DEFORMATION-RELAXATION CHARACTERISTICS OF BEEF MEAT UNDER AXIAL COMPRESSION

The texture of beef muscular tissue, which is complex, can be represented as muscle fibers bound with a spatial connective membrane. All the interstices of the structure are filled with tissue juice - loosely and strongly bound moisture. By the character and strength of bonds among the particles, muscular tissue can be partially referred to condensation-crystallization systems /1/. Such structures, possesing a number of properties of solid bodies, have certain specific peculiarities - elasticity, plasticity, etc. These should be taken into account when selecting most expedient methods and conditions for technological processing.

Though numerous detailed studies on the structural-and-mechanical (rheological) properties of ground meat /2, 3/ are known, properties of intact muscular tissue are studied insufficiently. Some authors /4, 8/ investigated muscular tissue deformation at axial compression as related to the load applied and to different conditions of loading. Besides, time effects characterized with elasticity and relaxation, were measured in dynamics /9. 10/. Pointing to the non-linear character of the deformation behaviour of meat, the authors /7-11/ suggest empirical formulae for the relation of sample relative deformation to load value. We should, however, mention the conditional character of the suggested relations as the degree of compression at a given load depends on the instant of observation, loading conditions, sample shape and size, kind of meat, its texture, anisotropy, etc.,the time factor here being of a decisive role due to the fact that the structure contains tissue juice of a certain viscosity.

This paper deals with the character of the deformation behaviour of intact beef muscular tissue at axial compression across the fibers. Experiments were performed on samples of beef quadriceps taken on the 2nd day after slaughter. Samples had a square cross-section, the area of 30x30 mm and were 10 to 20 mm high.

Test were made on a plastometer-type device, specially designed in the MTIMMP, which allows to record simultaneously deformation and load as related to time. A schematic diagram of this device is shown in Fig. 1. Samples were compressed in between two polished plates due to the movement of the upper plate under a pusher mounted in the guides. The lower plate is fixed to the baseplate. The device was driven with a d.c. motor. Torsional moment was transferred via a reducer to a pulley and further to the pusher via a flexible cable and a system of levers with a counterweight. Cyclic loading of samples was effected by replacing the pulley with a cam. The downward movement of the pusher was restricted with an end switch. Compressive strain was received with a resilient element, onto which tensometric transducers were glued, the latter being connected to a measuring self-recording KCП-4-type ponentiometer. Sample deformation was registered with a variable resistor attached to another self-recording KCП-4-type potentiometer.

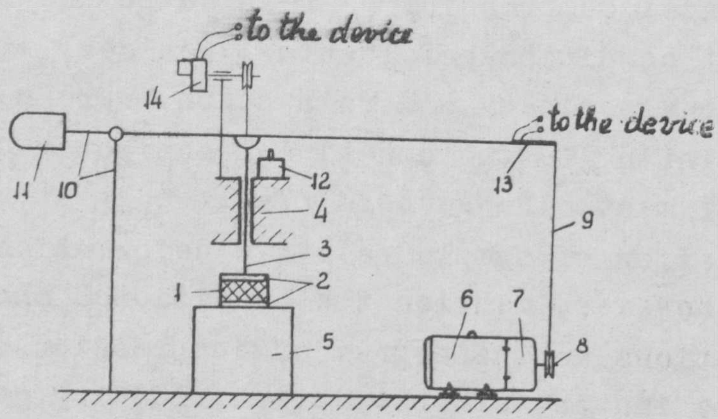

Fig. 1. A schematic diagram of plastometer
1 - sample; 2 - system of levers; 3 - counter-weight; 4 - variable resistor; 5 - end switch; 6 - guides; 7 - pusher; 8 - polished plates; 9 - baseplate; 10 - tensobar; 11 - flexible cable; 12 - pulley; 13 - reducer; 14 - d.c.motor

Axial compression was effected under two conditions - static and cyclic - within loads ranging from 0 to 1.2×10^5 Pa. Static loading lasted 180 sec. under a pre-set load; then the load was released and the character of the recovery of the deformed sample was studied. When studying creep, sample loading time was extended to 300 sec. For cyclic loading the time lasted 2 sec.

The character of sample deformation under static loading and the subsequent return to the initial state are shown in Fig. 2, curve $\varepsilon = f(t)$ with $\sigma = 0.11 \times 10^5$ Pa. As is seen, sample total deformation ε_{tot} at any moment "t" can be represented as a sum of three components:

$$\varepsilon_{tot} = \varepsilon_{res} + \varepsilon_{el} + \varepsilon_{pl}, \qquad (1)$$

where ε_{res} is instantaneous resilient deformation;
ε_{el} is elastic (relaxation) deformation;
ε_{pl} is plastic residual strain.

In its turn, ε_{pl} is a sum of two addends:

$$\varepsilon_{pl} = \varepsilon_{pl}^{ins} + \varepsilon_{pl}^{dev}, \qquad (2)$$

where ε_{pl}^{ins} is instantaneous plastic strain;
ε_{pl}^{dev} is developing plastic strain.

Instantaneous plastic strain is a result of microplastic strains occurring due to muscle fibers displacement throughout the sample; developing strain is connected with tissue juice separation and the subsequent compression of the structure; instantaneous resilient and elastic deformations are connected with visco-resilient properties of the material as a whole, connective tissue elasticity and tissue juice viscosity.

To reveal the character of the relations of different components of deformation to the value of the load applied, curves for creep were plotted (Fig. 3), and samples under cyclic loading were tested. The analysis of these curves indicated that at sufficiently long loading the rate of deformation tended towards the constant limit (at a pre-set load) and depended linearly on the value of the load applied. The total deformation of the sample for similar instants on the creep curves depended nonlinearly on the value of the load (Fig. 4, Curves 1-5). At the loads up to 0.8×10^5 Pa the yielding of the samples decreased gradually; then, at $\sigma = 0.8 \cdot 10^5$ Pa it increased sharply, this indicating the initiation of the local breakage of the fibers. From Fig. 4 it is obvious that the relaxation component of the deformation ε_{el} and the developing plastic strain ε_{pl}^{dev} depend linearly on .

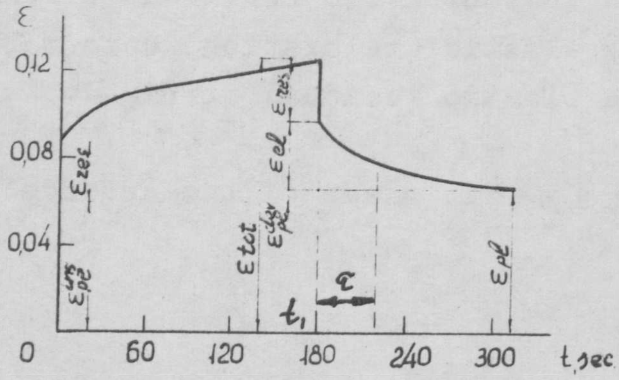

Fig. 2. A typical example of the deformation behaviour of meat samples at axial compression ($\sigma = 0.11 \times 10^5$ Pa)
t_1 = 180 sec. - the moment of releasing the external load

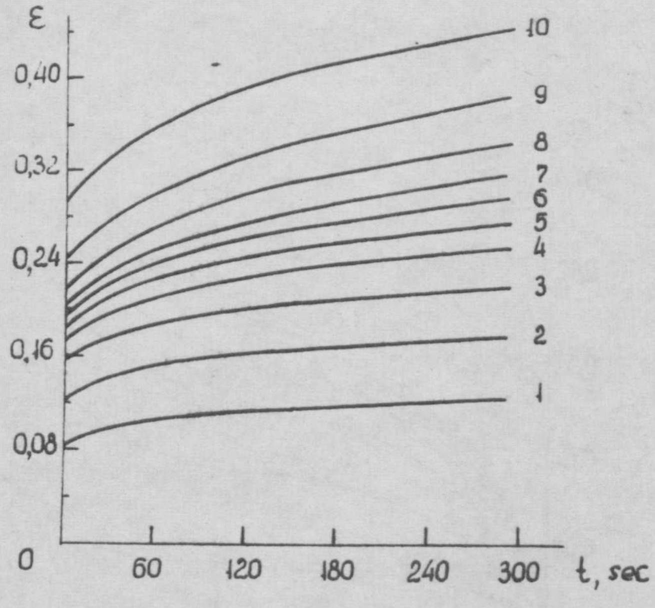

Fig. 3. Creep curves at a constant load; the values of $\sigma \times 10^5$ Pa:
1 - 0.11; 2 - 0.22; 3 - 0.33; 4 - 0.44; 5 - 0.55; 6 - 0.66; 7 - 0.78; 8 - 0.89; 9 - 1.00; 10 - 1.11

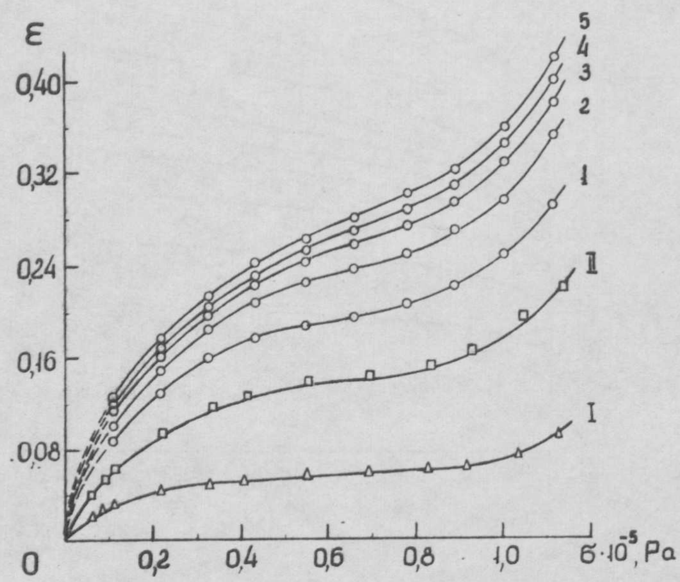

Fig. 4. The total deformation as related to the value of the load applied for similar instants "t", sec.: 1 - 0; 2 - 60; 3 - 120; 4 - 180; 5 - 240
Instantaneous resilient strain I and instantaneous plastic strain II as functions of the load applied

By the data obtained for cyclic loading it was determined that both ε_{res} and ε_{pl}^{ins} depended nonlinearly on the value of the load applied (curves I and II, Fig. 4). As these components of the deformation do not depend on "t", the general relation of and ε_{pl}^{ins} to σ can be represented as follows:

$$\varepsilon_{res}(\sigma) = \frac{\sigma}{E_I(\sigma)} ; \tag{3}$$

$$\varepsilon_{pl}^{ins}(\sigma) = \frac{\sigma}{E_{II}(\sigma)} \tag{4}$$

where $E_I(\sigma)$ is the effective modulus of elasticicty;
$E_{II}(\sigma)$ is the effective modulus of instantaneous plasticity.

In the system of coordinates $\frac{\sigma}{\varepsilon}(\sigma)$, the relationships (3) and (4) at loads within 0 to 0.85x10^5 Pa may be reduced to linear ones, i.e.:

$$\frac{\sigma}{\varepsilon_{res}(\sigma)} = \frac{\alpha_I}{A_I}\sigma + \frac{1}{A_I} \quad \text{or} \quad \varepsilon_{res}(\sigma) = \frac{A_I \sigma}{1+\alpha_I \sigma} ; \tag{5}$$

$$\frac{\sigma}{\varepsilon_{pl}^{ins}(\sigma)} = \frac{\alpha_{II}}{A_{II}}\sigma + \frac{1}{A_{II}} \quad \text{or} \quad \varepsilon_{pl}^{ins}(\sigma) = \frac{A_{II}\sigma}{1+\alpha_{II}\sigma} \tag{6}$$

where A_I , A_{II} , α_I and α_{II} are certain constants.

Comparing (3-4) with (5-6), we find:

$$E_I(\sigma) = \frac{1}{A_I}(1+\alpha_I\sigma); \tag{7}$$

$$E_{II}(\sigma) = \frac{1}{A_{II}}(1+\alpha_{II}\sigma) \tag{8}$$

Substituting the numerical values of constants for Expressions 7 and 8, we obtain:

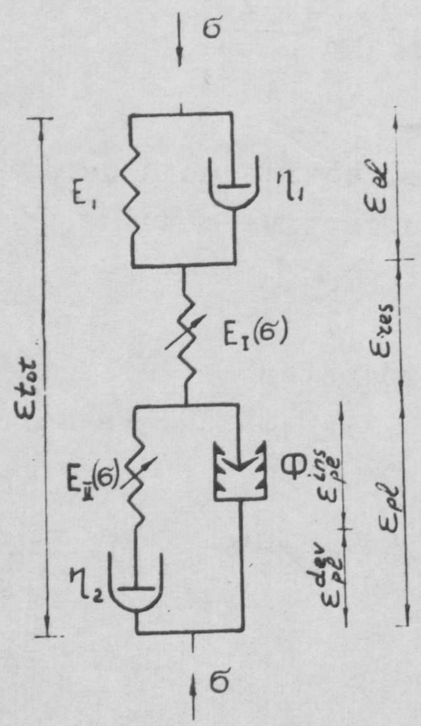

Fig. 5. Nonlinear rheological model of intact muscular tissue

$$E_I(\sigma) = 2.5x10^5+15 \quad , Pa; \qquad (9)$$

$$E_{II}(\sigma) = 1.25x10^5+5 \quad , Pa. \qquad (10)$$

On the basis of the experimental data obtained, a nonlinear rheological model of intact muscular tissue can be suggested (Fig. 5), which is composed of the following elements: Kelvin element (E_I, η_1) which provides the relaxation component of deformation ε_{el} ; nonlinear resilient element $E_I(\sigma)$ and nonlinear Maxwell element $E_{II}(\sigma)$, η_2 bridged with a lock Φ , the latter providing residual plastic strain ε_{pl} . When the load was applied, the rod of the lock moved freely downward; when the load was released, the lobes of the lock engaged the grooves and did not allow the spring $E_{II}(\sigma)$ to return to the initial position. Under a higher load the element deformed irreversibly again. The relation of the deformation ε_{pl} to the stress was determined by means of the parametres $E_{II}(\sigma)$ and η_2 and depended on the pre-history of deformation. The damper η_2 provided plastic strain ε_{pl}^{dev} , developing with time, and, when the external load was released, - the relaxation of residual stresses on the spring $E_{II}(\sigma)$; so, on the whole, the model was free from internal ("frozen") stresses.

The total deformation of the model is represented as ratios (1) and (2); the deformations of nonlinear elements ε_{res} and ε_{pl}^{ins} depending on the stress σ applied - as expressions (3) and (4) (respectively).

For the rest of the elements of the model, e.g. /12/,

$$\eta_1 \dot{\varepsilon} + E_I \varepsilon_{el} = \sigma ; \qquad (11)$$

$$\dot{\varepsilon}_{pl}^{dev} = \frac{\sigma}{\eta_2} \qquad (12)$$

Excluding particular deformations ε_{res} , ε_{pl}^{ins} , ε_{el} , ε_{pl}^{dev} from expressions (1-4), (11) and (12), we derived the following nonlinear differential rheological 2nd-order equation relative to σ and ε :

$$\tau \frac{d^2\varepsilon}{dt^2} + \frac{d\varepsilon}{dt} = \tau \frac{d^2}{dt}\left[\frac{\sigma}{E(\sigma)}\right] + \frac{d}{dt}\left[\frac{\sigma}{E(\sigma)}\right] + \frac{\tau}{\eta}\frac{d\sigma}{dt} + \frac{\sigma}{\eta_2}, \tag{13}$$

where
$$E(\sigma) = \frac{E_I(\sigma) \cdot E_{II}(\sigma)}{E_I(\sigma) + E_{II}(\sigma)} \tag{14}$$

is reduced nónlinear modulus of elasticity;

$$\eta = \frac{\eta_1 \cdot \eta_2}{\eta_1 + \eta_2} \tag{15}$$

is reduced coefficient of viscosity;

$$\tau = \frac{\eta_1}{E_1} \tag{16}$$

is deformation relaxation time.

Let us apply the above equation to studying the creep under constant load. At σ =const equation (13) will become

$$\tau \ddot{\varepsilon} + \dot{\varepsilon} = \frac{\sigma}{\eta_2} \tag{17}$$

This is a linear inhomogeneous differential 2nd-order equation, with the right member being constant.

The initial conditions (at t=0) were as follows:

$$\varepsilon(0) = \frac{\sigma}{E_I(\sigma)} + \frac{\sigma}{E_{II}(\sigma)} = \frac{\sigma}{E(\sigma)} \tag{18}$$

$$\dot{\varepsilon}(0) = \frac{\sigma}{\eta_1} + \frac{\sigma}{\eta_2} = \frac{\sigma}{\eta}. \tag{19}$$

Equation (17) with the initial conditions (18) and (19) is solved as follows:

$$\varepsilon(t) = \frac{\sigma}{E(\sigma)} + \frac{\sigma}{\eta_2} t + \frac{\sigma}{E_1}\left(1 - e^{-\frac{t}{\tau}}\right) \tag{20}$$

Differentiating (20) in relation to time "t" and to the limit at $t \to \infty$, we found that for the creep rate limit

$$\dot{\varepsilon}(\infty) = \frac{\sigma}{\eta_2}. \tag{21}$$

By means of equation (13) we studied the character of sample recovery after releasing the external load at t_1 (Fig. 2). In this case, instead of (17), we shall have (at $\sigma=0$):

$$\tau\ddot{\varepsilon}+\dot{\varepsilon}=0 \tag{22}$$

The initial deformation of the model was determined from the previous formula at $t=t_1$; minus the instantaneous resilient deformation of $E_I(\sigma)$ it was equal to:

$$\varepsilon(t_1)=\frac{\sigma}{E_{II}(\sigma)}+\frac{\sigma}{\eta_2}t_1+\frac{\sigma}{E_I}\left(1-e^{-\frac{t_1}{\tau}}\right) \tag{23}$$

The initial velocity was determined only with the initial deformation rate of the Kelvin element /12/:

$$\dot{\varepsilon}(t_1)=\frac{\sigma}{\eta_1}\left(1-e^{-\frac{t_1}{\tau}}\right) \tag{24}$$

Having solved equation (22) with the initial conditions (23) and (24), we obtained:

$$\varepsilon(t)=\frac{\sigma}{E_{II}(\sigma)}+\frac{\sigma}{\eta_2}t_1+\frac{\sigma}{E_1}\left(e^{\frac{t_1}{\tau}}-1\right)e^{-\frac{t}{\tau}} \tag{25}$$

Passing over to the limit at $t\to\infty$, we found residual deformation ε_{resid} (t_1), which depends on the instant of external load release:

$$\varepsilon_{resid}(t_1)=\frac{\sigma}{E_{II}(\sigma)}+\frac{\sigma}{\eta_2}t_1 \tag{26}$$

Phenomenological constants E_1, η_1 and η_2 and deformation relaxation time τ were determined by the experimental data in accordance with the above solutions. Proceeding from the ratio for creep rate limit (21) and from the data in Fig. 3, we calculated the values of the coefficient of viscosity η_2 as being about 5.2×10^8 Pa·sec. Relaxation time τ, calculated by recovery curves (Fig. 2), turned out to be equal to about 45 sec. Then, according to equation (25), $E_1\cong3.8\times10^5$ Pa. The second coefficient of viscosity η_1 was determined by expression (16) as $\tau\cdot E_1$ as equal to 1.7×10^7 Pa·sec.

The objective data obtained, which characterize muscular tissue texture, can be used both for technological purposes, and for the evaluation of certain quality aspects of foods.

L I T E R A T U R E

I. С о к о л о в А.А. Физико-химические и биохимические основы технологии мясопродуктов. М., изд. "Пищевая промышленность", 1965.

2. Р о г о в И.А., Г о р б а т о в А.В. Новые физические методы обработки мясопродуктов. М., изд. "Пищевая промышленность", 1966.

3. Г о р б а т о в А.В. Реология в мясной промышленности. М., ЦНИИТЭИмясомолпрома СССР, 1968.

4. П о т о к и н В.А. Механическое оборудование предприятий общественного питания. М., Госторгиздат, 1940.

5. К л и м е н к о М.Н. Канд.дисс. М., МТИММП, 1966.

6. С п и р и н Г.Е. Канд.дисс. М., МТИММП, 1970.

7. П е л е е в А.И. Пути механизации обвалки мяса. М., ЦИНТИПищепром, 1970.

8. П о з н ы ш е в А.Н. Тезисы докладов конференции молодых специалистов института по итогам научно-исследовательских работ. М., МТИММП, 1972, 146.

9. S t a n l e y D.W., P e a r s o n G.P. and G o n - w o r t h V.E. "J.of Food Science", 36, 2, 1971, 256.

IO. M o s h e n i n N.N. Physical properties of plant and animal materials. v.l. New-York, London, Paris, 1970.

II. Б е н д о л л Дж. Мышцы, молекулы, и движение. М., изд. "Мир", 1970.

I2. Г о л ь б е р г И.И. Механическое поведение полимерных материалов. М., изд. "Химия", 1970.