measure of egg shape in the stepwise multiple regressions on force and energy absorbed at failure in bird average per period and overall bird average analyses of Group One; however, in regressions of egg shape with stiffness on force at failure, shape index was slightly superior to roundness in explaining residual variation. It is noteworthy that measurement of roundness and practical sphericity was of relatively low accuracy because a planimeter was used to find the projected area of the egg. Application of average geometrical relationships of eggs in the derivation of true sphericity and practical three-dimensional sphericity detracted from their accuracy as measures of egg shape. In general, shape index was found to be the most suitable measurement of egg shape.

Shell Quantity

Egg weight, shell thickness, percent egg as shell, and shell weight per unit area were highly intercorrelated and all had high positive correlations with both measures of shell

strength. Shell thickness alone accounted for 45.6, 62.4, and 74.2 percent of the variation in force at failure, and 9.8, 19.0, and 26.2 percent of energy absorbed in pooled-egg, bird average per period, and overall bird average analyses respectively.

Partial correlation analyses (Table B7) showed that shell thickness was second only to stiffness in explaining residual variation of force at failure in pooled-egg and bird average per period samples after all other variables were considered. In corresponding analyses (Table B8), thickness was the most important characteristic with respect to explaining residual variation in energy absorbed.

Shell Hardness

Importance to Shell Strength

Egg shell hardness measured at the .25 shell level had significant correlations of .207 and .277 with force at failure in pooled-egg and bird average per period analyses. In its correlation with energy absorbed at failure, hardness was of significance only on a bird average per period basis.

Stepwise multiple regression of all variables as bird averages per period indicated that hardness was important in both force and energy absorbed at failure. After all other characteristics were considered, hardness explained .24 and 7.77 percent of the residual variation of load with corresponding percentages of .33 and 8.38 for maximum energy absorbed

in the two analyses.

The simple correlation coefficient of .740 between shell hardness and crushing strength reported by Brooks and Hale (1955) and Brooks (1958) was not confirmed by this study. Several differences between methods of selecting eggs, testing of hardness, and treatment of data were evident. The present study made use of a large sample of eggs produced by ten birds of a single cross fed a common ration and housed in one room, whereas the earlier work was done on the ten weakest and strongest eggs of a heterogeneous sample. Brooks and Hale considered hardness at the surface of the shell extrapolated from measurements at shell levels .25, .50, and .75 in contrast to tests made only at level .25 in this study. In view of the large discrepancies reported for the importance of hardness to egg shell strength, further investigations are warranted to clarify genetic and environmental effects on shell hardness.

Hardness Gradient

Radial section tests of egg shells indicated that hardness was not uniform between shell levels .25 and .75. Hardness tests of tangential sections from level .02 to .90 revealed a curvilinear gradient of hardness across the shell. The hardness gradient found by fitting polynomial curves to the data of a representative shell appears in Fig. 9, and the average gradient for nine shells is in Fig. 10. In all cases a second degree polynomial expression was observed to fit the

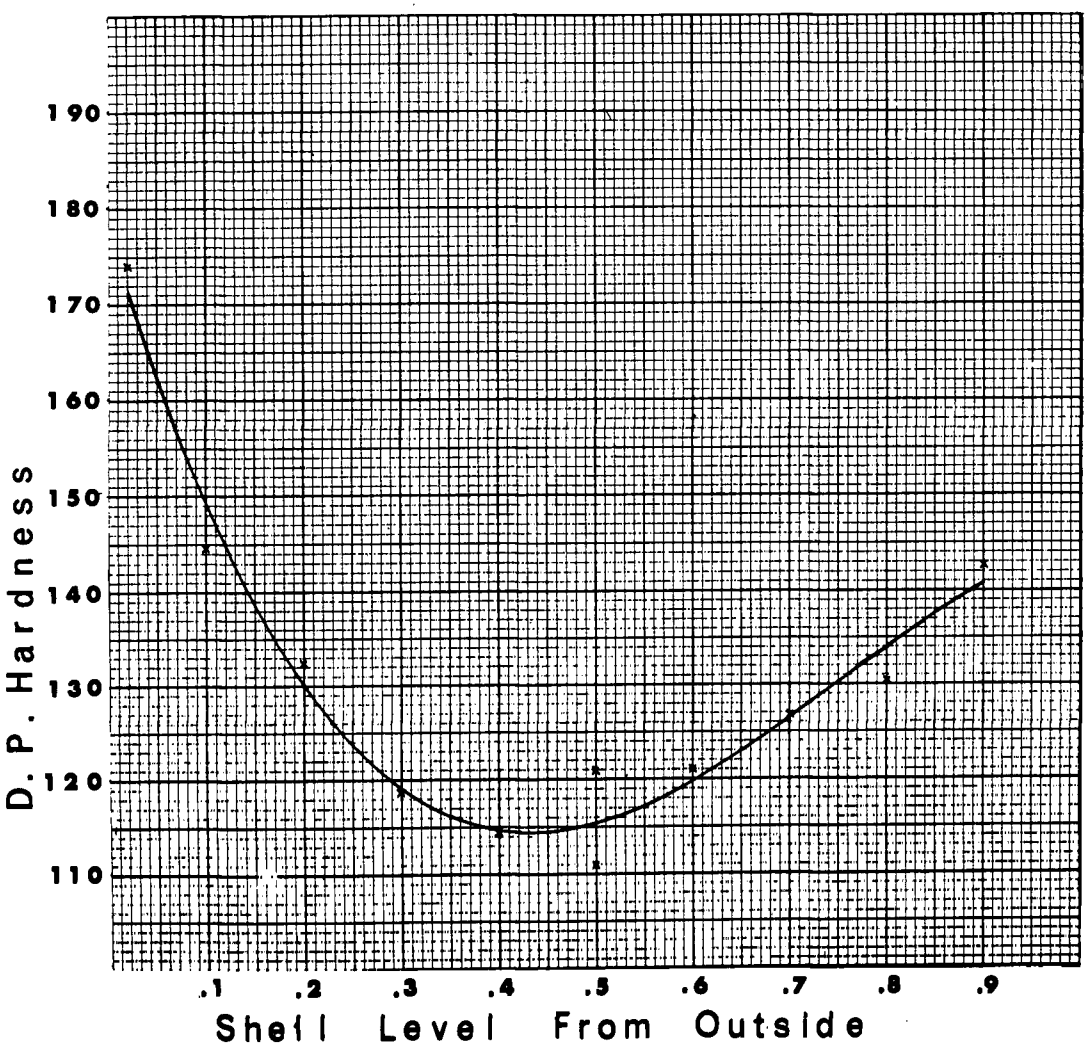

Fig. 9. Hardness Gradient of Shell No. 19a. Tests Made on a Tangential Section.

Equation of the Curve:

$$D.P.H. = 178.2 - 340.6X + 552.6X^2 - 244.7X^3$$

Standard Error of Estimate = 3.84, $R^2 = .968$

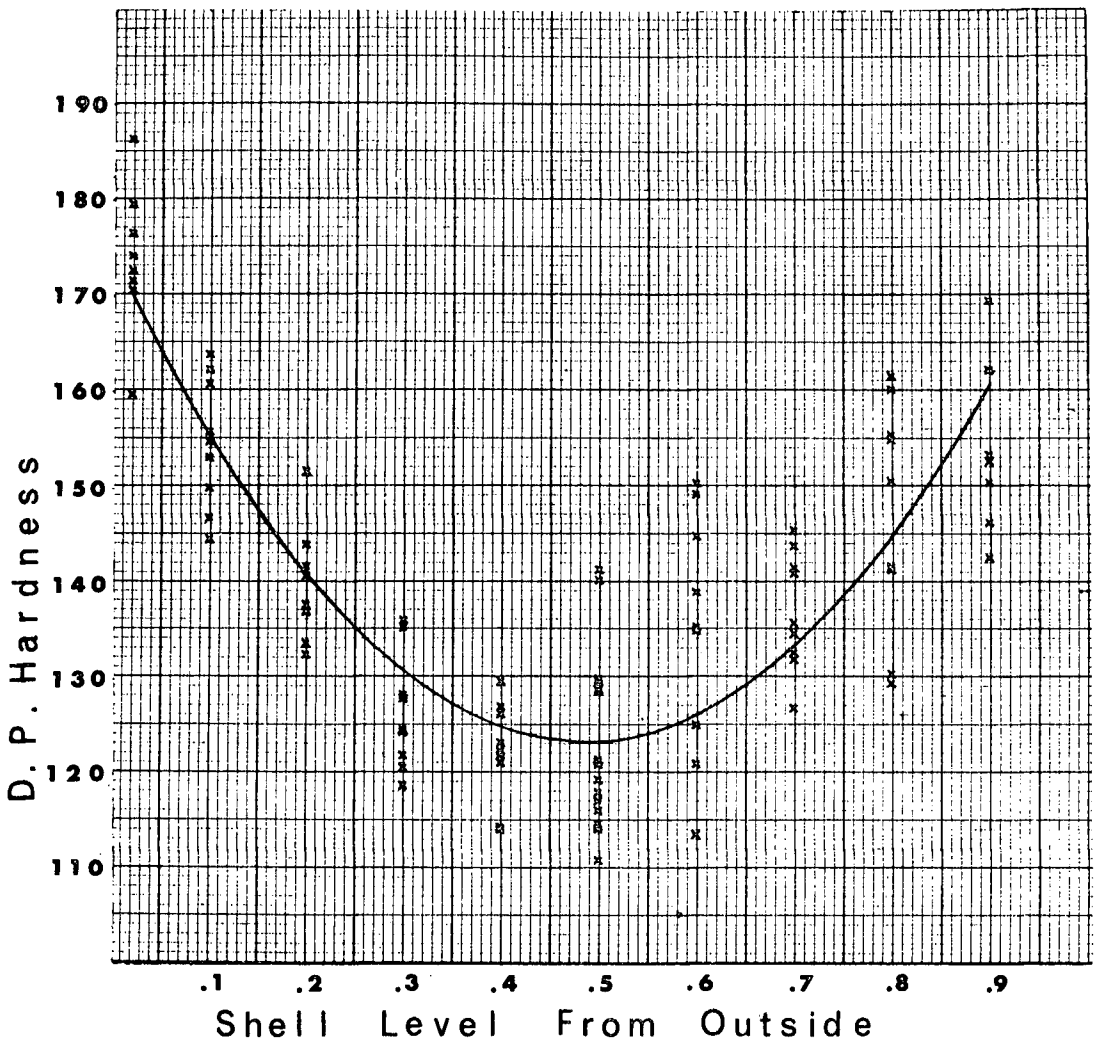

Fig. 10. Average Hardness Gradient of Shells of Birds No. 5, 9, 19. Tests made on Tangential Sections.

Equation of the Curve:

$$D.P.H. = 174.3 - 210.1X + 216.6X^2$$

Standard Error of Estimate = 9.38, $R^2 = .742$

data satisfactorily with only a small decrease in the standard error of estimate on using the cubic equation.

Comparison of radial and tangential hardness tests of the same shell between shell levels .20 and .70 resulted in similar curves. The data for three shells of one bird were plotted in Fig. 11 with separate curves fitted to radial and tangential points. The average hardness gradient curves for nine shells produced by three birds were included in Fig. 12. Examination of radial and tangential test results revealed that the gradient of hardness across the egg shell from levels .20 to .70 was largely independent of shell orientation.

Mechanical and chemical shell membrane removal were compared by duplicate tangential hardness testing between levels .02 and .90 of three shells that gave the following hardness gradient equations:

- Mechanical membrane removal

  $D.P.H. = 180.3 - 248.2X + 253.0X^2$

  Standard Error of Estimate = 13.01, $R^2 = .689$

- Chemical membrane removal

  $D.P.H. = 172.6 - 221.5X + 224.1X^2$

  Standard Error of Estimate = 9.21, $R^2 = .779$

Graphs of the two gradients were examined visually and judged to be essentially similar. On the basis of this comparison, chemical removal of shell membranes was assumed to have no appreciable effect on shell hardness.

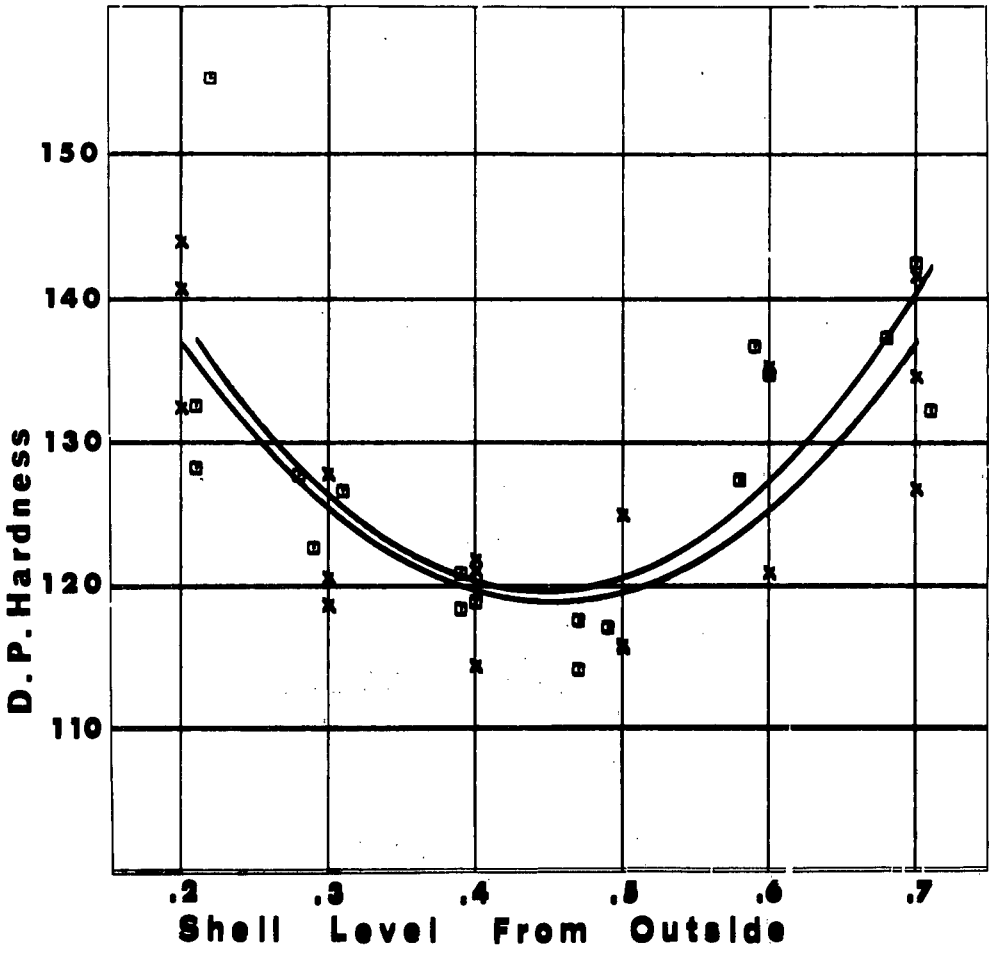

Fig. 11. Comparison of Radial (upper) and Tangential (lower) Hardness Gradients of Shells 19a, b, c. ▫ Radial Data, x Tangential Data.

Equations of the Curves:

D.P.H. (Radial) = $182.6 - 283.2X + 318.7X^2$

Standard Error of Estimate = 7.42, $R^2 = .558$

D.P.H. (Tangential) = $177.5 - 260.4X + 289.4X^2$

Standard Error of Estimate = 6.27, $R^2 = .614$

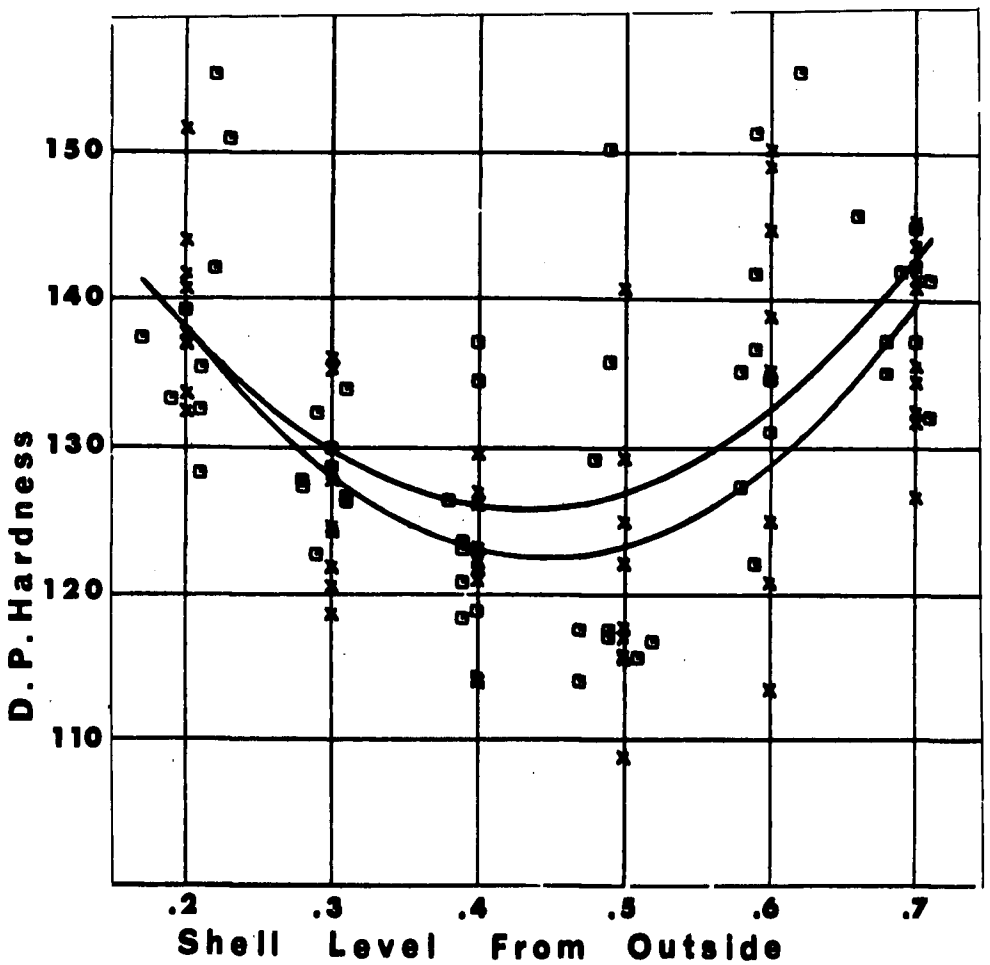

Fig. 12. Comparison of Radial (upper) and Tangential (lower) Hardness Gradients of Shells of Birds No. 5, 9, 19. ▫ Radial Data, x Tangential Data.

Equations of the Curves:

D.P.H. (Radial) = $168.6 - 199.9X + 233.4X^2$

Standard Error of Estimate = 8.83, $R^2 = .317$

D.P.H. (Tangential) = $174.2 - 233.0X + 262.9X^2$

Standard Error of Estimate = 8.37, $R^2 = .396$

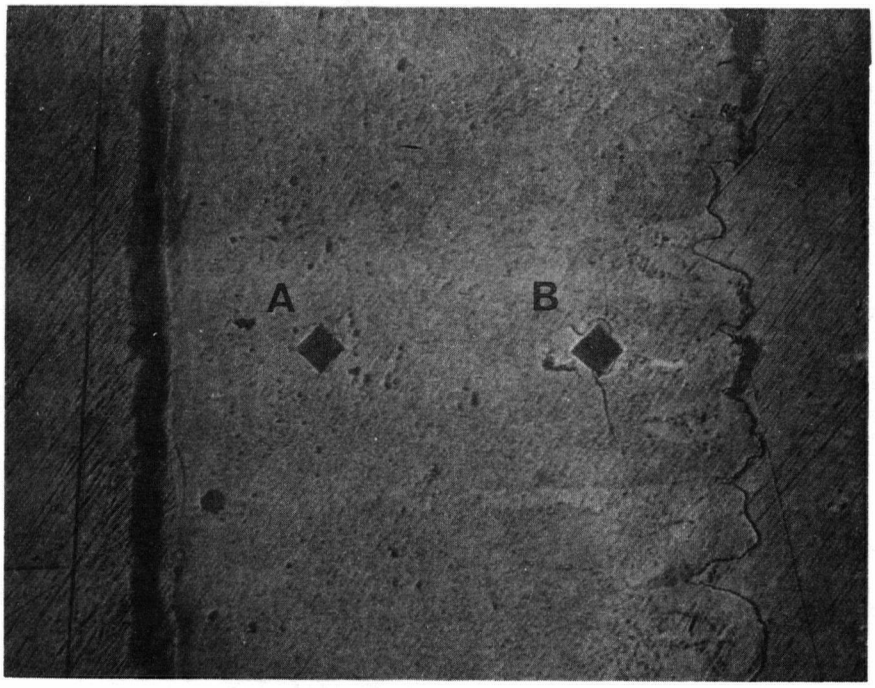

Fig. 13. Photomicrograph of a Radial Section of Egg Shell Showing Indentations at Shell Levels .25 (A), and .75 (B). (Mag. x 210)

The discovery of a curvilinear gradient of hardness across the thickness of the egg shell with a maximum at the outer edge, a minimum midway and a relative high again near the inner edge was not compatible with the report by Brooks and Hale (1955) of a linear gradient increasing toward the outer shell edge. The main point of disagreement was that of the hardness at shell level .75 because both studies contended that hardness was greater at level .25 than .50

Difficulty was experienced when testing hardness near the inner edge of the shell in radial sections because indentations often caused cracking of the shell (see Fig. 13,B)

which produced unusually large, invalid indentations. Hardness calculated from indentations enlarged by shell cracking would result in spuriously low values; therefore, such indentations were discarded in this study. Tangential tests of shells between levels .02 and .90 were found to minimize the incidence of cracking near edges of the shell and to confirm the presence of a parabolic hardness gradient across the egg shell. Hardness and its gradient across the thickness of the shell is worthy of further investigation.

Non-Destructive Estimation of Shell Strength

Multiple regressions of non-destructive measurements on egg shell strength measured as force at failure were examined in relation to corresponding regressions containing all shell characteristics (Table 5).

TABLE 5

COMPARISON OF NON-DESTRUCTIVE SHELL PROPERTIES WITH ALL SHELL MEASUREMENTS IN REGRESSION ON FORCE AT FAILURE. GROUP 1.

	Pooled-Egg Basis	Bird Av. Per Period	Overall Bird Av.
All Shell Properties	62.2	79.6	89.0
Non-Destructive Properties*	60.5	77.7	86.3

* Stiffness, egg weight, width, length, and shape index.

Deletion of destructive measurements of shell quantity caused small reductions in the coefficients of multiple

determination. The ability of non-destructive measurements to explain a large proportion of the variation in force at failure indicated their importance in estimating this measure of shell strength.

Egg weight, egg width, egg length, and shape index may be measured quickly and precisely by methods outlined in this study. Shell stiffness may be estimated with the use of a device similar to that of Schoorl and Boersma (1962) which allows measurement of deformation under a non-destructive load, or a compression testing machine that has been modified to automatically terminate loading at a predetermined force.

SUMMARY

Egg shell strength measured as maximum force and energy absorbed under quasi-static loading was studied in relation to shell stiffness, egg size, egg shape, shell quantity and hardness.

1. Losses caused by egg shell failure were estimated to be about 590 thousand dollars in British Columbia and 4.2 million dollars in Canada for the year 1965.

2. Physical properties of shells accounted for 62.2, 79.6, 89.0 percent of the variation in strength measured as force at failure in pooled-egg, bird average per period, and overall bird averages respectively. Corresponding figures for shell strength measured as energy absorbed

at failure were 20.2, 41.1, and 61.8 percent in the three analyses.

3. Mean values for shell characteristics were recommended when evaluating shell strength of individual birds due to intrinsic strength variation of the brittle shell material.

4. Shell stiffness was found to be the most important single predictor of crushing strength. Egg size, egg shape, shell quantity, and hardness were also related to shell strength.

5. The theoretically derived conclusion that stiffness was related to shell quantity, egg size and shape was verified by statistical analysis of the data.

6. Shape index proved to be the most satisfactory measure of egg shape when compared with roundness and sphericity concepts.

7. Egg shells were hardest at the outer surface, relatively hard near the inner surface, and softest midway across the shell.

8. Similar gradients of hardness were observed in radial and tangential test sections of shell material.

9. The non-destructive physical properties of stiffness, egg size, and shape may be used to estimate crushing strength of an egg shell.

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APPENDIX A

TABLE A1

TESTING PERIODS AND SAMPLE SIZES

Period	Dates of Period	No. of Eggs Tested
1	Jan. 2 - Jan. 29	342
2	Jan. 30 - Feb. 26	366
3	Feb. 27 - Mar. 26	351
4	Mar. 27 - Apr. 23	342
5	Apr. 24 - May 21	343
6	May 22 - Jun. 18	325
7	Jun. 19 - Jul. 16	322
8	Jul. 17 - Aug. 13	342
	Total Sample Size	2,733

TABLE A2

EGGS TESTED BY BIRD AND PERIOD

Bird	Period 1	2	3	4	5	6	7	8	Totals
1*	6	6	6	6	6	6	6	6	48
2	6	5	6	6	6	6	6	6	47
3*	5	1	0	2	0	0	0	0	8
4	6	7	6	6	6	6	6	6	49
5*	6	7	6	6	6	6	6	6	49
6	5	6	6	6	6	6	6	6	47
7*	5	6	6	6	6	6	6	6	47
8	5	6	6	6	6	6	6	6	47
9*	5	6	6	6	6	6	6	6	47
10	5	6	5	5	6	6	6	6	45
11*	7	7	6	6	6	6	6	6	50
12	6	7	6	6	6	6	6	6	49
13*	6	7	4	0	6	6	6	3	38
14	6	5	6	6	6	5	6	6	46
15*	5	5	6	6	6	6	6	6	46
16	7	7	5	6	6	6	6	6	49
17*	5	6	6	6	6	6	6	5	46
18	7	6	6	6	6	6	6	6	49
19*	5	6	6	6	6	6	5	6	46
20	4	5	5	6	6	6	6	6	44

* Shells from these birds tested for hardness.

cont'd...

TABLE A2 -- Continued

Bird	Period 1	2	3	4	5	6	7	8	Totals
21	5	6	6	6	6	6	6	6	47
22	5	7	6	6	6	6	6	6	48
23	6	6	4	6	6	6	6	6	46
24	5	6	6	6	6	6	6	6	47
25	6	8	6	6	6	6	6	6	50
26	6	5	6	6	5	5	6	6	45
27	5	7	6	6	6	6	6	6	48
28	6	7	6	6	6	6	6	6	49
29	6	7	6	6	6	6	6	6	49
30	6	0	0	6	6	6	6	6	36
31	5	5	4	6	6	6	6	6	44
32	5	6	7	6	6	6	6	6	48
33	6	6	6	6	6	0	0	6	36
34	6	7	6	6	6	6	6	6	49
35	7	7	6	6	6	6	6	6	50
36	5	6	6	6	6	5	3	6	43
37	5	4	4	6	2	5	5	6	37
38	6	6	7	6	6	6	6	6	49
39	7	6	7	6	6	6	6	6	50
40	6	7	7	6	6	6	6	6	50
41	6	6	6	6	6	6	4	6	46
42	7	6	6	6	6	6	6	6	49

cont'd...

TABLE A2 -- Continued

Bird	Period 1	2	3	4	5	6	7	8	Totals
43	6	6	6	6	6	6	6	6	48
44	6	7	7	6	6	6	6	6	50
45	5	7	6	6	6	6	6	6	48
46	5	6	6	6	6	5	6	6	46
47	6	6	7	6	6	6	5	6	48
48	6	7	7	6	6	0	0	6	38
49	5	7	7	0	0	0	0	0	19
50	6	7	6	6	6	6	6	6	49
51	7	7	7	6	6	6	6	6	51
52	6	7	7	6	6	6	6	6	50
53	5	6	7	6	6	6	6	6	48
54	5	7	5	6	6	6	6	6	47
55	6	7	6	5	6	0	0	6	36
56	5	6	7	6	6	6	6	6	48
57	5	6	6	6	6	6	6	4	45
58	6	7	7	6	6	6	6	6	50
59	6	6	7	6	6	6	6	6	49
60	7	6	7	6	6	6	6	6	50

TABLE A3

MEANS AND STANDARD DEVIATIONS. GROUP 1.

	Pooled-Egg Basis n=2733		Bird Av. Per Period n=461		Overall Bird Av. n=53	
	Mean	S.D.	Mean	S.D.	Mean	S.D.
Load	3557.0	578.3	3554.0	447.2	3559.0	375.2
Totdef	154.2	18.51	154.4	11.71	154.6	9.202
Stiff	23.30	4.264	23.26	3.498	23.26	3.062
Energy	27.54	6.096	27.55	4.027	27.60	3.142
Eggwt	58.94	4.354	58.92	4.017	59.02	3.308
Width	4.267	.118	4.265	.109	4.270	.095
Length	5.802	.215	5.802	.187	5.797	.136
Shelwt	5.299	.574	5.292	.521	5.295	.483
Thick	331.1	28.79	331.0	25.55	331.0	24.30
Persh	8.992	.745	8.977	.644	8.968	.575
Mgmcm2	74.89	6.393	74.81	5.613	74.79	5.211
Shindx	73.62	2.732	73.58	2.368	73.72	1.902
Round	72.87	2.955	72.82	2.494	72.94	1.894
Trusph	97.81	.845	97.80	.569	97.79	.464
Prasph	85.34	1.746	85.31	1.472	85.39	1.112
P3dsph	80.88	2.013	80.85	1.743	80.94	1.397

TABLE A4

MEANS AND STANDARD DEVIATIONS. GROUP 2.

	Pooled-Egg Basis n-425		Bird Av. Per Period Basis n=74	
	Mean	S.D.	Mean	S.D.
Load	3766.0	538.5	3755.0	411.8
Totdef	151.8	17.96	152.4	10.91
Stiff	25.15	4.666	25.02	3.867
Energy	28.60	5.385	28.59	2.988
Eggwt	59.16	4.749	58.95	4.242
Width	4.271	.129	4.264	.119
Length	5.793	.185	5.789	.135
Shelwt	5.544	.668	5.506	.625
Thick	343.7	28.73	342.6	25.30
Persh	9.359	.729	9.318	.628
Mgmcm2	78.08	6.780	77.72	6.100
Shindx	73.77	2.295	73.69	1.856
Round	73.03	2.576	72.94	2.120
Trusph	97.63	1.108	97.63	.567
Prasph	85.44	1.515	85.38	1.246
P3dsph	81.00	1.686	80.94	1.358
D.P.H.	137.7	11.60	137.8	6.663

TABLE A5

MEANS AND STANDARD DEVIATIONS BY PERIOD

	Period 1		Period 2		Period 3	
	Mean	S.D.	Mean	S.D.	Mean	S.D.
Load	3743.0	569.0	3720.0	590.9	3620.0	511.6
Totdef	161.3	17.69	151.2	18.05	150.6	17.06
Stiff	23.41	3.918	24.91	4.738	24.31	4.243
Energy	30.28	6.174	28.17	5.815	27.31	5.153
Eggwt	55.21	3.371	56.63	3.381	58.31	3.906
Width	4.191	.099	4.217	.099	4.244	.109
Length	5.638	.185	5.702	.180	5.794	.199
Shelwt	5.034	.532	5.256	.562	5.318	.576
Thick	331.2	28.46	338.7	29.75	335.5	28.17
Persh	9.111	.695	9.277	.785	9.117	.731
Mgmcm2	74.29	6.116	76.27	6.725	75.68	6.401
Shindx	74.39	2.661	74.02	2.559	73.32	2.706
Round	73.33	2.840	73.22	2.848	72.72	2.889
Trusph	97.81	.708	97.69	.706	97.70	.745
Prasph	85.62	1.665	85.55	1.658	85.25	1.703
P3dsph	81.45	1.944	81.17	1.880	80.67	1.994

TABLE A5 -- Continued

	Period 4		Period 5		Period 6	
	Mean	S.D.	Mean	S.D.	Mean	S.D.
Load	3529.0	525.1	3718.0	570.8	3398.0	557.6
Totdef	154.2	17.22	154.6	18.55	155.3	19.04
Stiff	23.10	3.886	24.29	4.180	22.09	3.958
Energy	27.30	5.498	28.88	6.360	26.53	6.105
Eggwt	59.15	3.523	59.60	4.022	60.73	4.004
Width	4.272	.099	4.278	.106	4.313	.115
Length	5.809	.194	5.836	.205	5.863	.185
Shelwt	5.309	.551	5.410	.563	5.357	.578
Thick	328.0	27.40	333.8	28.87	328.5	28.86
Persh	8.971	.691	9.078	.723	8.820	.728
Mgmcm2	74.82	6.169	75.89	6.273	74.20	6.401
Shindx	73.62	2.692	73.36	2.698	73.62	2.623
Round	74.04	2.816	73.46	3.063	72.12	2.670
Trusph	97.77	.803	97.76	.733	97.89	.799
Prasph	86.03	1.645	85.69	1.794	84.91	1.578
P3dsph	80.88	1.975	80.69	1.983	80.88	1.926

TABLE A5 -- Continued

	Period 7		Period 8	
	Mean	S.D.	Mean	S.D.
Load	3418.0	568.1	3277.0	545.2
Totdef	154.7	19.55	151.9	18.96
Stiff	22.30	3.994	21.77	3.961
Energy	26.62	6.307	25.04	5.878
Eggwt	61.00	4.344	61.31	4.183
Width	4.311	.121	4.322	.120
Length	5.886	.190	5.906	.230
Shelwt	5.394	.582	5.325	.562
Thick	328.2	28.33	323.9	27.75
Persh	8.839	.708	8.685	.711
Mgmcm2	74.48	6.278	73.30	6.207
Shindx	73.30	2.489	73.28	3.150
Round	72.03	2.518	71.90	3.181
Trusph	97.83	1.098	98.03	.862
Prasph	84.86	1.489	84.77	1.899
P3dsph	80.65	1.831	80.63	2.326

APPENDIX B

TABLE B1

SIMPLE CORRELATION COEFFICIENTS

GROUP 1. POOLED-EGG BASIS. n=2733.

	Load	Totdef	Stiff	Energy	Eggwt	Width	Length	Shelwt
P3dsph	.184	.179	.047	.233	-.081	.403	-.715	-.105
Prasph	.161	.135	.055	.191	-.109	.314	-.685	-.108
Trusph	-.084	.278	-.253	.097	.116	.311	.123	-.200
Round	.163	.136	.056	.192	-.111	.310	-.689	-.109
Shindx	.185	.179	.047	.234	-.082	.400	-.718	-.106
Mgmcm2	.665	-.351	.846	.289	.241	.128	.188	.899
Persh	.650	-.377	.849	.263	-.045	-.123	-.022	.735
Thick	.675	-.321	.836	.314	.241	.131	.194	.860
Shelwt	.576	-.252	.701	.279	.640	.490	.479	
Length	-.055	-.050	-.010	-.066	.737	.347		
Width	.177	.178	.048	.227	.867		.905	Persh
Eggwt	.117	.061	.071	.119		.957	.950	Mgmcm2
Energy	.843	.705	.290		-.087	-.066	-.091	Shindx
Stiff	.755	-.457		.904	-.075	-.046	-.092	Round
Totdef	.222		-.027	.115	-.311	-.348	-.276	Trusph
		-.017	.997	.904	-.074	-.045	-.093	Prasph
	.904	.122	.903	.999	-.086	-.066	-.092	P3dsph
	Prasph	Trusph	Round	Shindx	Mgmcm2	Persh	Thick	

$r_{.05} = .037$ $r_{.01} = .049$

TABLE B2

SIMPLE CORRELATION COEFFICIENTS

GROUP 1. BIRD AVERAGE PER PERIOD BASIS. n=461.

	Load	Totdef	Stiff	Energy	Eggwt	Width	Length	Shelwt
P3dsph	.245	.264	.065	.350	-.016	.421	-.682	-.069
Prasph	.230	.230	.070	.319	-.055	.349	-.682	-.081
Trusph	-.139	.398	-.311	.090	.135	.276	.119	-.232
Round	.231	.231	.070	.320	-.055	.348	-.683	-.082
Shindx	.244	.264	.064	.349	-.016	.421	-.683	-.069
Mgmcm2	.773	-.486	.918	.401	.292	.183	.230	.899
Persh	.769	-.505	.921	.388	-.012	-.093	.010	.722
Thick	.790	-.451	.914	.436	.281	.182	.223	.868
Shelwt	.649	-.370	.755	.356	.680	.547	.510	
Length	-.081	-.136	.014	-.142	.733	.372		
Width	.206	.164	.099	.262	.893		.920	Persh
Eggwt	.134	.011	.118	.118		.951	.967	Mgmcm2
Energy	.849	.523	.452		-.081	-.083	-.074	Shindx
Stiff	.854	-.513		.942	-.075	-.064	-.086	Round
Totdef	-.002		-.025	.106	-.376	-.429	-.312	Trusph
		-.019	.999	.942	-.074	-.064	-.086	Prasph
	.941	.111	.941	.999	-.080	-.081	-.073	P3dsph
	Prasph	Trusph	Round	Shindx	Mgmcm2	Persh	Thick	

$r_{.05} = .092$ $r_{.01} = .120$

TABLE B3

SIMPLE CORRELATION COEFFICIENTS

GROUP 1. OVERALL BIRD AVERAGE BASIS. n=53

	Load	Totdef	Stiff	Energy	Eggwt	Width	Length	Shelwt
P3dsph	.226	.324	.024	.389	.166	.542	-.593	.019
Prasph	.170	.283	-.005	.317	.140	.500	-.617	.001
Trusph	-.113	.523	-.323	.172	.095	.241	.073	-.278
Round	.166	.287	-.009	.316	.143	.504	-.614	-.002
Shindx	.233	.320	.032	.393	.165	.540	-.595	.025
Mgmcm2	.842	-.556	.958	.473	.388	.258	.313	.928
Persh	.792	-.630	.944	.390	.129	.012	.142	.793
Thick	.861	-.520	.956	.512	.395	.276	.318	.915
Shelwt	.809	-.376	.853	.535	.703	.569	.514	
Length	.137	-.070	.169	.074	.687	.354		
Width	.415	.291	.218	.531	.912		.940	Persh
Eggwt	.401	.134	.285	.430		.962	.981	Mgmcm2
Energy	.844	.413	.501		-.062	-.120	-.049	Shindx
Stiff	.886	-.574		.985	-.086	-.140	-.085	Round
Totdef	-.136		.022	.145	-.404	-.459	-.331	Trusph
		.019	.999	.984	-.080	-.133	-.080	Prasph
	.984	.151	.985	1.000	-.070	-.129	-.057	P3dsph
	Prasph	Trusph	Round	Shindx	Mgmcm2	Persh	Thick	

$r_{.05} = .268$ $r_{.01} = .348$

TABLE B4

SIMPLE CORRELATION COEFFICIENTS

GROUP 2. POOLED-EGG BASIS. n=425

	Load	Totdef	Stiff	Energy	Eggwt	Width	Length	Shelwt	Thick
D.P.H.	.207	-.136	.265	.067	-.073	-.159	.009	.184	.275
P3dsph	.119	.059	.039	.139	.095	.472	-.539	.014	-.045
Prasph	.145	.049	.068	.149	.068	.370	-.500	.029	-.014
Trusph	-.172	.203	-.268	.004	.000	.265	.053	-.223	-.279
Round	.144	.047	.068	.147	.067	.368	-.501	.028	-.013
Shindx	.118	.059	.038	.139	.095	.473	-.539	.013	-.045
Mgmcm2	.683	-.503	.866	.201	.482	.361	.377	.923	.947
Persh	.655	-.514	.854	.171	.210	.106	.172	.773	.898
Thick	.703	-.477	.864	.233	.474	.354	.382	.882	
Shelwt	.628	-.423	.765	.210	.781	.647	.604		
Length	.170	-.125	.216	.047	.767	.486		.957	Mgmcm2
Width	.304	-.066	.266	.198	.900		-.035	-.074	Shindx
Eggwt	.328	-.139	.336	.166		.862	.005	-.017	Round
Energy	.777	.644	.171		.035	.198	-.304	-.339	Trusph
Stiff	.750	-.625		.037	.999	.863	.006	-.017	Prasph
Totdef	.027		.863	.198	.861	.999	-.034	-.074	P3dsph
		-.159	-.090	-.214	-.091	-.161	.301	.358	D.P.H.
		P3dsph	Prasph	Trusph	Round	Shindx	Mgmcm2	Persh	

$r_{.05} = .095$ $r_{.01} = .124$

TABLE B5

SIMPLE CORRELATION COEFFICIENTS

GROUP 2. BIRD AVERAGE PER PERIOD BASIS. n=74

	Load	Totdef	Stiff	Energy	Eggwt	Width	Length	Shelwt	Thick
D.P.H.	.277	.039	.213	.283	-.133	-.225	.042	.071	.195
P3dsph	.188	.021	.090	.244	.346	.621	-.340	.168	.051
Prasph	.241	.059	.116	.320	.287	.532	-.346	.161	.075
Trusph	-.308	.290	-.349	-.121	-.072	.127	-.127	-.314	-.378
Round	.234	.058	.111	.311	.283	.529	-.349	.155	.069
Shindx	.184	.023	.087	.242	.341	.618	-.344	.163	.048
Mgmcm2	.831	-.723	.923	.390	.623	.503	.557	.943	.969
Persh	.812	-.706	.902	.378	.380	.258	.391	.812	.924
Thick	.869	-.704	.942	.442	.616	.503	.553	.919	
Shelwt	.767	-.656	.846	.369	.847	.738	.706		
Length	.324	-.390	.428	.065	.756	.525		.959	Mgmcm2
Width	.436	-.305	.435	.273	.942		.042	-.076	Shindx
Eggwt	.483	-.392	.518	.254		.907	.066	-.024	Round
Energy	.775	.233	.415		.158	.249	-.411	-.458	Trusph
Stiff	.895	-.733		.150	.999	.907	.073	-.018	Prasph
Totdef	-.427		.906	.248	.906	1.000	.046	-.073	P3dsph
		-.284	-.182	-.244	-.191	-.288	.177	.247	D.P.H.
		P3dsph	Prasph	Trusph	Round	Shindx	Mgmcm2	Persh	

$r_{.05} = .227$ $r_{.01} = .296$

TABLE B6

SIMPLE CORRELATIONS BETWEEN LOAD

AND SELECTED VARIABLES FOR EACH TEST PERIOD

	$r_{.05}$ $r_{.01}$	Stiff	Eggwt	Width	Length	Shindx	Round	P3dsph
Pd. 1 n=342	.106 .138	.772	.263	.273	.080	.111	.029	.108
Pd. 2 n=366	.103 .134	.773	.239	.241	.060	.109	.081	.109
Pd. 3 n=351	.105 .137	.752	.301	.295	.114	.100	.059	.101
Pd. 4 n=342	.106 .138	.753	.284	.307	.071	.130	.082	.129
Pd. 5 n=343	.106 .138	.706	.255	.358	-.032	.271	.171	.271
Pd. 6 n=325	.109 .142	.739	.255	.312	.041	.199	.142	.199
Pd. 7 n=322	.109 .143	.726	.325	.347	.064	.226	.210	.224
Pd. 8 n=342	.106 .138	.744	.250	.322	-.025	.226	.205	.225
All pds. n=2733	.037 .049	.755	.117	.177	-.055	.185	.163	.184

TABLE B7

SQUARES OF SIMPLE AND PARTIAL CORRELATIONS

BETWEEN LOAD AND SELECTED VARIABLES. GROUP 1.

	Pooled-Egg Basis n=2733		Bird Av. Per Period n=461		Overall Bird Av. n=53	
	$100(sc)^2$*	$100(pc)^2$**	$100(sc)^2$*	$100(pc)^2$**	$100(sc)^2$*	$100(pc)^2$**
Stiff	57.05	17.64	72.91	13.62	78.52	7.60
Eggwt	1.37	.00	1.78	.65	16.08	.24
Width	3.12	.22	4.26	.17	17.25	2.44
Length	.30	.05	.65	.02	1.87	1.45
Shelwt	33.21	.37	42.12	.76	65.42	3.49
Thick	45.58	1.43	62.38	2.86	74.17	2.21
Persh	42.19	.08	59.09	.96	62.65	1.44
Mgmcm2	44.16	.03	59.68	.00	70.91	.83
Shindx	3.43	.07	5.93	.17	5.45	8.93
Round	2.67	.49	5.35	.70	2.77	5.56
Trusph	.71	.00	1.92	1.23	1.28	4.45
Prasph	2.60	.46	5.29	.43	2.88	2.27
P3dsph	3.39	.37	5.98	.03	5.09	4.64
P=.05***	.16	.16	.84	.86	7.20	9.24
P=.01***	.24	.24	1.43	1.47	12.12	15.44

* $100(\text{simple correlation})^2$
** $100(\text{partial correlation})^2$
*** $100(\text{minimum correlation coefficient significant at indicated level})^2$

TABLE B8

SQUARES OF SIMPLE AND PARTIAL CORRELATIONS

BETWEEN ENERGY AND SELECTED VARIABLES. GROUP 1.

	Pooled-Egg Basis n=2733		Bird Av. Per Period n=461		Overall Bird Av. n=53	
	$100(sc)^2$*	$100(pc)^2$**	$100(sc)^2$*	$100(pc)^2$**	$100(sc)^2$*	$100(pc)^2$**
Stiff	8.43	.01	20.43	.07	25.12	1.41
Eggwt	1.41	.02	1.39	.59	18.49	.20
Width	5.16	.06	6.86	.16	28.21	1.82
Length	.43	.01	2.02	.03	.55	1.69
Shelwt	7.79	.33	12.69	.70	28.62	3.55
Thick	9.83	1.64	18.99	3.26	26.23	2.47
Persh	6.92	.04	15.03	1.03	15.23	.74
Mgmcm2	8.32	.05	16.05	.00	22.37	1.20
Shindx	5.45	.08	12.21	.13	15.47	8.84
Round	3.69	.26	10.25	.63	9.96	4.58
Trusph	.94	.05	.81	1.32	2.95	3.39
Prasph	3.65	.23	10.16	.37	10.02	1.82
P3dsph	5.41	.19	12.27	.01	15.09	4.48
P=.05***	.16	.16	.84	.86	7.20	9.24
P=.01***	.24	.24	1.43	1.47	12.12	15.44

* $100(\text{simple correlation})^2$

** $100(\text{partial correlation})^2$

*** $100(\text{minimum correlation coefficient significant at indicated level})^2$

TABLE B9

SQUARES OF SIMPLE AND PARTIAL CORRELATIONS

BETWEEN STIFFNESS AND SELECTED VARIABLES. GROUP 1

	Pooled-Egg Basis n=2733		Bird Av. Per Period n=461		Overall Bird Av. n=53	
	$100(sc)^2$*	$100(pc)^2$**	$100(sc)^2$*	$100(pc)^2$**	$100(sc)^2$*	$100(pc)^2$**
Eggwt	.51	.03	1.40	.02	8.12	.02
Width	.23	.04	.97	.04	4.74	3.00
Length	.01	.00	.02	.01	2.85	1.02
Shelwt	49.11	.04	57.02	.62	72.71	5.32
Thick	69.82	4.70	83.50	8.17	91.30	6.16
Persh	72.08	.04	84.90	.06	89.19	3.78
Mgmcm2	71.62	.10	84.18	.84	91.74	10.28
Shindx	.22	.00	.41	.00	.10	.29
Round	.31	.15	.49	.54	.01	.12
Trusph	6.40	.00	9.66	.31	10.44	.63
Prasph	.31	.09	.49	.25	.00	.30
P3dsph	.22	.02	.43	.02	.06	.50
P=.05***	.16	.16	.84	.86	7.20	9.24
P=.01***	.24	.24	1.43	1.47	12.12	15.44

* 100(simple correlation)^2

** 100(partial correlation)^2

*** 100(minimum correlation coefficient significant at indicated level)^2

TABLE B10

SQUARES OF SIMPLE AND PARTIAL CORRELATIONS

BETWEEN LOAD AND SELECTED VARIABLES. GROUP 2.

	Pooled-Egg Basis n=425		Bird Av. Per Period Basis n=74	
	$100(sc)^2$*	$100(pc)^2$**	$100(sc)^2$*	$100(pc)^2$**
Stiff	56.19	15.39	80.17	22.63
Eggwt	10.76	1.06	23.32	5.82
Width	9.22	.20	19.04	.97
Length	2.89	.98	10.47	2.21
Shelwt	39.38	1.60	58.80	.44
Thick	49.41	2.32	75.43	9.49
Persh	42.88	.01	65.90	5.56
Mgmcm2	46.69	.47	69.12	.66
Shindx	1.40	.09	3.40	.03
Round	2.06	.33	5.45	2.91
Trusph	2.97	.18	9.48	4.22
Prasph	2.10	.38	5.79	3.37
P3dsph	1.41	.07	3.53	.04
D.P.H.	4.27	.24	7.69	7.77
P=.05***	.91	.94	5.18	6.25
P=.01***	1.55	1.60	8.78	10.56

* $100(\text{simple correlation})^2$

** $100(\text{partial correlation})^2$

*** $100(\text{minimum correlation coefficient significant at indicated level})^2$

TABLE B11

SQUARES OF SIMPLE AND PARTIAL CORRELATIONS

BETWEEN ENERGY AND SELECTED VARIABLES. GROUP 2.

	Pooled-Egg Basis n=425		Bird Av. Per Period Basis n=74	
	$100(sc)^2$*	$100(pc)^2$**	$100(sc)^2$*	$100(pc)^2$**
Stiff	2.93	.15	17.24	.16
Eggwt	2.75	.89	6.44	4.71
Width	3.92	.19	7.45	1.21
Length	.22	.87	.43	1.87
Shelwt	4.43	1.35	13.58	.04
Thick	5.42	2.56	19.50	10.02
Persh	2.92	.00	14.29	6.32
Mgmcm2	4.03	.37	15.18	1.50
Shindx	1.94	.15	5.84	.00
Round	2.16	.33	9.68	3.31
Trusph	.00	.16	1.47	4.64
Prasph	2.22	.38	10.21	3.85
P3dsph	1.94	.02	5.95	.06
D.P.H.	.45	.33	8.03	8.38
P=.05***	.91	.94	5.18	6.25
P=.01***	1.55	1.60	8.78	10.56

* 100(simple correlation)^2

** 100(partial correlation)^2

*** 100(minimum correlation coefficient significant at indicated level)^2

TABLE B12

SQUARES OF SIMPLE AND PARTIAL CORRELATIONS

BETWEEN STIFFNESS AND SELECTED VARIABLES. GROUP 2.

	Pooled-Egg Basis n=425		Bird Av. Per Period Basis n=74	
	$100(sc)^2$*	$100(pc)^2$**	$100(sc)^2$*	$100(pc)^2$**
Eggwt	11.32	1.52	26.81	.41
Width	7.06	.02	18.96	.00
Length	4.67	.68	18.34	.03
Shelwt	58.54	2.06	71.54	.49
Thick	74.68	9.50	88.76	27.20
Persh	72.88	.82	81.40	.82
Mgmcm2	74.91	1.18	85.17	.01
Shindx	.14	.10	.76	.40
Round	.47	.15	1.24	1.66
Trusph	7.17	.51	12.19	.13
Prasph	.46	.13	1.35	1.61
P3dsph	.15	.65	.81	.38
D.P.H.	7.00	.03	4.55	.22
P=.05***	.91	.94	5.18	6.25
P=.01***	1.55	1.60	8.78	10.56

* $100(\text{simple correlation})^2$

** $100(\text{partial correlation})^2$

*** $100(\text{minimum correlation coefficient significant at indicated level})^2$

APPENDIX C

TABLE C1

STEPWISE MULTIPLE REGRESSION

WITH LOAD AS THE DEPENDENT VARIABLE

GROUP 1, POOLED-EGG BASIS. n=2733

Independent Variable	F - Ratio Analysis 1	2	3	4	5
Stiff	581.40	581.49	582.04	582.47	586.72
Eggwt	.10	--	--	--	--
Width	4.35	13.74	29.33	89.06	88.06
Length	1.09	1.01	1.03	--	--
Shelwt	9.57	10.80	28.02	28.04	77.48
Thick	39.53	39.45	39.84	39.77	41.18
Persh	1.91	2.24	2.77	2.47	57.81
Mgmcm2	1.01	.92	1.16	1.30	--
Shindx	2.24	2.14	2.10	7.37	6.80
Round	13.21	14.90	16.95	19.04	19.24
Trusph	.20	.11	--	--	--
Prasph	12.23	13.93	16.23	18.33	18.55
P3dsph	9.56	9.79	10.75	11.18	10.37
$100R^2$	62.2	62.2	62.2	62.2	62.2

$F_{.05} = 3.84$ $F_{.01} = 6.64$

TABLE C2

STEPWISE MULTIPLE REGRESSION

WITH ENERGY AS THE DEPENDENT VARIABLE

GROUP 1. POOLED-EGG BASIS. n=2733

Independent Variable	F - Ratio Analysis 1	2	3	4	5
Stiff	.22	.22	--	--	--
Eggwt	.84	.75	.74	1.18	12.42
Width	1.14	1.01	1.03	.60	--
Length	.14	--	--	--	--
Shelwt	9.52	9.38	9.46	11.98	11.50
Thick	45.27	45.21	48.93	48.99	49.30
Persh	.67	.63	.65	--	--
Mgmcm2	1.86	1.84	1.89	11.70	11.23
Shindx	2.58	4.85	4.87	5.63	7.69
Round	6.71	7.39	7.51	6.87	6.29
Trusph	1.89	1.79	1.79	3.04	76.21
Prasph	5.93	6.57	6.65	6.03	5.44
P3dsph	5.23	5.36	5.40	5.25	4.73
$100R^2$	20.2	20.2	20.2	20.1	20.1

$F_{.05} = 3.84$ $F_{.01} = 6.64$

TABLE C3

STEPWISE MULTIPLE REGRESSION

WITH STIFFNESS AS THE DEPENDENT VARIABLE

GROUP 1. POOLED-EGG BASIS. n=2733

Independent Variable	F - Ratio Analysis 1	2	3	4	5
Eggwt	.57	1.22	1.64	.87	--
Width	1.22	6.43	10.69	17.43	14.48
Length	.06	.30	--	--	--
Shelwt	1.41	1.34	1.12	2.17	65.02
Thick	134.53	135.17	135.41	136.09	145.53
Persh	.88	.92	.86	--	--
Mgmcm2	3.33	3.59	3.39	19.64	233.89
Shindx	.04	--	--	--	--
Round	4.09	4.41	5.00	3.57	18.15
Trusph	.03	--	--	--	--
Prasph	2.40	2.55	2.96	2.16	--
P3dsph	.68	1.01	1.75	--	--
$100R^2$	76.1	76.1	76.1	76.1	76.1

$F_{.05} = 3.84$ $F_{.01} = 6.64$

TABLE C4

STEPWISE MULTIPLE REGRESSION

WITH LOAD AS THE DEPENDENT VARIABLE

GROUP 1. BIRD AVERAGE PER PERIOD BASIS. n=461

Independent Variable	F - Ratio Analysis 1	2	3	4	5
Stiff	70.32	71.85	71.59	71.49	72.98
Eggwt	3.51	6.06	11.28	11.28	11.18
Width	1.08	1.02	--	--	--
Length	.06	--	--	--	--
Shelwt	4.37	12.71	12.06	12.12	12.09
Thick	13.05	13.35	13.61	14.71	15.36
Persh	3.64	13.24	12.53	12.40	11.96
Mgmcm2	.15	--	--	--	--
Shindx	.97	.88	.82	--	--
Round	3.46	3.34	3.87	4.49	91.04
Trusph	6.05	10.13	26.15	33.41	31.36
Prasph	2.20	2.09	2.52	2.48	--
P3dsph	.21	.26	--	--	--
$100R^2$	79.6	79.6	79.6	79.5	79.4

$F_{.05} = 3.86$ $F_{.01} = 6.69$

TABLE C5

STEPWISE MULTIPLE REGRESSION

WITH ENERGY AS THE DEPENDENT VARIABLE

GROUP 1. BIRD AVERAGE PER PERIOD BASIS. n=461

Independent Variable	F - Ratio Analysis 1	2	3	4	5
Stiff	.35	.33	.32	--	--
Eggwt	3.00	3.41	6.03	11.25	11.19
Width	.94	.89	1.03	--	--
Length	.13	.16	--	--	--
Shelwt	3.72	12.39	12.53	12.03	12.07
Thick	14.93	15.02	15.24	15.52	17.62
Persh	4.24	13.23	13.32	12.42	11.99
Mgmcm2	.05	--	--	--	--
Shindx	.82	.82	1.54	.76	--
Round	3.04	3.00	3.73	3.19	108.41
Trusph	6.22	6.36	11.22	30.58	37.03
Prasph	1.84	1.80	2.34	1.96	--
P3dsph	.12	.12	--	--	--
$100R^2$	41.1	41.1	41.0	40.8	40.5

$F_{.05} = 3.86$ $F_{.01} = 6.69$

TABLE C6

STEPWISE MULTIPLE REGRESSION

WITH STIFFNESS AS THE DEPENDENT VARIABLE

GROUP 1. BIRD AVERAGE PER PERIOD BASIS. n=461

Independent Variable	F - Ratio Analysis 1	2	3	4	5
Eggwt	.13	.12	--	--	--
Width	.14	.18	1.88	2.02	--
Length	.04	.06	--	--	--
Shelwt	2.89	2.89	3.93	6.78	127.00
Thick	39.98	40.15	40.26	42.09	41.20
Persh	.28	.28	.33	--	--
Mgmcm2	3.87	3.88	4.33	25.57	179.09
Shindx	.02	--	--	--	--
Round	2.42	2.68	2.73	10.11	93.93
Trusph	1.46	1.45	2.88	2.67	19.83
Prasph	1.13	1.27	1.28	--	--
P3dsph	.16	.29	1.57	1.78	--
$100R^2$	90.3	90.3	90.3	90.2	90.2

$F_{.05} = 3.86$ $F_{.01} = 6.69$

TABLE C7

STEPWISE MULTIPLE REGRESSION

WITH LOAD AS THE DEPENDENT VARIABLE

GROUP 1. OVERALL BIRD AVERAGE BASIS. n=53

Independent Variable	F - Ratio Analysis 1	2	3	4	5
Stiff	3.06	2.85	2.50	3.84	5.34
Eggwt	.07	--	--	--	--
Width	.79	.92	4.20	3.05	14.42
Length	.46	.48	--	--	--
Shelwt	1.17	4.58	3.68	2.60	10.53
Thick	.84	1.12	1.17	--	--
Persh	.45	--	--	--	--
Mgmcm2	.30	4.10	3.39	3.09	8.68
Shindx	3.09	3.39	2.48	2.04	--
Round	1.87	2.30	3.62	3.70	5.28
Trusph	1.49	2.74	1.84	1.23	--
Prasph	.65	.84	--	--	--
P3dsph	1.37	1.39	1.43	--	--
$100R^2$	89.0	88.8	88.5	87.8	87.2
$F_{.05}$	4.09	4.07	4.07	4.06	4.05
$F_{.01}$	7.33	7.27	7.26	7.23	7.20

TABLE C8

STEPWISE MULTIPLE REGRESSION

WITH ENERGY AS THE DEPENDENT VARIABLE

GROUP 1. OVERALL BIRD AVERAGE BASIS. n=53

Independent Variable	F - Ratio Analysis 1	2	3	4	5
Stiff	.59	1.03	--	--	--
Eggwt	.09	--	--	--	--
Width	.67	4.40	3.14	2.41	18.67
Length	.58	--	--	--	--
Shelwt	1.12	3.87	2.61	1.83	14.40
Thick	.95	1.53	.87	--	--
Persh	.25	--	--	--	--
Mgmcm2	.38	3.56	2.27	2.37	17.52
Shindx	3.24	2.93	2.16	1.70	--
Round	1.60	1.84	2.39	2.12	5.82
Trusph	1.24	1.78	.94	--	--
Prasph	.55	.63	--	--	--
P3dsph	1.44	1.83	1.37	1.13	--
$100R^2$	61.8	61.0	59.3	57.8	55.8
$F_{.05}$	4.09	4.07	4.06	4.05	4.04
$F_{.01}$	7.33	7.27	7.24	7.21	7.19

TABLE C9

STEPWISE MULTIPLE REGRESSION

WITH STIFFNESS AS THE DEPENDENT VARIABLE

GROUP 1. OVERALL BIRD AVERAGE BASIS. n=53

Independent Variable	F - Ratio Analysis 1	2	3	4	5
Eggwt	.01	--	--	--	--
Width	1.23	2.62	5.96	10.61	17.32
Length	.47	.67	2.35	--	--
Shelwt	2.04	4.17	4.03	15.37	26.25
Thick	2.74	3.04	3.21	3.05	5.24
Persh	1.56	1.80	1.92	1.69	--
Mgmcm2	4.27	7.42	7.51	11.54	36.30
Shindx	.17	.27	--	--	--
Round	.16	2.97	3.97	2.66	--
Trusph	.27	1.08	1.14	--	--
Prasph	.03	--	--	--	--
P3dsph	.27	.35	--	--	--
$100R^2$	95.9	95.9	95.9	95.6	95.2
$F_{.05}$	4.08	4.07	4.06	4.05	4.04
$F_{.01}$	7.31	7.27	7.24	7.21	7.19

TABLE C10

STEPWISE MULTIPLE REGRESSION

WITH LOAD AS THE DEPENDENT VARIABLE

GROUP 2. POOLED-EGG BASIS. n=425

Independent Variable	F - Ratio Analysis 1	2	3	4	5
Stiff	74.74	75.28	74.75	75.01	74.44
Eggwt	4.79	5.18	7.25	8.61	12.81
Width	.83	1.09	2.97	2.56	--
Length	4.41	4.33	3.08	2.98	8.80
Shelwt	7.07	8.95	8.57	9.51	10.11
Thick	9.63	10.06	9.54	9.23	9.06
Persh	.04	--	--	--	--
Mgmcm2	2.26	7.59	7.25	8.27	8.73
Shindx	.52	3.74	2.77	2.33	--
Round	.99	.83	--	--	--
Trusph	.80	.80	--	--	--
Prasph	1.16	.99	.74	--	--
P3dsph	.18	--	--	--	--
D.P.H.	.99	.99	1.07	--	--
$100R^2$	60.2	60.2	60.0	59.9	59.6

$F_{.05} = 3.86$ $F_{.01} = 6.70$

TABLE C11

STEPWISE MULTIPLE REGRESSION

WITH ENERGY AS THE DEPENDENT VARIABLE

GROUP 2. POOLED-EGG BASIS. n=425

Independent Variable	F - Ratio Analysis 1	2	3	4	5
Stiff	.60	--	--	--	--
Eggwt	4.09	4.84	6.59	7.82	12.55
Width	.78	1.05	2.87	2.42	--
Length	3.81	4.00	2.71	2.58	7.89
Shelwt	6.18	8.54	8.19	9.04	9.97
Thick	10.66	10.43	9.79	9.42	9.21
Persh	.03	--	--	--	--
Mgmcm2	1.92	6.89	6.58	7.52	8.23
Shindx	.64	3.51	2.52	2.08	--
Round	1.01	.97	--	--	--
Trusph	.73	.80	--	--	--
Prasph	1.18	1.13	.71	--	--
P3dsph	.06	--	--	--	--
D.P.H.	1.36	1.42	1.51	--	--
$100R^2$	11.8	11.7	11.3	10.8	10.2

$F_{.05} = 3.86$ $F_{.01} = 6.70$

TABLE C12

STEPWISE MULTIPLE REGRESSION

WITH STIFFNESS AS THE DEPENDENT VARIABLE

GROUP 2. POOLED-EGG BASIS. n=425

Independent Variable	F - Ratio Analysis 1	2	3	4	5
Eggwt	6.46	8.01	10.50	10.26	10.03
Width	.06	--	--	--	--
Length	2.71	3.26	5.01	4.74	4.70
Shelwt	8.93	9.21	9.99	9.98	9.74
Thick	43.63	43.90	43.72	44.38	44.30
Persh	3.65	3.91	4.24	4.07	4.16
Mgmcm2	5.32	5.77	6.37	6.24	6.14
Shindx	.44	.36	--	--	--
Round	.41	.49	.35	.30	--
Trusph	2.06	2.67	4.14	3.88	4.06
Prasph	.35	.42	.29	--	--
P3dsph	2.69	2.71	6.17	5.89	6.35
D.P.H.	.14	--	--	--	--
$100R^2$	79.3	79.3	79.3	79.2	79.2

$F_{.05} = 3.86$ $F_{.01} = 6.70$

TABLE C13

STEPWISE MULTIPLE REGRESSION

WITH LOAD AS THE DEPENDENT VARIABLE

GROUP 2. BIRD AVERAGE PER PERIOD BASIS. n=74

Independent Variable	F - Ratio Analysis 1	2	3	4	5
Stiff	16.97	17.58	16.89	16.88	16.91
Eggwt	3.38	8.43	7.72	6.47	7.98
Width	.67	1.02	3.42	.19	--
Length	1.21	1.74	3.42	3.62	8.22
Shelwt	.44	6.29	6.10	6.95	6.84
Thick	6.13	6.19	6.35	5.07	5.02
Persh	2.72	4.73	4.77	5.51	5.44
Mgmcm2	.17	--	--	--	--
Shindx	.09	.35	--	--	--
Round	1.44	1.36	--	--	--
Trusph	2.47	3.47	2.95	--	--
Prasph	1.70	1.63	1.44	--	--
P3dsph	.00	--	--	--	--
D.P.H.	4.92	5.52	7.58	8.97	9.50
$100R^2$	87.1	87.0	86.7	85.7	85.7
$F_{.05}$	4.00	4.00	3.99	3.99	3.99
$F_{.01}$	7.08	7.07	7.05	7.04	7.03

TABLE C14

STEPWISE MULTIPLE REGRESSION

WITH ENERGY AS THE DEPENDENT VARIABLE

GROUP 2. BIRD AVERAGE PER PERIOD BASIS. n=74

Independent Variable	F - Ratio Analysis 1	2	3	4	5
Stiff	.11	--	--	--	--
Eggwt	2.77	3.21	4.77	4.50	9.43
Width	.68	.94	2.57	1.96	--
Length	1.10	1.16	2.57	3.90	11.34
Shelwt	.15	.19	--	--	--
Thick	6.43	7.97	8.12	7.94	7.09
Persh	2.93	3.50	5.53	5.01	6.20
Mgmcm2	.42	.47	6.72	6.14	7.50
Shindx	.05	.20	--	--	--
Round	1.59	1.81	2.16	--	--
Trusph	2.57	2.84	2.61	2.15	--
Prasph	1.89	2.14	2.53	--	--
P3dsph	.00	--	--	--	--
D.P.H.	5.38	5.57	5.89	8.80	9.54
$100R^2$	46.2	46.1	45.8	42.2	40.3
$F_{.05}$	4.00	4.00	3.99	3.99	3.99
$F_{.01}$	7.08	7.07	7.05	7.04	7.03

TABLE C15

STEPWISE MULTIPLE REGRESSION

WITH STIFFNESS AS THE DEPENDENT VARIABLE

GROUP 2. BIRD AVERAGE PER PERIOD BASIS. n=74

Independent Variable	F - Ratio Analysis 1	2	3	4	5
Eggwt	.17	.52	2.90	2.41	7.78
Width	.00	--	--	--	--
Length	.04	.04	--	--	--
Shelwt	.26	1.90	2.36	1.90	--
Thick	22.57	23.45	27.11	28.26	438.08
Persh	.44	.97	1.23	.93	--
Mgmcm2	.00	--	--	--	--
Shindx	.19	.20	--	--	--
Round	.96	1.03	.88	--	--
Trusph	.08	.15	.31	--	--
Prasph	.94	1.01	.86	--	--
P3dsph	.15	.20	.84	6.34	4.59
D.P.H.	.16	.16	--	--	--
$100R^2$	90.8	90.8	90.8	90.6	90.0
$F_{.05}$	4.00	4.00	3.99	3.99	3.99
$F_{.01}$	7.08	7.07	7.05	7.04	7.03

TABLE C16

SELECTED NON-DESTRUCTIVE CHARACTERISTICS

IN MULTIPLE REGRESSION ON LOAD. GROUP 1

POOLED-EGG BASIS. n=2733

	Analysis 1	2	3	4	5
Stiff	103.5* 3731.3**	103.2 3748.7	102.5 3911.9	101.5 3745.6	101.5 3724.3
Eggwt	-51.1 28.4	-46.6 25.8	-31.3 95.1	--	--
Width	3239.3 17.8	2069.0 72.7	1691.6 204.0	--	691.3 132.0
Length	-542.8 1.4	175.8 3.2	--	--	--
Shindx	-61.7 2.6	--	--	31.8 150.6	--
Sy	363.9	364.0	364.1	369.2	370.4
Constant	-1973.5	-5950.4	-4205.2	-1146.6	-1759.2
$100R^2$	60.5	60.4	60.4	59.3	59.0

$F_{.05} = 3.84$ $F_{.01} = 6.64$

* Partial Regression Coefficient
** F - Ratio

TABLE C17

SELECTED NON-DESTRUCTIVE CHARACTERISTICS

IN MULTIPLE REGRESSION ON LOAD. GROUP 1

BIRD AVERAGE PER PERIOD BASIS. n=461

	Analysis 1	2	3	4	5
Stiff	111.0* 1365.1**	111.2 1369.6	109.1 1444.1	107.6 1375.0	107.6 1256.6
Eggwt	-82.5 16.7	-85.9 18.3	-41.9 57.6	--	--
Width	1377.1 1.2	3012.5 31.5	1876.1 85.8	--	505.3 27.0
Length	1564.3 4.1	477.1 5.2	--	--	--
Shindx	90.9 2.1	--	--	35.8 69.7	--
Sy	212.6	212.8	213.8	217.3	226.6
Constant	-15807.5	-9586.2	-4517.2	-1582.3	-1104.0
$100R^2$	77.7	77.5	77.3	76.5	74.4

$F_{.05} = 3.86$ $F_{.01} = 6.69$

* Partial Regression Coefficient
** F - Ratio

TABLE C18

SELECTED NON-DESTRUCTIVE CHARACTERISTICS

IN MULTIPLE REGRESSION ON LOAD. GROUP 1

OVERALL BIRD AVERAGE BASIS. n=53

	Analysis 1	2	3	4	5
Stiff	110.3* 221.8**	109.8 221.1	105.8 225.1	107.8 223.6	102.3 204.0
Eggwt	-114.3 4.9	-114.6 4.9	-35.2 5.1	--	--
Width	188.3 .0	4073.1 8.7	2018.5 14.4	--	922.8 15.9
Length	3690.0 1.6	867.7 2.6	--	--	--
Shindx	225.3 .9	--	--	40.4 12.1	--
Sy	146.2	146.1	148.4	159.0	154.4
Constant	-31061.2	-14655.3	-5442.5	-1928.1	-2762.3
$100R^2$	86.3	86.0	85.3	82.7	83.7
$F_{.05}$	4.05	4.04	4.04	4.03	4.03
$F_{.01}$	7.20	7.19	7.18	7.17	7.17

* Partial Regression Coefficient
** F - Ratio

TABLE C19

SELECTED NON-DESTRUCTIVE CHARACTERISTICS

IN MULTIPLE REGRESSION ON LOAD

FOR EACH TEST PERIOD

	F - Ratio of Independent Variable					
Period	Stiff	Eggwt	Width	Length	Shindx	$100R^2$
1	472.26	3.08	.59	.23	.03	62.4
2	504.14	2.51	1.77	.17	.34	62.0
3	424.04	5.74	1.13	.23	.01	60.4
4	420.69	.72	1.06	.09	.13	60.5
5	336.96	4.40	5.18	.52	1.03	57.7
6	462.08	23.71	2.09	.91	.08	63.4
7	345.51	.15	.08	.51	.64	60.4
8	462.92	5.38	.10	5.62	4.26	63.3

$F_{.05} = 3.87$ $F_{.01} = 6.72$