Application of the Statistical Theory of Rubber Elasticity to Gluten and Dough

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ABSTRACT

The statistical theory of rubber elasticity has been applied to wheat gluten. Gluten washed from a strong flour appeared to be more heavily cross-linked than gluten from a soft flour. Heating or treatment with potassium iodate or cupric sulfate increased the number of cross-links per unit volume. The theoretical implications of these findings are discussed.

Flory and Rehner (1) have developed an equation based on the statistical theory of rubber elasticity (2) by means of which the number of elastically effective chain segments and the number of cross-links per unit volume of an ideal, swollen elastomer can be determined from its rheological behavior. Wiederhorn and Reardon (3) and Cater (4,5) have applied this equation to collagen; it is here being applied to wheat gluten.

For an elastomer swollen in a liquid under simple elongation,

$$\frac{f = RT\,\rho\,v_2{}^{1/3}}{M_c}\;\left(a - \frac{1}{a^2}\right),$$

where M_c is the average molecular weight of the chain between the cross-links, a is the stretched length of the swollen polymer divided by the initial length, ρ is the density of the dry material, R the gas constant, T the absolute temperature, and f the tensile stress; v_2, the volume fraction, equals

$$\frac{W_o \times q}{W \times p - W_o\,(p - q)}$$

where W_o is the dry weight of the polymer, p its dry density, W its wet weight, and q the liquid density.

Since two cross-linked chain segments contribute to each cross-link, the number of cross-links per unit mass is given by $1/(2M_c)$. Taylor and Cluskey (6) have estimated the molecular weight of gluten to be of the order of 100,000; hence the number of cross-links may be given in molecular-weight units of 10^5.

MATERIALS AND METHODS

Two flours were used for this work. The first was a strong bread flour containing 13.0% protein at 14% moisture. The second was a soft flour containing 8.5% protein at 14% moisture. Both were commercially milled and untreated.

For the tests, gluten was washed out in the usual way and 15 g. flattened between microscope slides spaced 0.30 cm. apart. Polyethylene film was used to prevent the gluten from adhering to the slides. The assembly was rested in water for 45 min. at 30°C. and then frozen at −15°C. Two test pieces, 1.0 by 5.0 cm., were then cut out with a box cutter (Fig. 1) placed in a water bath or solution of chemicals at 30°C. for 45 min., and stretched in water for 20 sec. under a load of 1.784 g. The load was then removed, whereupon the gluten contracted. A reading of the final length was taken between 2 and 2.5 min., when the change of length was only very slight.

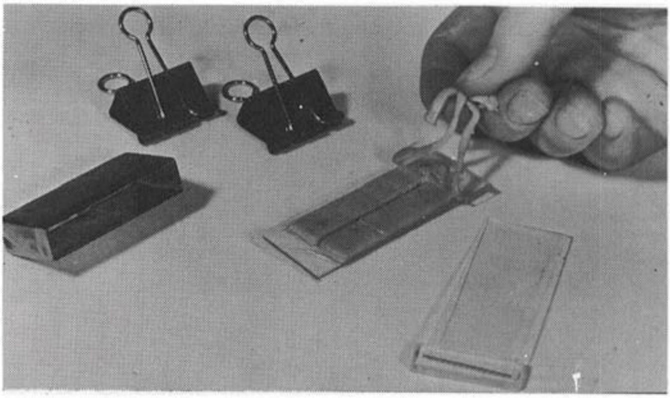

Fig. 1. Cut gluten samples. Box cutter on left, microscope slide and spacer on right.

The apparatus is shown in Fig. 2. The gluten strip is suspended in water and loaded by the weight. Gluten and weight are attached by hooks made from stainless-steel wire. The two marks on the gluten strip, 3.0 cm. apart, were made by applying a wire dipped in carbon powder. Behind the gluten a mirrored aluminum strip and a scale made from mm.-sized graph paper are discernible. The paper had been made waterproof with colorless nail varnish. Parallax error is thus largely avoided. The hook in front of the beaker serves to engage and disengage the weight.

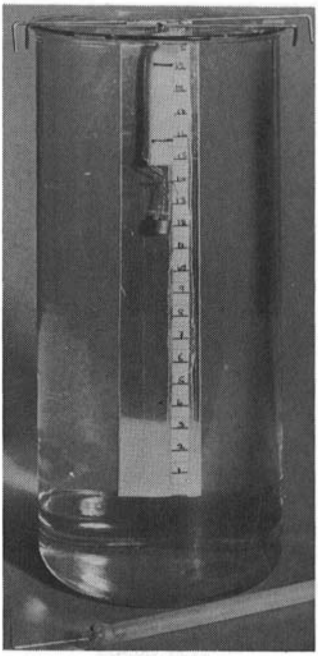

Fig. 2. Extension test. The gluten sample is visible in front of the mirrored scale. Hook to lift off weight after 20-sec. extension in foreground.

RESULTS AND DISCUSSION

For a load of 1.784 g., a sample width of 1 cm., and a sample thickness of 0.30 cm., the stress was 5,834 dynes per cm^2, R was 8.316×10^7 ergs per mole per °C., T was 303°A, and ρ was 1.34, a figure taken from the literature (7,8). The volume ratio v_2 was determined experimentally and found to be 0.305 (mean of 12 tests); Alpha was the original length of the gluten piece plus the elastic deformation, divided by the original length. The viscous deformation was eliminated by using the elastic recovery.

The elasticity theory applies to an ideal elastic system and α must not change with time. When gluten pieces were extended from 1 to 5 min., the M_C calculated showed no significant difference at the 0.1% level. The average molecular weight of gluten chain between cross-links and the number of cross-links in molecular weight units of 10^5 are given in Table I.

TABLE I. AVERAGE MOLECULAR WEIGHT OF GLUTEN CHAIN BETWEEN CROSS-LINKS (M_C) AND NUMBER OF CROSS-LINKS IN MOLECULAR-WEIGHT UNITS OF 10^5

	$M_C \times 10^6$	$1/(2M_C)$	No. of Determinations
Strong gluten	8.9	5.6	60
Soft gluten	10.9	4.6	20
Strong gluten	9.3	5.4	20
with 100 p.p.m. KIO_3	7.4	6.8	20
Strong gluten	8.6	5.8	10
with 500 p.p.m. $CuSO_4$	7.8	6.4	10
Strong gluten	8.4	5.9	10
preheated to 75°C. in water	3.2	15.7	10

Since the rubber elasticity theory was derived for an idealized system, these quantitative data must be interpreted with caution. Nevertheless, the qualitative implications of this approach provide the basis of gluten and dough rheological tests.

It would appear possible that the much-debated concept of "gluten quality" is essentially one of cross-linkage. A strong-flour gluten is more heavily cross-linked than a soft-flour gluten. Commercial improvers such as potassium iodate increase the number of cross-links per unit volume. When boiling (baking) is done, new intermolecular bonds are formed. When dough is mixed, a similar structure is developed which on relaxation reverts partially to an intramolecularly bonded one. The present hypothesis of dough relaxation by disulfide-sulfhydryl interchange (9,10) must be modified to allow for an increase of M_C during relaxation. The importance of elasticity which is not measured with commercial gluten and dough-testing instruments is emphasized.

At present the work is being extended to wheat flour dough by way of network theories of filler reinforcement (11), the starch being the filler.

It should also be pointed out that the elasticity theory can be used to explain gluten-swelling phenomena (Berliner test) and that the mathematical basis has already been laid (11).

Acknowledgment

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