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RHEOLOGICAL PROPERTIES OF DOUGH

This study presents general properties of dough as demonstrated within the period of its technological usefulness (i.e. approx. up to 30 min). Eight (8) types of dough made of four (4) types of flour were subjected to experimental tests. During examination of dough, treated as a non-Newtonian fluid, its non-Newtonian (apparent) viscosity was determined as well as its correlations with other rheological quantities. The results of the study were shown in diagrams presenting the course of particular quantities and model correlations of examined types of dough. These relations were used to determine one general expression modeling rheological properties of examined doughs.

1. Introduction

The physical and technological properties are becoming particularly important while making or processing dough, especially when greater quantities of bread are produced in a production process that makes use of suitable devices and machinery. It is difficult to mechanize the production and processing of dough due to its complex nature (numerous technological functions) and due to the fact that it is necessary to ensure steady, high quality of bread, with changing properties of dough [1], [5].

Dough is a material that is characterized by complex composition and internal structure. The process of mechanical processing, especially in dough forming, is significantly affected by its technological properties stemming from the physicochemical composition and the method of preparation (production). Dough is prepared according to various recipes, whose basic ingredient is flour, and it is flour's properties (which are changeable) that profoundly affect the dough properties [3], [7], [8]. Wheat flour is primarily

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used in the production of small bakery products. Occasionally, a mixture of flours is applied, for example, a wheat flour plus rye flour, oat flour or even maize flour.

Apart from containing flour, dough may frequently contain additions such as water, salt, sugar, fats, milk, yeast, seeds (e.g. poppy seed, caraway seed) and raisins and other ingredients as well as the so-called enhancing agents. Of the applied additions, only certain types may be met with. The presence of additions has a bearing on the properties of prepared dough, causing its biological activity (fermentation) leading, as a result, to a change of physical properties over a period of time.

Among technological properties of the produced dough, the rheological properties are of particular importance. These show particularly while preparing dough (kneading) and during mechanical processing in dividing and forming dough pieces. During kneading, forming and dividing, the rheological properties of dough strongly influence the course of such processes, also affecting the performance of machinery and devices used in the technological operations, particularly in the area of selecting suitable working settings of mechanisms such as revolutions, speed, operation time as well as power needed to put the mechanisms into motion – dough should be characterized by optimum technological properties referred to as the so-called machinability [1], [2], [3], [5].

The basic technological operation shaping dough properties is its kneading, during which we can distinguish two stages:
– mixing the ingredients to obtain a homogenous mass,
– dough plasticizing; mechanical and structural development of dough.

Physical, biochemical, microbiological and colloidal processes are observed during the second stage of kneading. Raw materials of plant origin, including flour, contain substances in the form of complex colloidal systems [1], [2], [7], [8]. The impact of water on colloids contained in flour (hydration) and mechanical impact lead to forming a complex multi-component system such as dough. During kneading, swollen water-insoluble proteins are formed. In wheat dough they form gluten – a spatial spongy network structure constituting the so-called dough framework. The framework decides about the dough's rheological properties, in particular about elasticity and plasticity. In kneading, also the dough consistence increases, reaching its peak (the stability of maximum consistence usually lasts a few minutes depending on the quality of flour) at which the best technological properties, including the rheological ones, are observed. If kneading is continued (after reaching the maximum consistence) it results in the worsening of technological properties, thus the rheological ones as well (e.g. drop in viscosity as a result of damaging the gluten structure).

Rheological properties exert decisive impact on the technological indices pertaining to bread quality. It is the mechanical and structural properties of dough that influence such characteristics as gas-retaining capacity and surface tension – properties deciding about volume, porosity, shape and characteristics of the bread crumb. The set of technological changes bringing the dough, as a result of kneading and fermentation, to a condition optimum for further processing (dividing, forming, growth, baking) is called the dough maturing.

The dough properties and their values are observed to be time-dependent, such dependence being related to biological activity. This is why the time of technological processing of dough should (and is) short (sometimes up to several minutes). Breaks for the so-called dough resting are introduced between certain operations. During such breaks, the dough restores (relaxes) its technological properties disturbed by mechanical processing [1], [5].

Mechanical processing of formed dough causes its flow, which, in character, is like a flow of a non-Newtonian fluid, determining the way the dough behavior in forming is described. Real materials such as dough behave in processing like bodies (mediums) characterized by complex rheological properties, including all, usually time-dependent, elementary rheological properties. Certain deformations – elastic, plastic and viscous – take place under influence of forces (loads) causing dough forming (shape transformation, motion, flow).

2. Description of dough properties as a non-Newtonian material

With the phenomenological approach to the rheology of non-Newtonian materials, there are two ways to describe their properties – theoretical and experimental. The theoretical description (axiomatic approach to issues under consideration) referring to behavior and description of non-Newtonian mediums (outside the description of viscoelastoplastic bodies by the Newton's law) is based on the concept of "fluid deformation history" (and, to be precise, on the history of deformation tensors and the deformation rate in the description of the history of the deformation process, for which corresponding tensors are equivalent in case of very small gradients of relocation) as well as on the occurrence of the so-called nonlinear effects (Barus and Weissenberg), stress relaxation and elastic recovery in a flowing medium, and the possibility of secondary flows [6], [9], [12]. The fact of basing on the concept of kinematic history of a medium defined by the history of its movement, makes it possible to determine the stresses present in a flowing medium at a considered moment of time and results from the application of the principle of determinism in continuous mediums.

The models defining fluid properties formed within the theoretical description usually have a three-dimensional form allowing us to formulate equations for fluid motion within the space of the flow phenomenon. Numerous constitutive equations modeling the properties of considered fluids have been formulated. They are, however, usually characterized by multiparameter solutions and complex formulas (hypothetical bodies are frequently under considerations), thus limiting the possibility of use, particularly in practice, in technological applications.

It is often insufficient to apply classic models of continuous mediums to the description of mediums demonstrating rheological properties, since certain rheological materials (including doughs) are characterized by occurrence of time effects.

The simplest rheological mediums are the bodies whose time-dependent properties can be described by means of linear models (analogously to the linear, one-dimensional models). Constitutive equations for linear bodies link together the basic properties (elasticity, plasticity, viscosity) and their time derivatives in a linear way, making use of the superposition of certain quantities [9], [12]. Models, created this way, incorporate classic medium models such as the viscoelastic medium (Maxwell and Kelvin-Voigt models). The multiparameter models usually reflect faithfully the rheological properties of certain real materials.

The description of a mechanical behavior of a body subjected to forces and stresses (dynamic values) leading to its deformation (forming causing shape transformation of dough piece), involves basic principles of conservation used in mechanics (mass conservation law, principle of conservation of momentum, principle of conservation of angular momentum, energy conservation law). These principles allow one to formulate a system of equations describing behavior of bodies – unfortunately, the number of variables in the equations exceeds the number of equations. By establishing the relationships between stresses and deformations in the form of determined correlations modeling the properties of transformed materials, it becomes possible to close this system of equations and further to solve it.

The relationships between stresses and deformations describe functional correlations in the form of constitutive equations modeling mathematically the rheological properties. The constitutive equations, which define ideal materials in terms of the model, describe physical properties concerning the correlations linking together the kinematic, dynamic and thermal values. These equations also describe the reaction ("response") of mediums to external forces (usual mechanical load). The reaction (response) of the material to the action of forces is connected with the so-called material's (substance's) natural time – as a measure of spontaneous diffusion and the

reciprocal motion of molecules, and even the material's atoms. The value of the natural time for materials occurring in nature ranges from 10^{-13} to 10^{13}s, with the lower limit (immediate reactions) corresponding to non- or low-viscous substances (e.g. water) and the upper limit (millions of years) corresponding to hard solid bodies (e.g. rocks). It is important for the behavior of bodies (their reaction) what relationship is established between the time during which the forces act on the body and the natural time – if there is a big difference between the times (fast relative action), the reaction will be elastic; in a small difference (slow relative action), the reaction will be viscous. All deformations (reactions) of real bodies, i.e. elastic, plastic, viscous, are contained within the described time limits for the course of the phenomena. Real bodies typically react after approx. $10^{-1} - 10^3$ s [6].

Generally, constitutive equations may take on any form relating together the dynamic and kinematic values, but allowing for limitations stemming from the postulates of physics and requirements regarding the construction of constitutive correlations [9], [12].

In the experimental approach to the rheology of non-Newtonian materials, for the obtained results of experiments, adequate formulas are sought for to describe these results. As a result, many expressions, wholly or partly empirical, modeling the properties of examined fluids were created. These empirical models usually have a simple construction and a small number of parameters, therefore they are widely used despite limitations in some cases consisting in the impossibility to build three-dimensional equations.

2.1. Application of the generalized Newton's law

The use of the so-called generalized Newton's law (as proposed by Stokes) may turn out very useful in many practical applications. This generalization allows one to formulate, in a simple and convenient way, the correlations modeling the rheological properties of various real materials for which it can be assumed that the relationships between the quantities describing motion depend to a small extent on the history of such motion (or there may be problems with allowing for the history of motion at all). The generalized Newton's law enables linearization of correlations between basic rheological properties for non-Newtonian materials for which correlations between real rheological properties are nonlinear. This generalization plays an important role in formulating expressions modeling the rheological properties of various non-Newtonian materials, particularly for models determined empirically. It is usually possible to give mathematical models of various fluids a form formally similar and that is useful in formulating equations describing the flow of rheological materials, especially when, in

practical approach to the problem, viscosity of the material (fluid) is the decisive property in describing it [5], [6].

Vital importance in the functioning of the generalized Newton's law is assigned to viscosity (changing for many materials of complex rheological properties), which, despite its changeability, is considered as constant – thus treated as a parameter. Such generalized viscosity, characterizing properties of a material, is called effective, apparent or non-Newtonian. Relating this value, i.e. the effective viscosity to Newtonian viscosity, it is possible to determine a relation defining the effective viscosity in one-dimensional notation in the following form:

$$\eta_e = \frac{\tau}{\dot{\varepsilon}} \neq const, \tag{1}$$

In the three-dimensional system, the generalized viscosity Γ can be noted as the following correlation:

$$\Gamma = f(A, \eta_e). \tag{2}$$

Analogously to formula (1), the viscosity parameter Γ – generalized viscosity, may take on the following form:

$$\Gamma = \frac{\tau_e}{A} \tag{3}$$

where: τ_e – effective stress (characteristic of fluid in a three-dimensional system).

Being an argument in correlation (3) parameterizing the generalized viscosity Γ, the A value is the so-called deformation rate stress (modulus of deformation rate deviator) defined by the relation:

$$A = |2\dot{\varepsilon}_{ik} \cdot \dot{\varepsilon}_{ki}|^{1/2}. \tag{4}$$

The deformation rate stress A is, to some extent, a substitute for the deformation rate $\dot{\varepsilon}$ in expressions describing relationships between stresses and the deformation rate [5].

The following relation defines the shear stress in tensor notation:

$$\tau_{ij} = \Gamma\dot{\varepsilon}_{ij}. \tag{5}$$

A complex correlation between the viscosity value and material properties and quantities referring to material deformation can be, in many cases, treated parametrically accepting this approximation. On the other hand, with such a definition of the effective viscosity, it becomes possible to determine it by experiment as a complex property of material, in a way and by methods similar to the determination of Newtonian viscosity.

Application of the generalized Newton's law to practice consists in determining generalized viscosity for a used fluid model, as for (1) or (3). In the conducted study, the Newton's generalization was used in order to define basic relationships for the rheological properties (shear stress τ, deformation rate $\dot{\varepsilon}$, generalized viscosity – non-Newtonian viscosity).

3. Experimental examination

Experimental examinations of rheological properties of dough allow one to determine basic values describing such properties, with the values influencing the behavior of dough while processing – these values may be used to determine expressions modeling its properties. By knowing the mathematical model, it becomes possible to combine deformations and deformation rate with stresses present in the material through determining appropriate correlations describing the transformations of the dough piece and flow of dough during forming.

The aim of the study is to determine the non-Newtonian (apparent) viscosity of dough as a quantity containing "the resultant" of rheological properties of dough (using the generalized Newton's law) and to determine its changeability in time in comparison with the time used for forming the dough pieces. Generally, due to the possibility of losing technological usefulness, the dividing and forming of dough into pieces should not exceed 20 to 30 minutes counting from the end of the initial dough fermentation. As a result, the machines used in this operation should have sufficient efficiency [1], [4], [10].

3.1. Quantities describing dough properties

Being arguments in constitutive equations, the determined rheological quantities (non-Newtonian viscosity, shear stress, deformation rate) are dependent variables expressed through certain correlations containing independent variables (dependent variables are values derived from independent variables). Independent variables are physical quantities determined by direct measurements (direct quantities) made with appropriate measuring devices. The values of dependent variables result from the relationship that defines them and are functions of values of independent variables [4], [10], [11].

Determining the non-Newtonian viscosity, as a quantity derived (dependent variable) from independent variables, is done by measurements of basic quantities (independent variables), e.g. the falling time of the ball in the dough, load.

Non-Newtonian viscosity of dough (dependent variable), is a basic physical quantity describing dough properties – it is determined through measure-

ments. The measurement of non-Newtonian viscosity of dough is a measurement of an intermediate quantity, whose arguments (independent variables) are:

- load (M), controlled vital variable
- test-tube constant (K), uncontrolled vital variable
- falling time (t_1, t_2, t_S) of a plunger with a ball, controlled vital variable; s,
  - t_1 – half falling time at half-way, i.e. 15 mm,
  - t_2 – total falling time at a covered distance of 30 mm,
  - t_S – mean falling time at a covered distance of 30 mm; arithmetic mean of $2t_1$ and t_2,
- time (t_P), of starting each measurement (current time), controlled vital variable.

The non-Newtonian viscosity resulting from measurements done by the Hoeppler rheoviscosimeter is determined on the basis of the relation (specified in the device's manual – defining variable) in the form:

$$\eta = 10^{-3}M \cdot t_S \cdot K; \quad Pa\ s, \tag{6}$$

where: M – load on device's pan; G/cm^2,

K – test-tube constant (K = 100); $Pa\ cm^2/G$,

η – non-Newtonian viscosity (apparent); Pa s.

The load quantity M is a vital independent variable with constant accuracy. This variable can be treated parametrically. All measurements of dough samples were conducted in a test-tube with the constant K = 100, suited for the material under examination. The influence of the constant K on the determined value of dependent variable was also treated parametrically. The mathematical form of the above relation confirms that decisive for the measurement is determination of the quantity of falling time of plunger with ball in a test-tube with dough. Correctness and accuracy of the falling time measurements have major influence on the quality of examination of dough properties.

Shear stress (viscous) (dependent variable), determined from independent variables, defines expression (as in the manual) in the following form:

$$\tau = 0.0981\ M = 9.81\ 10^{-2}\ M;\ kPa. \tag{7}$$

The accuracy of determination of the stress value is directly related to the accuracy defined for the load M and acceleration of gravity g.

Shear rate (dependent variable), can be determined based on the above-defined quantities with the use of the generalized Newton's law yielding the following:

$$\dot{\varepsilon} = \frac{\tau}{\eta}10^3; \ 1/s, \tag{8}$$

The rheological quantities defined are the basic ones in formulating constitutive equations.

3.2. Basic devices and measuring equipment

The following devices and measuring equipment were used while conducting examination of rheological properties of dough:
1) Hoeppler rheoviscosimeter (Rheo – Viskometer nach Hoeppler 202G) (Fig. 1 and Fig. 2)
   - Measuring range $(4 - 4 \cdot 10^6$ mPa·s)
   - Measuring accuracy up to ±2% for Newtonian fluid
   Equipment:
   - set of glass test-tubes, 5 units, capacity 16–25 ml, /constant K = 0.01; 0.1; 1; 10; 100/
   - two measuring plungers with balls /for K = 0.01; 0.1 and for K = 1; 10; 100/
   - mercurial thermometer 0–100°C, scale interval 0.5°C
   - set of weights, 5 units, marking: /10; 2×20; 50; 100/ in g-f/cm^2 (gram-force/cm^2), the mass of weights is, respectively: 40; 2×80; 200; 400; g.
   The following equipment was used during the examination of non-Newtonian viscosity:
   - test-tube with constant K = 100, (biggest),
   - measuring plunger suitable for the above test-tube (2 flat),
   - 2 sets of weights.
2) Laboratory thermostat.
3) Air washer; 3 heating rate settings,temperature and humidity settings, adjustable thermometer, accuracy 0,1°C, adjustable hygrometer, and accuracy 0.1%.
4) Set for measuring water absorbability SZ (consistometer) with thermostat with constant setting at 30°C, Fig. 3, (manufacturer: ZBPP in Bydgoszcz, PL).
5) Dough-kneading machine MML – 25, Fig. 4; trough capacity 25–50 g.
6) Laboratory burette with water vessel (0.25 l).
7) Laboratory clock with sound and light signal.
8) Electronic balance, type WPE 150, class. II, measuring accuracy 0.05g, reading accuracy 0.005g, RADWAG.
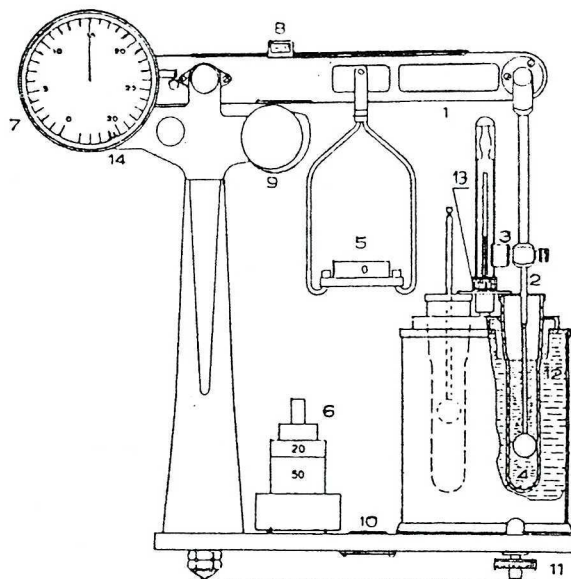9) Timer.

Fig. 1. Hoeppler rheoviscosimeter

1 – measuring lever arm, 2 – measuring plunger with ball, 3 – grip for plunger with follower, 4 – measuring test-tube, 5 – scale pan as load for lever arm (1), 6 – set of weights, 7 – distance meter for measuring plunger (micrometric gauge), 8 – compensation slider for density of measured fluid, 9 – arm movement switch on/off knob (1), 10 – device level gauge, 11 – leveling adjustable knob, 12 – fluid (water) in thermostat vessel, 13 – knob for mounting test-tubes in the thermostat vessel, 14 – ring for setting the pitch for the distance meter
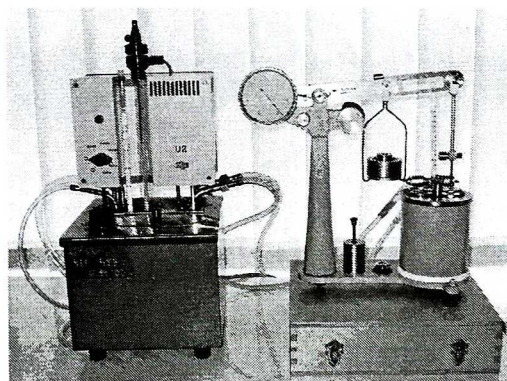

Fig. 2. Stand for examining the viscosity of dough – Hoeppler rheoviscosimeter with laboratory thermostat

10) Digital thermohygrometer, type LB – 725, reading accuracy 0.1°C and 0.1%, manufacturer LAB-EL.
11) Wall hygrometer, reading accuracy 0.5%.
12) Laboratory mercurial thermometer; range 0–50°C, reading accuracy 0.25°C.
13) Laboratory pipette; capacity 10 ml.

3.3. Preparation of dough ingredients

The subject of examination is dough (8 types) made from appropriate ingredients. Table 1 presents the types of dough and the amounts of particular ingredients added to make the dough under examination.

Table 1.

Ingredients for examined dough

No.	Ingredient type and content	Amount of ingredient per measuring sample
1	Flour: – wheat flour 500; P500 – wheat flour 750; P750 – rye flour 720; Ż720	30 g 30 g –
2	Mixed flour: – 70% P750 + 30% Ż720 – 50% P750 + 50% Ż720	30 g 30 g
3	Distilled water: Amount of water in sample dependent on flour's water absorbability.	–
4	Brine 9% (9% of salt in water): Amount of brine in sample dependent on flour's water absorbability	–
5	Salt: 1.5% of flour content, 0.45g of salt in 5ml of distilled water	0.45 g
6	Yeast: – bakery type, fresh, 3% of flour content – instant (Dr Oetker), 0.84% of flour c.	0.9 g 0.252 g
7	Enhancing agent: AKO Plus, 2% of flour content	0.6 g

Flour. The basic ingredient of dough, which decides about the properties and use of dough, is flour. In the examination, three types of dough were used – two types of wheat flour with extracts 500 and 750, one type of rye flour with extract 720 (this flour was marked Ż720). Using the three types of flour, one prepared four flour ingredients for dough making:
1) Wheat flour type 500, marked as P500.
2) Wheat flour type 750, marked as P750.

3) Mixed flour made by mixing 70% of P500 and 30% of Ż720, marked as M70.
4) Mixed flour made by mixing 50% of P500 and 50% of Ż720, marked as M50.

The flour for examination was put in closed handling containers (made of plastic approved for use with food products), containing 150g of each kind of flour. The containers were marked with symbols corresponding to the type of flour they contained. After weigh adequate amount of ingredients, the mixed flour (M70 and M50) was homogenized through mixing consisting in pouring the material inside closed container for approx. 3 minutes. Next, open containers with flour were placed in the air washer with stable nominal values of temperature ($T_K = 30°C$) and humidity ($H_K = 60\%$). The containers with flour were kept in washer's atmosphere for min. 24 hours, thanks to which there occured stabilization and equalization of flour's temperature and humidity in the whole volume; besides, at least once in 24 hours, flour's homogenization and aeration, through pouring it inside closed container for about 1 min, was done. Pouring of the material in a closed container was also done for 0.5 min., prior to taking samples of each type of flour for measurements from the containers.

Distilled water. Stock of distilled water necessary for measurements within one day was kept in a closed vessel in the air washer. The amount of water determined on the basis of water absorbability (for 30 g of flour) was decreased by 5 ml and added directly to the dough-kneading machine's trough.

Brine. In order to make it easier to dose salt, saline solution in distilled water, in the proportion 0.45 g of salt and 5 ml of water, was prepared. Brine, in the amount of 5 ml per 30 g of flour, was added directly to the dough-kneading machine's trough, thus completing the specified amount of water in the dough. Necessary stock of brine (approx.1l) was stored in a closed vessel placed in the air washer.

Yeast, enhancing agent AKO. Due to their small amounts, both ingredients were added directly to flour in the kneading machine's trough as the ambient temperature (usually about 20°C).

3.4. Measurements of water absorbability of flour

Water absorbability of flour is a quantity of fundamental importance for physical and technological parameters of dough made. The amount of water absorbed by flour, apart from an impact on dough properties, also has economic significance (the amount of water has a marked influence on the dough mass).
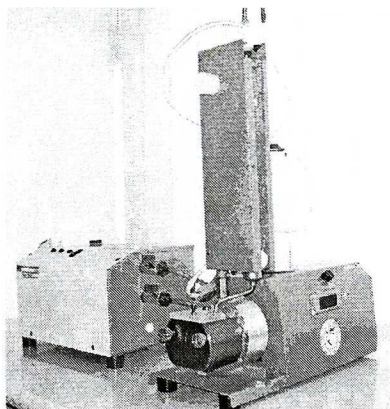
Fig. 3. Set for measurement of water absorbability SZ – 1

Table 2.

Measurements of water absorbability of flour

Type of flour	Ambient temp./humidity T_o/H_o [°C/%]	Temp./humidity of flour T/H [°C]	Measurement temp. [°C]	Average water absorbability for 500 consistographic units [%]	Amount of distilled water [ml]	Amount of salty water [ml]
P500	19.5/20.3	30.1/59.1	30	61.58	18.47	18.11
P750	21/20.2	30.1/59.8	30	64.1	19.23	18.84
M70	20.5/26.9	30.1/60.1	30	61.2	18.36	17.99
M50	19.7/19.3	30.1/61	30	60.33	18.10	17.74
Ż720	19/17	29.9/60	30	58.6	17.58	17.23

Determined in the set SZ – 1 (Fig. 3), water absorbability of flour corresponds to such an amount of added water for which the dough consistence is optimal, i.e. has 500 consistographic units or corresponding to them 500 Brabender units.

Based on the measurements of flour's water absorbability, it is possible to determine the amounts of particular ingredients for the measured sample of 30 g of examined type of dough. Table 2 presents the results of water absorbability of flour (amount of distilled water and salty water – calculated), averaged for five measurements in relation to the measured sample.

3.5. Preparation of dough for measuring samples

The dough was prepared with the use of equipment shown in Fig. 4. Two kinds of dough prepared for each type of flour were accepted for measurements:

- dough type "O"; ingredients: flour and distilled water,
- dough type "D"; ingredients: flour, salty water, yeast, enhancing agent AKO.

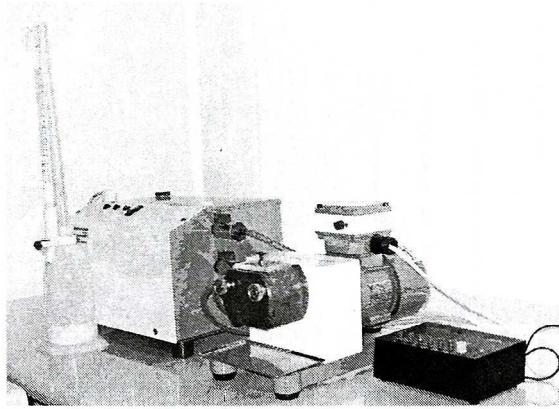Fig. 4. Set for preparing dough samples Laboratory dough-kneading machine MML – 25, thermostat with a constant setting, burette, signaling clock

Dough type"O":

1) Take out the handling vessel containing flour suitable for a particular type of dough from the air washer. Close the container and pour the contents inside, thus mixing and aerating flour, for about 0.5 min.
2) Take out of the container and weigh 30 g of flour putting it on pre-prepared paperboard tray. Put back the open handling container into the air washer.
3) Pour the weighed sample into the dough-kneading machine's trough, close the lid and start the machine. Flour's mixing, aeration and equalization of temperature takes 3 minutes.
4) After elapse of mixing times measured by the clock with sound signal, add distilled water from burette's feeder to the working chamber of the kneading machine in the amount as prescribed for particular prepared type of dough.
5) Then, dough kneading should take 5 minutes. When kneading is complete, the laboratory clock with signal set for 30 minutes goes off. After that time, the measurements of dough non-Newtonian viscosity will start.
6) The prepared dough is now taken out of the kneader with the components of the chamber disassembly at the same time. The dough is placed on a paperboard tray and immediately it is put in the measuring test-tube up to certain level, using 25 g of dough, with a glass rod (the biggest available).

Dough type"D":

Preparation of dough type "D", containing apart from flour other ingredients than those used in the case of the dough type "O", demonstrates differences in the procedure, described above:

2) After preparation of sample of suitable type of flour, adequate amounts of yeast and enhancing agent AKO Plus are weighed.
3) Portions of yeast and enhancing agent are poured into prepared flour sample, and then are poured together into the kneader's chamber.
4) After elapse of time for mixing the flour with additions (measured by sound-signal clock), a suitable amount of distilled water from burette and brine dosed manually with pipette are added to the kneader's working chamber.

The remaining actions from other points are the same as those for the dough type "O".

Table 3 presents the contents of ingredients for particular types of dough made at the temperature of 30°C and mass and density of dough.

Table 3.

Types of dough and ingredients /at temp. of 30°C

No	Type of dough /type of flour/	Amount of ingredient					Amount of dough [g]	Average dough density [g/cm^3]
		Flour [g]	Water brine [ml]	Salt [g]	Enhancing agent AKO [g]	Yeast instant [g]		
1	OP500 /100% P500/	30	18.1	0.45	–	–	48.55	1.179
2	OP750 /100% P750/	30	18.85	0.45	–	–	49.30	1.167
3	OM70 /70% P750 + 30%Ż720/	30	17.99	0.45	–	–	48.44	1.150
4	OM50 /50% P750 + 50% Ż720/	30	17.74	0.45	–	–	48.19	1.134
5	DP500 /100% P500/	30	18.1	0.45	0.6	0.252	49.4	1.145
6	DP750 /100% P750/	30	18.85	0.45	0.6	0.252	50.15	1.166
7	DM70 /70% P750 + 30% Ż720/	30	17.99	0.45	0.6	0.252	49.29	1.145
8	DM50 /50% P750 + 50% Ż720/	30	17.74	0.45	0.6	0.252	49.04	1.118

3.6. Procedure for measuring dough rheological properties

The measurements of non-Newtonian viscosity (apparent, substitute) are conducted indirectly through the measurement of the falling time of the ball at the measuring plunger in the test-tube containing dough after release of the cam blocking the lever with load – constant or changing. During every measurement, the falling time of the ball for the distance of 15 mm and 30 mm is measured with timer (with two hands). The starting and ending times are registered for each measurement. After completing every measurement of falling time of the ball, the measuring plunger with the ball should be retracted to its initial (upper) position and a break of at least 3 minutes should be made for dough relaxation. After that time, another measurement of the falling time of the ball is conducted for the same dough sample again. 12 subsequent measurements with 6–9 minute intervals are conducted for each dough sample.

The measurements were taken for two load cases:
– for steady load (M = const), in a series of (12) subsequent measurements,
– for changing load (M), during each consecutive measurement in a series of (12) subsequent measurements, the load was changed every 10 G/cm^2, 16 measuring sessions altogether (4 types of flour, 2 types of dough – 8 types of dough, 2 cases of load). The load M should be greater than the load corresponding to initial stresses that cause start of dough flow. The value of loads on the device's scale pan was chosen (in trials) in such a way that the falling time of the plunger with the ball is long enough for conducting measurements without rushing (over 2 minutes). Also, a sufficiently long time guarantees that the flow of dough around the ball in the test-tube will have the character of a laminar flow ($R_e << R_{e\ kryt}$). The initial load M_o, while the plunger with the ball starts immersing into the test-tube with dough, is also determined by trial method (due to the difficulty in determining the starting moment for the ball motion) – the initial load M_o for examined doughs ranged 80–125. The value of the initial load (determined for each type of dough as an average of at least three measurements) was placed in the headline of the tables providing the measurements' results.

For each type of dough, 3 measurements of samples prepared as described here were conducted. The tables with measurement results present averaged results (arithmetic means) of 3 measurements of the falling time of the ball t_1 and t_2 for each dough sample and deviations from average.

3.7. Measurement results

The results of measurements for the above quantities were put in the measurement result tables (16 tables for all types of dough and load cases). For quantities, determined through measurements and calculations, diagrams were drawn, these diagrams describing correlation between such quantities defining dough properties. The correlations shown in diagrams allowed us to define model expressions for dough properties.

For both types of dough (type "O" and type "D"), one diagram was drawn presenting four curves marked with adequate numbers of tables providing data for the drawing. The curves drawn refer to the following functional relations:

– $\tau = f(\dot{\varepsilon})$; shear stress as a function of deformation rate,
– $\eta = f(t)$; non-Newtonian viscosity as a function of nondimensional time coefficient t,
– deformation rate as a function of nondimensional time coefficient t.

The introduction of the nondimensional coefficient t for the measurement time allows us to keep consistency of dimensions in correlations describing the changing course of particular curves in the diagrams. The nondimensional coefficient of measurement time t is defined by the correlation:

$$t = \frac{t_p}{t_o}, \tag{9}$$

where: t – nondimensional coefficient of measurement time,

t_p – current (present) time of measurement commencement,

t_o – reference time; duration of measurements.

The reference time was defined in relation to maximum (or approximate) value of duration of a measurement series (in an experiment in a series of 12 measurements, the maximum time equals to $t_{p\,max} = 77$ minutes), as : $t_o \geq t_{p\,max}$. On the basis of an analysis of times for particular measurement series and a condition resulting from the above correlation, it was assumed that: to = 80 minutes.

The curves of functional relations were drawn for two cases:

1) measurements within full (total) time range (t_p = max); functional relations $\tau(\dot{\varepsilon})$;

2) measurements within time range limited to approx. 30 min., being part of the full time range during which measurements were made, i.e. time which elapsed from nearest measurement after 30 minutes (t_p = ok. 30 min.); functional relations $\eta(t)$ and $\dot{\varepsilon}(t)$.

The need for two cases of the time range results from the fact that duration time for a series of 12 measurements usually exceeds 70 minutes, much more than the technological usefulness of dough (approx. 30 min.) during forming.

The course of the curves for the functional correlations between examined quantities can be described, in full range of measurements, in many cases only in the form of polynominal expressions. With the measurement time limited to approx. 30 minutes, the functional correlations, in particular viscosity and deformation rate, can be described (assuming sufficiently high correlation coefficient) with relatively simple and convenient in use exponential functions – for all types of dough and load cases.

For each curve drawn, a regression equation was formulated along with corresponding determination coefficients marked in the diagram as R^2 (square of the correlation coefficient). The type of curve was adopted (with the use of computer software) in such a way that the determination coefficient was closest to one.

The equations describing the changing course of particular quantities in diagrams were provided for:

– correlation $\tau(\dot{\varepsilon})$ in full measurement time range; power function,
– correlation $\eta(t)$ and $\dot{\varepsilon}(t)$ in a measurement time range limited to approx. 30 min.; exponential function.
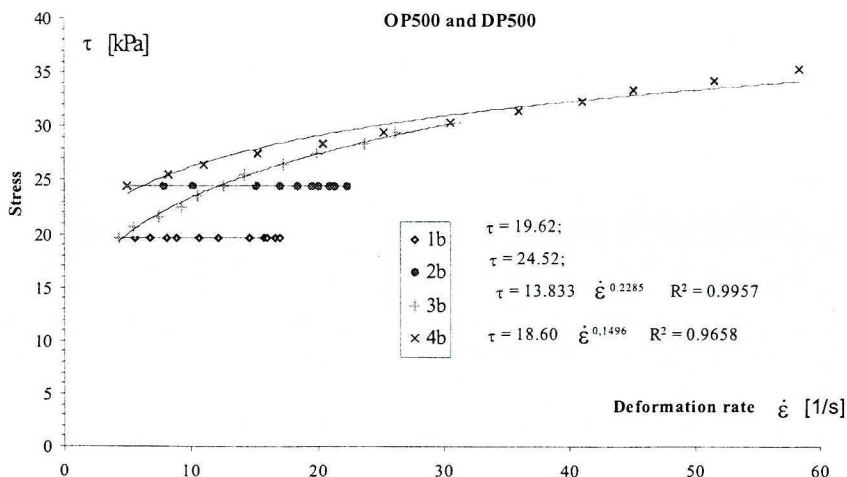

Fig. 5. Correlation between stress τ and deformation rate $\dot{\varepsilon}$ and equations for the course of the correlations for the following cases:

– Tab. 1b, OP500, M = const; Tab. 2b, DP500, M = const,

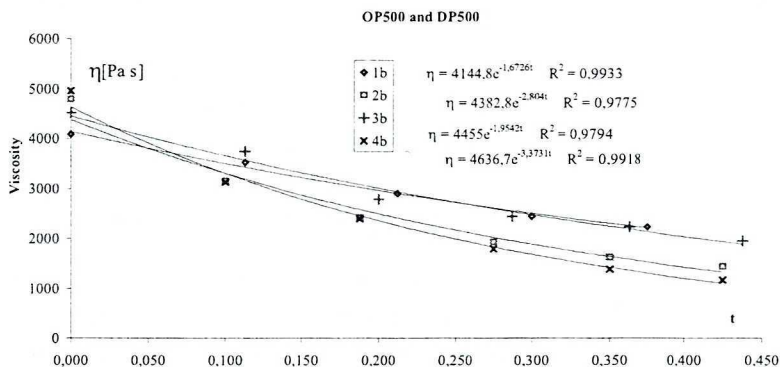– Tab. 3b, OP500, M ≠ const; Tab. 4b, DP500, M const

Fig. 6. Correlation between viscosity η and nondimensional coefficient of time t and equations for the course of these correlations for the cases:
– Tab. 1b, OP500, M = const; Tab. 2b, DP500, M = const,
– Tab. 3b, OP500, M ≠ const; Tab. 4b, DP500, M const

The type of curves (power and exponential function) were chosen due to their simplicity and convenience, bearing in mind the fact that these functions allow one to approximate (through R^2 value) the distribution of experiment results.

To illustrate the obtained correlations between quantities describing the rheological properties of examined doughs, diagrams, based on obtained measurement results, with curves modeling properties of examined dough (Fig. 5–7) were provided for dough OP500 and DP500.
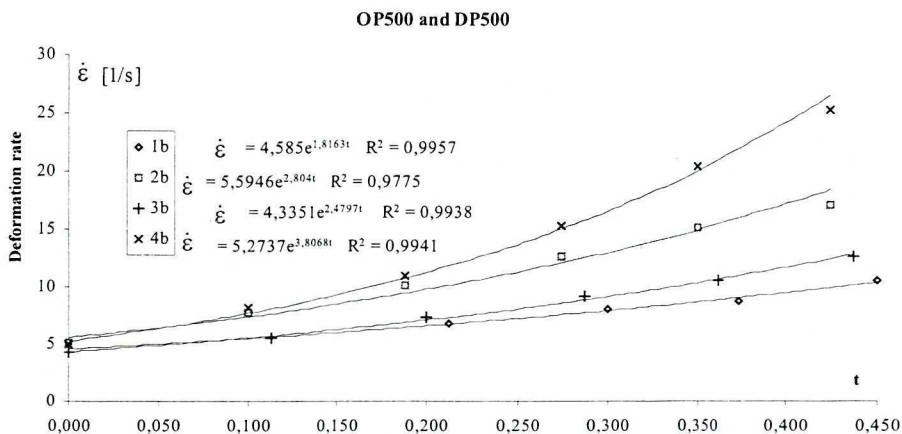

Fig. 7. Correlation between deformation rate $\dot{\varepsilon}$ and nondimensional coefficient of time t and equations for the course of these correlations for the cases:
– Tab. 1b, OP500, M = const; Tab. 2b, DP500, M = const,
– Tab. 3b, OP500, M ≠ const; Tab. 4b, DP500, M const

In these diagrams, for corresponding curves, mathematical expressions mod-
eling the dough properties were provided. The character of change of the
curves and the mathematical relations describing them are similar in all types
of dough, therefore the measurement results and the course of corresponding
curves can be considered representative.

3.8. Analysis of measuring uncertainties

The values of measured physical properties are burdened with measuring
uncertainty (measuring error), defined theoretically as the difference between
the measured value and the real value. In practice, the measuring uncertainty
can be determined by the deviation (difference) of an individual measurement
value from the average value of measurements [11].

The measuring uncertainty is formed by uncertainties (deviations, errors)
of systematic character (device accuracy, maximum uncertainty) and random
character (bigger than systematic uncertainty). In the considered measure-
ments (of the ball falling time), random uncertainties, differentiating the
results of measurements under the same conditions, are incidental and are,
in particular, caused by:
- changeability of properties of examined material (rheological properties);
  e.g. biological activity of dough – release of fermentation gas bubbles,
  deviations in dough preparation time, deviations in amount of dough
  ingredients,
- influence of deformations and stresses history as a result of conducted
  measurements,
- influence of measuring conditions; e.g. temperature, humidity of ingredi-
  ents, inaccurate filling of test-tube,
- influence of the method of conducting measurements; e.g. impact of
  equipment properties, influence of senses determining the readings of
  the devices.

Due to the incidental character of random uncertainties, it is necessary
to make use of the instruments of mathematical statistics and probability
mathematics in determining their values for conducted measurements [11].

For the prepared results of measurements, the following measured times
and corresponding to them deviations from the mean values were used:
1) – halfway falling time t1 - falling time of the ball halfway through the
     distance of 30 mm, i.e. 15 mm, determined as average of $n_1 = 3$
     measurements,
   – deviation from the mean value δ_{1i},
2) – total falling time t_2 – falling time of the ball through the distance of
     30 mm, determined as average of $n_2 = 3$ measurements,
   – deviation from the mean value δ_{2j},

3) – average falling time t_s – determined as an arithmetical average of the times: halfway $2t_1$ and total t_2,
  – deviation from the mean value δ_k.

To determine the measuring uncertainty, the relation for standard deviation with a very small number of measurements was used, i.e. $3 < n < 30$ in the following form:

$$\sigma = \sqrt{\frac{1}{n(n-1)} \sum_{i=1}^{n} \delta_i^2}, \tag{10}$$

or

$$\sigma = \frac{1}{\sqrt{n}} \sigma_n, \tag{11}$$

where for a normal distribution, δ_n is a standard deviation for a number of measurements falling within the range of: $10 < n < 30$, thus:

$$\sigma_n = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} \delta_i^2}. \tag{12}$$

In order to obtain a similar certainty as with a big number of measurements with normal distribution, in case of a very small number of measurements of determined quantity, the Student's probability distribution function is used – standard deviation in the Student's probability distribution approaches the deviation value of the normal distribution. The following correlation exists between the standard deviations of the Student's and normal distributions:

$$\sigma_t = b_{n,\alpha} \sigma_n \tag{13}$$

or

$$\sigma_t = b_{n,\alpha} \sigma, \tag{14}$$

where: δ_t – standard deviation in the Student's distribution, $b_{n,\alpha}$ – correction coefficient, critical value of probability distribution (probability of obtaining value b bigger than the critical is equal to the significance level α).
The critical value can be defined as follows:

$$b_{n,\alpha} = \frac{\delta}{\sigma_n} \sqrt{n} = \frac{\delta}{\sigma}, \tag{15}$$

where: δ – average deviation, arithmetic average of moduluses of deviation δ_i from the average value.

The following relation defines average deviation of measurements:

$$\delta = \frac{1}{n} \sum_{i=1}^{n} |\delta_i| \quad \text{for} \quad i = 1, 2, \ldots n. \tag{16}$$

Table 4.

Values range for the significance level α

No.	Type of dough	Length of axis of absolute time coordinates	Value range of coefficient $b_{n,\alpha}$ min/max		Value of significance level α max/min [%]	
		t	M = const	M ≠ const	M = const	M ≠ const
1	OP 500	max.	1.9267/2.1039	1.9687/2.1073	11.75/8.3	11/8.1
		ok. 30'	1.9382/2.1039	1.9687/2.0972	11.4/8.3	11/8.5
2	DP500	max.	1.7882/2.0843	2.0342/2.1037	14/8.75	9.7/8.2
		ok. 30'	1.8761/2.0843	2.065/2.1037	13/8.75	9.1/8.2
3	OP750	max.	1.5202/2.0741	1.6707/2.084	19.2/8.95	16.5/8.75
		ok. 30'	1.5202/2.0741	1.7619/2.049	19.2/8.95	14.5/8.15
4	DP750	max.	1.797/2.1005	1.7315/2.055	14/8.25	15/9.2
		ok. 30'	1.9517/2.1005	1.9119/2.055	11.1/8.25	10.2/9.2
5	OM70	max.	1.8151/2.1057	1.8439/2.0973	13.7/8.2	13/8.5
		ok. 30'	1.8151/2.1057	1.9011/2.0467	13.7/8.2	12/9.4
6	DM70	max.	1.7742/2.0592	1.9161/2.1043	14.5/8.25	11.6/8.2
		ok. 30'	1.9877/2.0592	1.9368/2.094	10.4/8.25	11.4/8.6
7	OM50	max.	1.9626/2.0849	1.9483/2.1014	11/8.75	11.2/8.25
		ok. 30'	2.0243/2.0849	1.9483/2.1014	9.8/8.75	11.2/8.25
8	DM50	max.	1.9269/2.0964	1.8755/2.0928	11.75/8.5	12.5/8.5
		ok. 30'	1.9979/2.0748	1.9674/2.0928	10.3/8.95	10.6/8.6

By determining the correction coefficient for a known number of measurements (thus for a known value of the number of degrees of freedom), it becomes possible to determine, with the help of the Student's distribution tables, the significance level α or the limits of its values. Knowing the significance level, it is possible to determine the confidence interval, defining the probability that the measurements conducted are falling within the limits of the confidence interval, which is described by the relation:

$$\Delta = (1 - \alpha) 100\%. \tag{17}$$

For the determined values of the Student's correction coefficient, using the distribution tables, a numerical value of the significance level α (Table 4) was determined for both load cases and for two ranges of measurement times:

- range for a time corresponding to the last measurement from the series of 12 measurements (maximum time),
- range for a time corresponding to the measurement closest to a measurement over 30 min. of measuring (time of approx. 30 min.).

Based on an analysis of values of the Student's correction coefficient in Table 4 and the value of the significance level for conducted measurements, it results that:

- for measurement time up to maximum value and steady load, the maximum value of the significance level α (apart from one case, i.e. 19.2% for dough OP750) does not exceed 15%, therefore the confidence interval equals to 85%.
- for measurement time up to maximum value and changing load, the maximum value of the significance level α (apart from one case, i.e. 16.5% for dough OP750) does not exceed 15% either, which corresponds to the confidence interval of over 85%.
- for measurement time up to approx. 30 min., and for both load cases, the maximum value of the significance level α (apart from one case, i.e. 16.5% for dough OP750, for $M \neq const$) does not exceed the value of 15%, which corresponds to the confidence interval of over 85%.

For the considered case of measurements, i.e. for average falling time, based on the relations (10) and (14), the following expression for the standard deviation of the average value results:

$$\sigma_t = b_{n,\alpha} \sqrt{\frac{1}{n(n-1)} \sum_{k=1}^{n} \delta_k^2}, \quad \text{for} \quad k = 1, 2, \ldots n; \; n = 6. \qquad (18)$$

The determined values of the measuring uncertainties for quantities related to measurements of falling time of the ball in test-tube filled with dough (values of direct measured quantities) make it possible to determine adequate values of measuring uncertainties for the derived quantities (intermediate measuring quantities). The measuring uncertainty for non-Newtonian viscosity may be determined in the form of standard deviation with the use of adequate values of the standard deviation for the average falling time of the ball as:

$$\sigma_s = 10^{-3} M K \sigma_t. \qquad (19)$$

Knowing the absolute value of the standard deviation for viscosity, it is possible to determine the relative value of the deviation in the following form:

$$\sigma_w = \frac{\sigma_s}{\eta} 100\%. \tag{20}$$

Corresponding to the measured direct values, the values of measuring uncertainties σ, δ, σ_t, $b_{n,\alpha}$ were presented in the measurement results tables. An analysis of the values of measuring uncertainties, especially of the relative standard deviation, allows declaring that, apart from one case (i.e. $\sigma_w = 12.2\%$ dough OP500), the relative deviation does not exceed 8.8%, which in technical and scientific applications, and in relation to such material as dough, is a satisfactory value.

3.9. Analysis of obtained expressions modeling the dough properties

Functional expression $\eta(t)$

For time range for measurements limited to approx. 30 min., the curve of correlations $\eta(t)$, for all types of dough and loads, is described by an exponential function placed in the diagram for any curve, in a general form:

$$\eta = \eta_0 e^{-\frac{1}{n}t} = \eta_0 \exp\left(-\frac{1}{n}t\right), \tag{21}$$

where: η_0 – initial viscosity of material, for $t_p = 0$,

$\quad\quad$ t – nondimensional coefficient of measurement time

$\quad\quad$ n – index of the power, $\left(\frac{1}{n} = 0.0126 - 0.0422\right)$.

The determination coefficient assumes values from $R^2_{min} = 0.9545$, (OP and DP750) to $R^2_{max} = 0.9987$, (OM and DM70).

Functional expression $\dot{\varepsilon}(t)$

For measurement time limited to approx. 30 min., the curve of functional correlation $\dot{\varepsilon}(t)$, for all types of dough and loads, can be described by an exponential function in a general form:

$$\dot{\varepsilon}(t) = \dot{\varepsilon}_0 e^{\frac{1}{w}t} = \dot{\varepsilon}_0 \exp\left(\frac{1}{w}t\right), \tag{22}$$

where: $\dot{\varepsilon}_0$ – coefficient of deformation rate, for $t_p = 0$,

$\quad\quad$ t – nondimensional coefficient of measurement time,

$\quad\quad$ w – index of the power ($1/w = 0.0162 - 0.0476$).

The range of values for the determination coefficient is from $R^2_{min} = 0.9547$ (OP and DP750) to $R^2_{max} = 0.9986$ (OM and DM70).

Functional expression $\tau(\dot{\varepsilon})$

The correlation $\tau(\dot{\varepsilon})$ in diagram (Fig. 2) is presented only in full range of the time range of the measurements conducted, which corresponds to the value of nondimensional coefficient of measurement time t nearing one. For all types of dough and both types of loads, the course of the correlation $\tau(\dot{\varepsilon})$ has identical character – identical general mathematical form – power-type correlation:

$$\tau = \tau_p + \eta \dot{\varepsilon}^{\frac{1}{m}} \tag{23}$$

where: τ_p – limiting shear stress, flow limit,

$\qquad \eta$ – non-Newtonian viscosity,

$\qquad \dot{\varepsilon}$ – deformation rate,

$\qquad$ m – indexes of the power ($1/m = 0.1496 - 0.2285$).

For a steady load (M = const), the above correlations are reduced to the form (as shown in the diagrams):

$$\tau = const \tag{24}$$

The form of the correlation (23) corresponds in the mathematical form to the Herschel-Bulkley model expression for arguments independent of time. The arguments present in correlation (23) η and $\dot{\varepsilon}$ are functions of time, which results in that in the general case also the stress τ is a function of time (its nondimensional coefficient t):

$$\tau = f(\eta, \dot{\varepsilon}, t). \tag{25}$$

For measurement time range of approx. 30 min., for which the expression (23) was determined, after substituting the correlations (21) and (22) for it, it follows:

$$\tau = \tau_p + \eta_o \dot{\varepsilon}_o^{\frac{1}{m}} e^{\left(\frac{1}{m}\frac{1}{w} - \frac{1}{n}\right)t}, \tag{26}$$

or

$$\tau = \tau_p + \eta_o \dot{\varepsilon}_o^{\frac{1}{m}} \exp\left[\left(\frac{1}{m}\frac{1}{w} - \frac{1}{n}\right)t\right]. \tag{27}$$

The value of the indexes and initial coefficients $\left(\tau_p, \eta_o, \dot{\varepsilon}_o\right)$ for particular types of curves corresponding to the types of doughs and the types of loads, were provided in the correlations describing the curves in the diagrams.

Additionally, the values of these coefficients are collected in Table 5. From analysis of the values of the indexes and initial quantities from Table 5, it stems that the change of these values is contained in the following range:

$$\frac{1}{m} \in (0.1496 - 0.2285); \qquad \eta_o \in (3385 - 5482); \qquad Pa\ s,$$

$$\frac{1}{w} \in (1.2999 - 3.8068); \qquad \dot{\varepsilon}_o \in (4.3351 - 7.2357); \quad 1/s,$$

$$\frac{1}{n} \in (-3.3731 - -1.3001); \qquad \tau_p \in (7.85 - 12.26); \qquad kPa.$$

Nondimensional coefficient of measurement time t: $\tau \in (0 - 0.4375)$.

Table 5.

Values of indexes and initial quantities in correlations modeling rheological properties

Type of dough	Curve marking	Index			Initial viscosity η_o	Initial deformation on rate $\dot{\varepsilon}_o$	Initial load and stress M_o/τ_o
		1/m	1/n	1/w			
		[–]	[–]	[–]	[Pa s]	[1/s]	[kPa]
OP500	1b	–	-1.6726	1.8163	4144.8	4.6206	90/8.83
	3b	0.2285	-1.9542	2.4797	4455	4.3351	100/9.81
DP500	2b	–	-2.804	2.8040	4382.8	5.5946	115/11.28
	4b	0.1496	-3.3731	3.8068	4636.7	5.2737	120/11.77
OP750	5b	–	-2.1126	2.1124	3599.1	5.4515	80/7.85
	7b	0.2183	-2.5932	3.1016	3829.2	5.1209	80/7.85
DP750	6b	–	-2.3087	2.3097	3622.7	6.7692	100/9.81
	8b	0.1818	-2.4894	2.9505	3384.9	7.2357	90/8.83
OM70	9b	–	-1.5803	1.5803	4532.2	5.4101	115/11.28
	11b	0.1927	-2.3166	2.7468	5054.7	4.8397	120/11.77
DM70	10b	–	-1.6614	1.6614	5286.2	4.6384	125/12.26
	12b	0.1861	-1.8172	2.1880	5482	4.4778	125/12.26
OM50	13b	–	-1.3001	1.2999	5399	4.5418	125/12.26
	15b	0.2128	-2.0092	2.4327	5182.1	4.7086	125/12.26
DM50	14b	–	-1.3602	1.3601	5337.3	4.5941	115/11.28
	16b	0.1958	-1.9258	2.3108	5384.5	4.5441	115/11.28

The correlation (26) may thus be formulated as follows:

$$\tau = \tau_p + \tau_o e^{\frac{t}{\lambda}}, \tag{28}$$

where, respectively, are definitions:
– characteristic, initial, stress for the fluid model; having the character of power-type expression

$$\tau_o = \eta_o \dot{\varepsilon}_o^{\frac{1}{m}}, \tag{29}$$

– nondimensional substitute index of the power

$$\frac{1}{\lambda} = \left(\frac{1}{m}\frac{1}{w} - \frac{1}{n}\right). \tag{30}$$

Since the expression (28) is a function of time, the level of influence of time on the description of the material deformation should be estimated using the Debora number [6] as follows:

$$De = \frac{t_m}{t_{pr}}, \tag{31}$$

where: t_m – time characteristic of flowing material,
$\qquad$ t_{pr} – time characteristic of the flow process.
The application of the above criterion is related to allowing for the so-called viscosimetric functions – N_1, N_2, N_3, describing the normal components of the stress tensor.

$\qquad$ Generally, in many technical problems, it is enough to assume for time t_m the value of time constant in an appropriate model equation of fluid. Estimated value range of time t_m can be determined from the relation:

$$t_m \approx \frac{N_1}{\tau \cdot \dot{\varepsilon}}. \tag{32}$$

Estimated time characteristic of the flow process t_{pr}, can be defined from the relation:

$$t_{pr} \approx \frac{L_c}{v_c}, \tag{33}$$

where: L_c – characteristic linear value in the flowing direction,
$\qquad$ v_c – characteristic flow rate (e.g. deformation rate).
$\qquad$ For the values of measured quantities occurring in empirical determination of the rheological properties of dough, i.e.:

$$t_{pr} \approx \frac{L_c}{v_c} \approx \frac{L_c}{\dot{\varepsilon}} \approx 0.15s; \quad \text{and} \quad N_1 \approx \tau; \quad \dot{\varepsilon} \approx 5s; \tag{34}$$

it is possible to determine the time quantity t_m:

$$t_m = \frac{N_1}{\tau \cdot \dot{\varepsilon}} \cong \frac{1}{\dot{\varepsilon}} \cong 0.2s, \tag{35}$$

thus the Debora number will equal to:

$$De = \frac{t_m}{t_{pr}} \cong 1.33. \tag{36}$$

The value of the De number cannot be treated as small enough, since both characteristic times t_m and t_{pr} are comparable and, as a consequence, we cannot disregard the memory effects of the process of dough deformation. This leads to taking into account the nondimensional coefficient of measurement time t in the rheological correlations (21, 22, 26).

4. Conclusions

The results of experiments presented in this study refer to rheological values of examined doughs to the extent the dough is technologically suitable for forming – i.e. up to approx. 35 minutes of making (kneading). The measurements were conducted for 8 types of dough made of 4 types of flour (two wheat types and two mixed ones).

The results of the measurements were discussed in order to determine the values of the measuring uncertainties, which were placed in Tables. Further, the significance level and confidence interval for the obtained results were determined and presented.

The results obtained were prepared in the form of tables and diagrams (due to the scope of material not presented in the paper) – as representative enough were provided diagrams for dough OP500 and DP500. As a result of analysis of diagrams presenting correlations between particular quantities, one common universal mathematical formula modeling the rheological properties of examined doughs was defined. The defined model formula incorporates the relation of particular quantities with time (nondimensional coefficient of time t).

The mathematical model of dough properties can (after presenting in a suitable coordinate system) be applied to a scientific description of the process of forming (spherical and cylindrical forming) of dough pieces.

A simple and convenient form of the model expression makes it possible to use the expression in descriptions of technical applications (e.g. in the construction of dough-piece forming machines).

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Właściwości reologiczne ciasta

Streszczenie

W opracowaniu przedstawiono ogólnie właściwości ciasta w zakresie odpowiadającym czasowi jego technologicznej przydatności (tj. do ok. 30 min.). Badaniom eksperymentalnym poddano 8 rodzajów ciasta sporządzonego z 4 rodzajów mąki. W trakcie badań ciasta, traktowanego jako płyn nienewtonowski, wyznaczono jego lepkość strukturalną (pozorną) oraz określono relacje dla pozostałych wielkości reologicznych. Wyniki badań przedstawiono w postaci wykresów pokazujących przebieg poszczególnych wielkości oraz zależności modelowe dla badanych ciast. Zależności te wykorzystano do określenia jednego ogólnego wyrażenia modelującego właściwości reologiczne badanych ciast.