Research of deformation properties of food material under the influence of normal stresses

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Abstract. The article covers research of mechanical characteristics of raw macaroni products when compressed at constant speed, deformation curves of kinetics of deformation of layer of raw macaroni products, as well as developed experimental setup for studying the compressibility of macaroni tubes.

1. Introduction

Food material undergoes complex physical-chemical, biological and mechanical processes during its processing.

Most food structures have both elastic and plastic properties [1]. Therefore, when measuring their mechanical properties, it is often necessary to determine both reversible resilient elastic and irreversible plastic deformations arising under the action of external forces. [6, 7]

According to the laws of change in the deformation of the layer of raw macaroni products under tension or compression, the main mechanical characteristics, i.e. modulus of elasticity, proportionality limit, relaxation period, etc. can be obtained [2, 3].

Methods for testing the mechanical properties of food materials and measuring the values of the acting stresses \( \sigma \), resulting deformations \( \varepsilon \) and their speeds \( U \) can be reduced to three cases or varieties. In each of them, one of the three listed indicators remains constant; the second indicator is measured as a function of the third indicator. Thus, the main methods are:

1. Measurement of deformation \( \varepsilon \) during deformation \( t \) at constant stress \( \sigma = \text{const.} \)
2. Measurement of the stress of structure \( \sigma \) depending on the value of deformation \( \varepsilon \) at its constant speed \( U = \text{const.} \)
3. Measurements of the structure stress \( \sigma \) depending on curing time \( t \) at constant deformation \( \varepsilon = \text{const.} \)

2. Methods

Mechanical characteristics of raw macaroni under compression at constant deformation speed were studied on experimental installation, schematic diagram of which is shown in figure 1.

Loading of the prepared sample is carried out from the electric motor 1 through the gearbox 2 and the cone belt drive 3. The pulley 4 is fixed on the nut 5 screwed onto the shaft thread 6. A key is installed on the shaft, which enters the trapezoidal groove made in the bearing unit cover. Thus, the rotational movement of the pulley is converted into the translational movement of the shaft 6, which, through the dynamometer 7 and the pusher 8, deforms the layer of raw tubes 9 laid in the cassette 10.
With the help of a metal ruler 11 installed on the machine bed, and an arrow fixed on the pusher, the initial position of the pusher is controlled and the magnitude of its stroke is equal to the total compression deformation.

Fixation of the compression efforts of the layer of macaroni tubes was carried out according to the usual scheme of strain measurements [4] with the use of a “Topaz-2” amplifier, N 041 oscilloscope and P-104 time marker. Deformation speed value was chosen from the condition of complete exclusion of possible dynamic loads and was 0.011; 0.018; 0.20; 0.026; 0.030 m/s. The dough was kneaded from macaroni (middling) and bakery flour. The moisture content of the dough was 29-30%. Temperature was 298 °K. Prepared macaroni tubes 5.0 mm in diameter and 110 mm in length were placed in a special cassette 110x60x40 mm in size. In a typical stacking cassette, 96 tubes were placed.

After the formation of a layer of macaroni in the cassette 10, the pusher 8 is preliminarily brought in until it touches the surface of the tubes. In this case, the starting point on the ruler II is fixed by the position of the arrow. Then, turning on the motor I provided the movement of the pusher, the absolute deformation $S_i$ of the sample and the corresponding ordinate were found from the abscissa of the oscillogram, taking into account the time marks, which allows finding the compression forces when using the calibration graph.

Magnitude of the relative compression was determined by the formula:

$$
\varepsilon_i = \frac{S_i}{S} \cdot 100 \%
$$

(1)

where: $S_i$ is absolute deformation; $S$ is initial width of raw macaroni bundle in the cassette.

Strain $\sigma$ were determined by formula:

$$
\sigma = \frac{P}{F} \text{ Pa}
$$

(2)

Where: $P$ is force acting on the sample, $F$ is pusher area, m$^2$.

3. Results

According to the experimental data, curves (figure 2) were plotted in “deformation ($\varepsilon$, %) - stress ($\sigma$, Pa)” coordinates. Curve I corresponds to the compression of raw macaroni products (tubes) at a deformation speed $U = 0.011$ m/s; 2- $U = 0.018$ m/s; 3- $U = 0.020$ m/s; 4- $U = 0.026$ m/s; 5- $U = 0.030$ m/s.

Analysis of the nature of deformation of layer of raw products in $U = \text{const.}$ mode shows that at the initial stage there is some redistribution of the tubes and the compaction of the laying of the tubular frame.
In this case, the level of stresses is low, and the magnitude of relative deformations is 8-12%. Then the deformation of the frame elements begins. This stage proceeds layer by layer, i.e. first, the tubes adjacent to the pusher are deformed (I layer), and then the subsequent layers are covered by compression. At $\varepsilon=38-44\%$ almost all tubes are already deformed. The compression processes at the second stage are unsteady, because, in addition to the complex development of deformation in the volume of the tubular frame, the contact surface is successively increased due to flattening of the macaroni tubes. Hence, it can be seen that the calculation of $\sigma$ by formula (2) is a certain assumption. Nevertheless, the experimental $\sigma$-$\varepsilon$ dependence (figure 2) is characterized at this stage by a linear form. When relative deformations $\varepsilon$ of about 55-65% are reached, a noticeable fracture of the $\sigma$-$\varepsilon$ graph occurs, which is associated with complete flattening of the macaroni tubes and subsequent compression of the compacted mass of dough.

Thus, a typical diagram of the compressibility of a layer of raw macaroni has three characteristic areas:

1. Curved section in the range $\varepsilon=20-60\%$, associated with a change in the arrangement of elements in the tubular frame and its preliminary compaction within the limits of maintaining the stability of the shape of each of the elements;
2. Rectilinear section in the range $\varepsilon=20-60\%$, characterizing the process of the development of tube deformation in the layer volume;
3. Rectilinear section with a large angle of inclination to the abscissa axis, describing the process of further compression of the tubes after flattening their walls.

Determination of the maximum permissible $\sigma$ value can be performed by comparing the deformation parameters with the value of the quality indicators $K_I$ and $K_{II}$, since with an increase in $\varepsilon$ and $\sigma$ above certain values, pronounced adhesion properties are manifested between the elements of the tubular frame.

The experiments carried out have shown that the I section of the typical diagram ($\varepsilon$-$\sigma$) can be taken as the working range of stresses and deformations. The stability margin of the tubular elements of the layer ensures the minimum deviation of the $K_I$ coefficient from the optimal values. So, for example, for compressed macaroni tubes with a moisture content of $W=29\%$ to a value of $\varepsilon=20\%$, the weighted average value is $K_I \approx 0.969$. It was not possible to use the $K_{II}$ parameter to determine the permissible values of $\varepsilon$ and $\sigma$ due to the lack of a clear correlation between the studied characteristics.
The formation of sticky tubes in the layer corresponded to deformation of $\varepsilon \geq 30\text{-}35\%$ at $W=30\text{-}31\%$ and $\varepsilon \geq 40\%$ at $W=28\text{-}29\%$. Longer blowing shifted these characteristics towards higher deformation values.

The alignment of the experimental curves of preliminary compression (of I section) in semi-logarithmic coordinates showed that the most accurate empirical equation is an expression of the form:

$$\sigma = \frac{C}{A}(e^{a\varepsilon} - 1)$$

(3)

where $A$ and $C$ are experimental coefficients.

For the sections 2 and 3, the ratio of form is correct.

The main rheological characteristics of a layer of molded macaroni products during deformation in $U = \text{const}.$ mode are shown in Table 1 for the initial moisture content of the batch $W=30\%$ and the duration of blowing the half-finished product $t=10\ s$.

Table 1. Rheological properties of the layer of molded macaroni products at $U = \text{const}$.

| Diagram section $\varepsilon - \sigma$ | Parameters | Deformation speed $u \cdot 10^2$, m/s |
|--------------------------------------|------------|--------------------------------------|
|                                      |            | 1.1  | 1.8  | 2.0  | 2.6  | 3.0  |
| I                                    | A          | 0.9  | 2.1  | 2.8  | 3.9  | 4.7  |
|                                      | C          | 10.2 | 9.2  | 8.6  | 8.1  | 7.4  |
| II                                   | $E_2 \times 10^3$ Pa | 4.2  | 6.3  | 7.3  | 8.3  | 9.0  |
| III                                  | $E_3 \times 10^3$ Pa | 10.5 | 12.5 | 14.5 | 16.5 | 18.0 |

4. Discussion

One of the most common methods for studying the structural and mechanical properties of food products is to construct deformation kinetics curves [5]. These curves provide the most information on the deformation behavior of materials.

We carried out the study of the curves of the kinetics of deformation of the layer of raw macaroni on an improved AP-4/1 penetrometer with a 30x30 mm cargo square fixed to the immersion system.

In the result of preliminary experiments, the duration of the impact of the load on the sample $t=60\ s$, and the range of nominal voltages $4.2 \times 10^3 \text{ Pa} - 16.7 \times 10^3 \text{ Pa}$ were selected.

In all experiments, a fivefold repetition was adopted. The maximum relative error, as shown by statistical calculations, did not exceed $8\%$.

Fig. 3 shows the characteristic curves of the kinetics of deformation with instantaneous unloading for raw macaroni, with moisture content $W=30$, 31, and 32\%, at constant voltages $\sigma=7.5 \times 10^3 \text{ Pa}$ and $\sigma=14.5 \times 10^3 \text{ Pa}$, built according to the experimental data given in table 2.

Presented in figure 3 curves of the kinetics of deformation of raw macaroni tubes consist of two periods - loading and unloading. In turn, two sections can be distinguished on the load part of the curve. The initial section is a period of unsteady deformation, which is explained by the process of irreversible plastic flow and is characterized by a constant deformation speed.

Determination of the elasticity limit and elasticity of both high-polymer and food structures associated with serious difficulties is of great importance [III]. With a known approximation, $\varepsilon_U$ can be determined by a graphical method, drawing a tangent to the deformation curve in the period of steady-state speed until it intersects the ordinate axis. The cut off segment $\varepsilon_U$ correspond to the resilient and elastic part of the curved section.

Qualitative assessment shows that the intensity of the deformation process of raw macaroni products depends on magnitude of the compressive stress $\sigma$ and the moisture content $W$.  

Figure 3. Curves of the dependence of deformation ε on the duration of deformation t at constant stress ((σ=const): a) without blowing, 1-4-W=30% 2-5-W=31%; 3-6-W=32%; 1-2-3-σ=7.5\times10^3 Pa; 4-5-6-σ=14.5\times10^3 Pa; b) with blowing, 1'-4'-W=30%; 2'-5'-W=31%; 3'-6'-W=32%; 1', 2', 3'-σ=7.5\times10^3 Pa; 4'-5'-6'-σ=14.5\times10^3 Pa.

Table 2. Experimental data for kinetic curves.

| Moisture, % | σ\cdot10^3 Pa | ε, % | E_ε\cdot10^5 Pa | η\cdot10^3 N\cdot s/m^2 | η_{pv}/E_ε, c |
|-------------|--------------|------|---------------|-----------------|----------------|
| 30          | 4.2          | 12.4 | 0.339        | 5.1             | 15.1          |
|             | 7.5          | 22.5 | 0.333        | 6.7             | 20.1          |
|             | 14.5         | 46.0 | 0.315        | 7.9             | 25.1          |
|             | 16.7         | 55.1 | 0.303        | 9.1             | 3.1           |
|             | 4.2          | 1.2  | 0.296        | 4.4             | 14.9          |
|             | 7.5          | 26.6 | 0.282        | 5.6             | 19.9          |
|             | 14.5         | 51.6 | 0.281        | 7.0             | 24.9          |
|             | 16.7         | 63.5 | 0.262        | 7.9             | 30.0          |
|             | 4.2          | 18.1 | 0.232        | 3.5             | 15.1          |
|             | 7.5          | 3.1  | 0.241        | 4.8             | 19.9          |
|             | 14.5         | 58.3 | 0.249        | 6.2             | 24.9          |
|             | 16.7         | 69.3 | 0.241        | 7.2             | 29.9          |

The loading part of the deformation kinetics curve shows that the specified time of stress action (60 s) is sufficient for the development of all components of the deformation of raw macaroni tubes.

The value of the relative compression ε was determined by the formula:

$$\varepsilon = \frac{\Delta S}{S} \cdot 100\%$$  \hspace{1cm} (4)$$

where ΔS is - instrument readings, mm (absolute compression deformation)
S is the height of sample, mm.

The data obtained were used to determine the main structural and mechanical characteristics of raw macaroni tubes, i.e. steady-state modulus of elasticity E_ε, plastic viscosity η_{pv} and relaxation time θ.

In this case, the following relations were used
\[ E_\varepsilon = \frac{\sigma}{\varepsilon_e}; \]
\[ \eta_{pv} = \frac{\sigma}{\left(\frac{d\varepsilon}{dt}\right)_{res}}; \]

where \( \sigma \) is compressive stresses; \( \varepsilon_e \) is resilient elastic deformation:

\( \left(\frac{d\varepsilon}{dt}\right) \) is plastic deformation speed.

The resulting values are shown in table 2.

Analysis of the numerical values given in table 2 shows that molded macaroni products can be attributed to solid bodies according to the qualifications of B.A. Nikolaev [5], and have pronounced properties of elasticity and plasticity.

5. Results

Structural, mechanical and strength properties of a layer of raw macaroni tubes depend on the complex of technological rheological properties of macaroni dough, molding conditions, features of the geometric shape of the half-finished product and the density of their packing in the layer.

Working range of stresses and deformations of the macaroni layer during its cutting should be considered the first section of the compressibility diagram (\( \varepsilon = 0-20\% \)), associated with a change in the packing of the tubular frame elements and its preliminary compaction within the limits of maintaining the stability of the shape of each of the elements. This ensures the minimum deviation of the coefficient \( K_1 \) from the optimal values.

The obtained numerical values of the rheological characteristics (\( E, \eta, \eta/E \)) of the molded macaroni products allows classifying the layer of raw half-finished product as solid body with marked properties of elasticity and plasticity.

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