DISCUSSION PAPER

A GENERALIZED PHENOMENOLOGICAL RHEOLOGICAL MODEL FOR FISH FLESH

E. A. JOHNSON and M. PELEG

Department of Food Engineering
University of Massachusetts
Amherst, MA 01003

AND

R. A. SEGARS and J. G. KAPSALIS

Food Chemistry Group, Physical Sciences Division, Food Sciences Laboratory, U.S. Army Natick R&D Command, Natick, MA 01760

(Manuscript received April 17, 1981; in final form September 3, 1981)

ABSTRACT

The mechanical properties of raw and cooked fish were qualitatively characterized by a generalized Maxwell model in which each of the Maxwell elements is modified by incorporation of a contact and two fracture elements. The activation and inactivation of elements have been used as a means of expressing transformation of the rheological characteristics, not only as a function of the strain and strain rate history but also as a function of temperature and time. Although no attempt has been made to quantify the number of elements and their characteristic constants, it is shown that the different modes of rheological behavior exhibited by fish flesh can consistently be described by this kind of model.

INTRODUCTION

Some of the major quality attributes of edible fish are their textural characteristics. These, naturally, are closely associated with the mechanical characteristics of raw flesh and the way heat affects

This work forms part of a project supported by the U.S. Department of Commerce, National Marine Fisheries Service, under Interagency Transfer Act Contract No. 01-8-M01-6320.

Reprinted from
Journal of Texture Studies 12 (1981) 413-425. *All Rights Reserved.*

them. The edible part of the fish consists mainly of muscles connected by tissues, which give it a segmented structure. The size of the segments (myomers) depends largely on the type of fish and its size, and may vary with the location along the fish. (Johnson *et al.* 1980a,b). The mechanical properties of the raw fillet can be attributed to the strength of the connective tissues and to that of the muscle bundles. During frying, baking or other means of cooking the fish there is simultaneous change of both the fibers and the connective tissues (Dunajski 1980). The degree of differential change will vary, resulting in a product that is regarded as having various degrees of flakiness.

The general textural variability within a fish fillet is mainly associated with flakiness and the orientation of the muscle fibers. There is also a compositional variability between and within species as a result of the feeding habits of the fish and native environment (Jacquot 1961). The latter is mainly reflected in the protein-fat-water content ratio as well as the water holding capacity of the flesh, a factor that may play a decisive role in producing drip losses during processing and handling. Within the same species, especially in ocean fish, large seasonal fluctuations in composition are recorded, with maximum difference between fall and early spring.

Detailed analysis of these seasonal and other biological factors of fish composition and overall texture are reported by Love (1975) and Howgate (1977). A recent review on their relationship to textural measurements has been published by Dunajski (1980). Much of the reported data on fish flesh texture is based on mechanical tests that can be termed empirical (e.g. the shear press, penetration tests). Although these tests may be sufficient for monitoring and recording changes, and have the obvious advantage of being quick and simple to perform, they cannot provide the kind of information that will characterize texture in rheological terms. In this work we have attempted to characterize the qualitative rheological behavior of fish flesh through a conceptual generalized model that has previously been proposed for other foods and polymers. (Peleg 1976).

THE GENERAL MODEL

A generalized form of a phenomenological-rheological model is shown in Fig. 1. The mathematical properties of the models have been discussed elsewhere (Peleg 1976; 1977; 1978; 1979). One of the major characteristics of the model is that it is logically consistent when

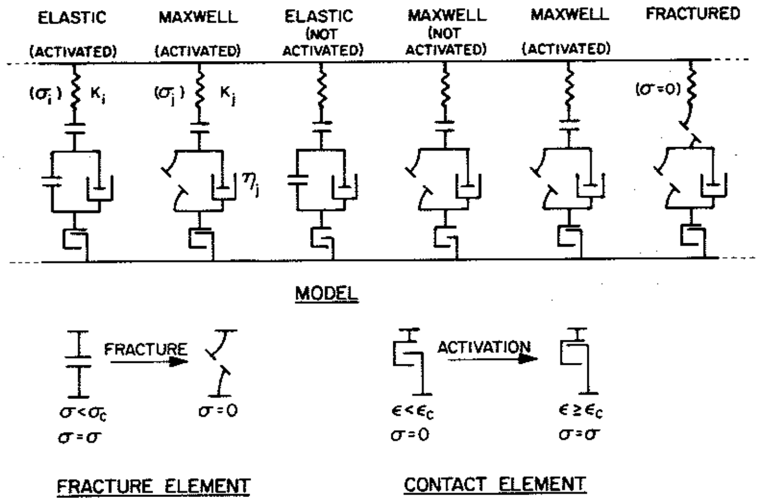

FIG. 1. SCHEMATIC VIEW OF A GENERALIZED RHEOLOGICAL MODEL FOR SOLID MATERIALS (Adapted from Peleg 1979)

applied to different tests (i.e. the same model array is applicable to straining, relaxation creep, etc.).

The major shortcomings of the model are that it cannot fully account for the three dimensional aspects of real stresses and strains because of its unidimensional structure, and that it does not offer any clue to the identity of its elements, their total number and their distribution. In certain cases the latter difficulty can be overcome, to a large extent, by evaluation of the elastic element's overall contribution to the strength through relaxation or creep analyses. It has also been demonstrated that by doing so in selected solid polymers, a quantitative prediction of tensile failure conditions could be derived from these relaxation and creep data (Peleg 1978; 1979). Application of this methodology in soy extrudates in tension was also successful (Finkowski and Peleg 1981). For compressive tests in other foods, however, such a procedure had only limited accuracy (mainly because of large natural variability) although general trends of compressibility and yielding could clearly be detected. (Pollak and Peleg 1980; Peleg 1980).

Let us therefore consider the model shown in Fig. 1 as a *qualitative representation* of the rheological behavior of solids. Mathematically, it is a "piano model", i.e. a model in which the characteristic constants can and do vary with strain and time. The differential equation of the model is as follows (Peleg 1978; 1979)

$$d\sigma_T = \left(\sum_{i=1}^{N_E} K_i + \sum_{j=1}^{N_M} K_j \right) d\epsilon - \sum_{j=1}^{N_M} \frac{K_j \sigma_j}{\eta_j} dt \qquad (1)$$

where σ_T is the total stress, ϵ the strain, K_i and K_j elastic constants, η_j viscous constants, σ_j the momentary stress supported by each Maxwell element, and N_E and N_M the momentary number of active elements in elastic and Maxwellian states, respectively.

Since both N_E and N_M are functions of the strain, the strain rate ($\dot{\epsilon}$) and the past history of the model,

$$\begin{aligned} N_E &= f(\epsilon, \dot{\epsilon}, t) \\ N_M &= g(\epsilon, \dot{\epsilon}, t) \end{aligned} \qquad (2)$$

are essentially the representatives of the rheological memory of the model.

Unlike classic or conventional phenomenological rheological models, this model's applicability is not limited to small strains and it can be valid until failure (in both tension and compression). Furthermore, since there are no restrictions on the functions N_E and N_M, the model is equally applicable to materials that are nonuniform in structure. The textural variability in such cases will simply be expressed by the different values that these functions will assume. In the cases where nonuniformity is expressed in a different mode of rheological behavior, the functions N_E and N_M are of a different kind. It should also be mentioned that a sudden switch in rheological behavior (due, for example, to failure of a specific structural component) will be reflected in a discontinuity in these functions (Peleg 1976).

It ought to be borne in mind, that the elements shown in the mechanical analog only represent the coefficients of the differential equation of the model. They should not be treated, under any circumstance, as analogs of individual structural elements on a tissue, cellular or molecular level. It would be futile to try to associate them with fibers, flakes, muscle bundles, etc.

Modifications of the Fracture and Contact Elements

The fracture element as representative of an irreversible switch in rheological behavior has been described by Lerchental and Funt (1967) and Drake (1971). In both cases, the treatment was for isothermal conditions and could not account for time effects that have no corresponding change in strain.

For perishable commodities as well as for foods that are cooked, both time and temperature are significant factors. The resulting softening (in most but not all cases) with time and temperature can conveniently be described as lowering the critical stress σ_c of the fracture elements, thus maintaining the general mathematical formulation of the model.

Schematic presentation of the operational mode of the suggested modified fracture element is shown in Fig. 2. Similarly, "hardening", such as that due to rigor mortis or muscle contraction, (Almacher

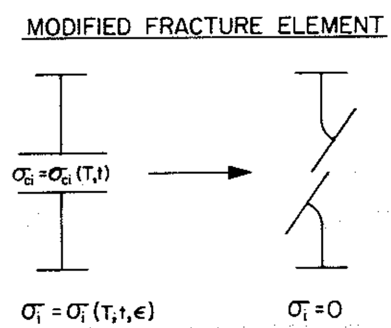

FIG. 2. A MODIFIED FRACTURE ELEMENT WHOSE CRITICAL STRESS (σ_{ci}) IS A FUNCTION OF TEMPERATURE (T) AND TIME (t)

1961; Woodbury *et al.* 1966) can be expressed as an increase of the critical value. When rigor mortis occurs, however, it is fair to assume that the total change in rheological behavior is also caused by the addition of elements. This concept was previously expressed in the form of the "contractile element" (the force generating element) whose properties are discussed by Stoner *et al.* (1974). The contact elements of the suggested model can account for time and temperature effects only after modification as presented in Fig. 3. In the general model array it is, of course, possible that the fracture and contact elements will vary independently, thus producing almost all possible modes of rheological response.

A similar mathematical outcome can be produced by continuous modification of the elements' elastic and viscous constants (K's and η's). Such modification, however, will produce nonlinear elements and the visualization of the model properties will become extremely difficult. In the suggested modification (i.e. of the σ_c's and ϵ_c's only) the model retains its mathematical format (eq 1) and any subsequent change in its properties will only be expressed in the absolute numbers and relative distribution of the elements in each position.

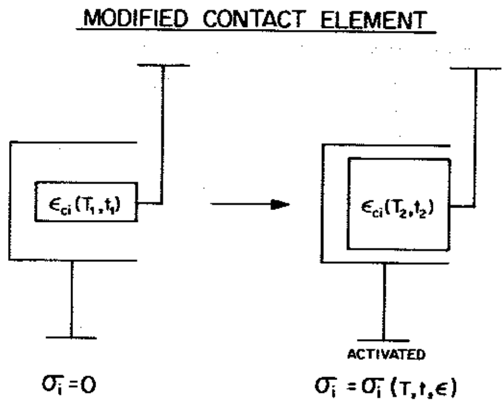

FIG. 3. A MODIFIED CONTACT ELEMENT WHOSE CRITICAL ACTIVATION STRAIN (ϵ_{ci}) IS A FUNCTION OF TEMPERATURE (T) AND TIME (t)

THE MECHANICAL BEHAVIOR OF FISH FLESH

One of the main difficulties in mechanical testing of fish flesh (both raw and cooked) is how to form proper specimens with regular and measurable shape. The procedure of cutting specimens for uniaxial compression by an electric knife has previously been described (Johnson *et al.* 1980a). Once a proper specimen is obtained, it ought to be constrained to the surfaces of the testing machine in order to avoid slippage. Such a procedure, however, introduces significant end effects, especially in specimens having relatively "flat" shape, (i.e. low length-to-diameter ratio). A modified correction procedure for such testing conditions, based on theories that were developed for rubbery materials (Lindley 1978), has been applied to numerous experimental results, of a variety of fish species. It has been confirmed in this way (Johnson *et al.* 1980b) that the measured textural variability in fish is indeed real and cannot be explained merely as a result of the variability in the specimen shape.

EFFECT OF STORAGE AND COOKING

Generally, the fish muscle tissues soften during prolonged storage (Deng 1981) mainly due to proteolytic enzymatic activity. This, however, is not true at the time of and after rigor mortis when the stiffness and rigidity of the tissue increases and decreases due to the activity of different kinds of physiological systems (Almacher 1961). In terms of the model this stage is expressed as activation of elements and/or elevation of the fracture level of already active elements. The extent and rate of the phenomenon is temperature dependent. In general, an increase in temperature will accelerate the effect. High storage temperatures below the cooking level will also accelerate the enzymatic decomposition rate which will result in textural collapse. In terms of the model, this stage is characterized by a decline in number of active elements resulting from both early fracture (lower σ_{ci}'s) of functioning elements, and a reduced number of newly activated elements (higher ϵ_{ci}'s).

In cooking, a similar process may occur but as a function of time. Initial contraction may, on a time scale of minutes, increase the overall strength of the cooked specimen. However, in many species continued cooking will result in considerable textural changes and eventually in the physical disintegration of the specimen. (The rate and temperature range at which these changes occur depend on the species and the physiological conditions). Schematic presentation of all these changes as expressed in the elements' critical constants is demonstrated in Fig. 4, 5 and 6.

Comparison of the Rheological Characteristics of Cooked and Raw Fish

The typical stress-strain relationships as well as the corresponding relaxation data of raw and fully cooked flesh are presented in Fig. 7 and 8 (Johnson *et al.* 1980a; Segars *et al.* 1981). From the generalized model viewpoint these kinds of responses can be expressed by arrays

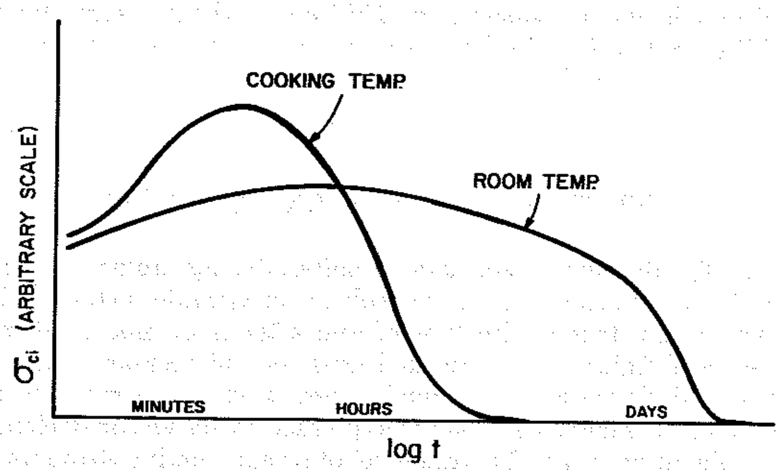

FIG. 4. THE EFFECT OF TIME ON THE CRITICAL FRACTURE STRESSES (σ_{ci}) OF THE MODEL ELEMENTS REPRESENTING FISH FLESH

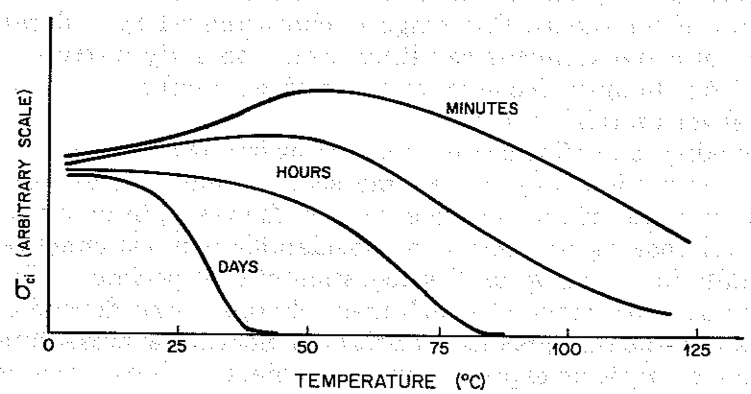

FIG. 5. THE EFFECT OF TEMPERATURE ON THE CRITICAL FRACTURE STRESSES (σ_{ci}) OF THE MODEL ELEMENTS REPRESENTING FISH FLESH

in which the total number and the relative distribution of elements between elastic, Maxwellian and fractured positions is initially different and vary with the strain along different patterns. Schematic representation of this pattern is shown in Fig. 9 and 10.

Johnson *et al.* (1980) reported stress-strain relationships (after correction for area expansion and plotting the results versus the

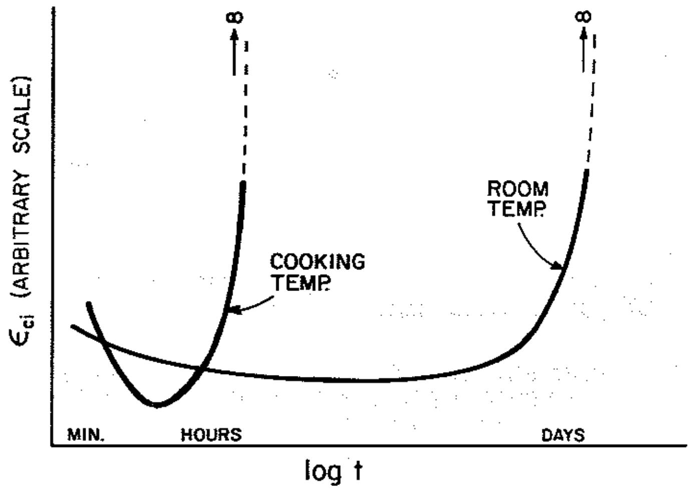

FIG. 6. THE EFFECT OF TIME ON THE CRITICAL ACTIVATION STRAIN (ϵ_{ci}) OF THE MODEL ELEMENTS REPRESENTING FISH FLESH

natural [Henky's] strain) that had the typical shape shown in Fig. 4. As could be expected, however, relaxation tests even at the linear region (up to about 20–25% deformation) demonstrated that fish flesh, raw or cooked, cannot be considered as an ideally rubbery material and its viscoelastic characteristics are quite noticeable even at these strain levels (Segars *et al.* 1981). It seems that part of the apparent elasticity is attributed to a balance between antagonistic mechanisms that include internal fracture or yielding, compaction of the solid matrix and the development of hydrostatic pressure (Calzada and Peleg 1978). At larger deformation the distinct behavior is typified by the domination of internal yielding mechanisms in cooked fish flesh and hydrostatic pressure in raw flesh (Johnson *et al.* 1980a).

These figures demonstrate that while compacted raw flesh gains apparent strength, the deformation of cooked flesh is accompanied by a continuous loss of elasticity and overall rigidity. They also demonstrate that at each strain level the model contains a different number of elements and therefore rheological characteristics (e.g. relaxation times) when determined experimentally must vary with the strain and the strain history of the specimen. Furthermore, according to the model the changes in the elements are largely irreversible. This implies that it would be theoretically impossible to reproduce the

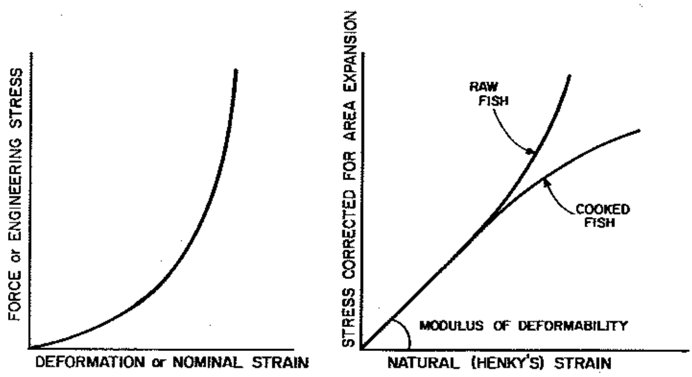

FIG. 7. ENGINEERING AND TRUE COMPRESSIVE STRESS-STRAIN RELATIONSHIPS OF RAW AND COOKED FISH FLESH (FROM JOHNSON *ET AL.* 1980a).

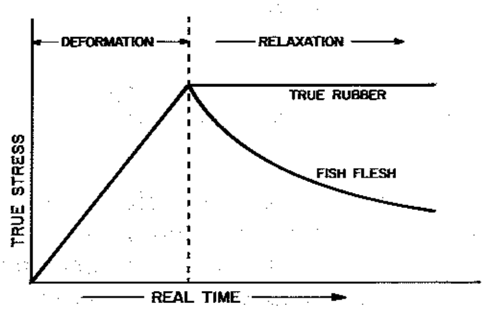

FIG. 8. STRESS RELAXATION OF FISH FLESH (FROM SEGARS *ET AL.* 1981)

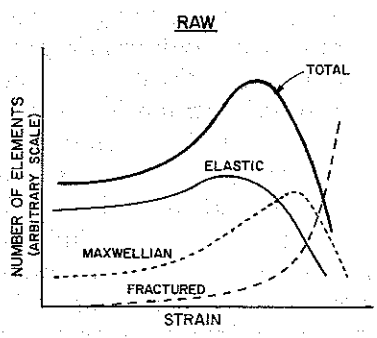

FIG. 9. SCHEMATIC VIEW OF THE CHANGE IN THE MODEL ELEMENTS NUMBERS DURING THE DEFORMATION COURSE OF RAW FISH FLESH

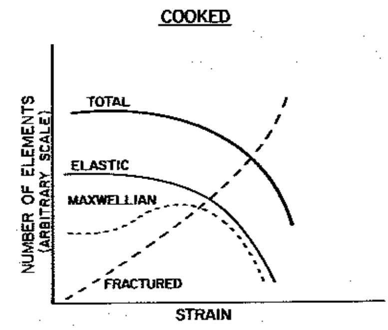

FIG. 10. SCHEMATIC VIEW OF THE CHANGE IN THE MODEL ELEMENTS NUMBERS DURING THE DEFORMATION COURSE OF COOKED FISH FLESH

rheological characteristics accurately by repetitive tests performed on the same specimen. This is especially true in the case of the cooked flesh where fracture of elements is the dominant pattern.

CONCLUSIONS

This paper presents an attempt to develop a conceptual model for the complex mechanical properties of fish flesh. The framework of the model is a generalized Maxwell array in which the number and type of active Maxwell elements are permitted to vary through activation and inactivation (Peleg 1977). This kind of model is applicable in both small and large deformations and is internally consistent when applied to different types of mechanical tests. In its generalized form, it implies nonlinear viscoelasticity, memory and irreversibility. (It can also be reduced to a linear viscoelastic model and even to an elastic model).

The activation and inactivation of elements is presented in a form of contact (addition) and fracture (modification and substraction) operations. These, however, ought to be expressed as functions of time and temperature. In this way textural changes in storage and during cooking can be included in a single continuous rheological domain.

This possibility is demonstrated in a qualitative way through graphical relationships. No attempt has been made to quantify these relationships at this stage. It seems, however, that the pattern by which the rheological behavior is transformed is by itself a unique mechanical characteristic and may, in the future, serve as a means of textural evaluation and characterization of fish flesh. This can be done by rheological analysis of fish specimens that will include, for example, both stress-strain and stress relaxation tests. The results of these tests can reveal the overall ratio between the elastic and Maxwellian contributions as a function of the strain (Peleg 1980; Pollak and Peleg 1980). The level and shape of such relationships at different temperatures, after different storage conditions or chemical treatments could serve as objective rheological indices of texture and freshness. It is expected that the scatter in the mechanical measurements will be large (Johnson *et al.* 1980a) but that despite the scatter the curves' general shape will be unambiguously evident, at least in the case of a few commercially important species (Segars *et al.* 1981).

ACKNOWLEDGMENT

The authors express their thanks to Mr. R. J. Grant for his graphical aid.

REFERENCES

AMLACHER, E. 1961. Rigor mortis in fish. In *Fish as Food,* Vol. 1, (G. Borgstrom, ed.) pp. 385-409, Academic Press, New York.

BRAMSNAES, F. 1965. Handling of fish flesh. In *Fish as Food,* Vol. 5, (G. Borgstrom, ed.) pp. 1-163, Academic Press, New York.

CALZADA, J. F. and PELEG, M. 1978. Mechanical interpretation of compressive stress-strain relationships of solid foods. J. Food Sci. *43,* 1087.

DENG, J. C. 1981. Effect of temperature on fish alkaline protease, protein interaction and texture quality. J. Food Sci. *46,* 62-65.

DRAKE, B. 1971. A quasi rheological model element for fracture. J. Texture Studies *2,* 365.

DUNAJSKI, E. 1980. Texture of fish muscle. J. Texture Studies *10,* 301-318.

FINKOWSKI, J. W. and PELEG, M. 1981. Some rheological characteristics of soy extrudates in tension. J. Food Sci. *41,* 207-211.

HOWGATE, P. 1975. Aspects of food texture. In *Sensory Properties of Foods* (D. S. Burch, ed.) pp. 249-269, Applied Science Publishing Co., England.

JACQUOT, R. 1961. Organic constituents of fish flesh and other aquatic animal foods. In *Fish as Food,* Vol. 1. (G. Borgstrom, ed.) pp. 145-209, Academic Press, New York.

JOHNSON, E. A., SEGARS, R. A., KAPSALIS, J. G., NORMAND, M. D., and PELEG, M. 1980a. Evaluation of the compressive deformability modulus of fresh and cooked fish flesh. J. Food Sci. *45,* 1318.

JOHNSON, E. A., SEGARS, R. A., KAPSALIS, J. G., NORMAND, M. D. and PELEG, M. 1980b. Textural variability in fish fillets. Proceedings of the 5th Annual Tropical and Subtropical Fisheries Technological Conference of the Americas.

LERCHENTAL, C. H. and FUNT, C. B. 1967. The strength of wheat flour dough in uniaxial tension. Proc. Symp. on Rheology and Texture of Foodstuffs. SCI Monograph No. 27.

LINDLEY, P. B. 1978. Engineering design with natural rubber. The Malaysian Rubber Producers Research Association. Hertford, England.

LOVE, M. R. 1975. Variability in Atlantic cod from the Northeast Atlantic: A review of seasonal and environmental influences on various attributes of the flesh. J. Fisheries Res. Board Canada *32*, 2333-2342.

PELEG, M. 1976. Considerations of a general rheological model for the mechanical behavior of viscoelastic solid food materials. J. Texture Studies *7*, 243-255.

PELEG, M. 1977. Contact and fracture elements as components of the rheological memory of solid foods. J. Texture Studies *8*, 36-48.

PELEG, M. 1978. An empirical method for estimation of the yield stress from relaxation data. Mater. Sci. Eng. *33*, 289-293.

PELEG, M. 1979. A model for creep and early failure. Mater. Sci. Eng. *40*, 197-205.

PELEG, M. 1980. Linearization of relaxation and creep curves of solid biological materials. J. Rheol. *24*, 451-463.

POLLAK, N. and PELEG, M. 1980. Early indications of failure in large compressive deformation of solid foods. J. Food Sci. *45*, 825-830.

SEGARS, R. A., JOHNSON, E. A., KAPSALIS, J. G. and PELEG, M. 1981. Some tensile characteristics of fish flesh. J. Texture Studies *12*, 375-387.

STONER, D. L., HAUGH, G. C., FORREST, J. C. and SWEAT, V. E. 1974. A mechanical model for post-mortem striated muscle. J. Text. Studies *4*, 483-493.

WOODBURY, J. W., GORDON, A. M. and CONRAD, J. T. 1966. Muscle. In *Physiology and Biophysics*, (T. C. Ruch and H. D. Patton, eds.) pp. 113-152. W. B. Saunders Company, Philadelphia.