MECHANICAL PROPERTIES OF GRANULAR AGRO-MATERIALS AND FOOD POWDERS FOR INDUSTRIAL PRACTICE

Part II

Material properties in grinding and agglomeration

Janusz Laskowski, Grzegorz Łysiak, Stanisław Skonecki

Edited by
Józef Horabik, Janusz Laskowski

Centre of Excellence for Applied Physics in Sustainable Agriculture AGROPHYSICS

Institute of Agrophysics Polish Academy of Sciences

Agricultural University of Lublin

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PREFACE

In recent decades granular materials have gained great interest of both industrial specialists and researchers. Growing competition on the global market, combined with an increase in the scale of operations, enforced producers to use raw materials and final products in granular form that is relatively easy for storage, handling and processing. On the other hand, after fairly complete description of solid, liquid and gaseous states of matter, scientists turned their attention to granular materials. With their unique behaviour, some researchers postulate to consider this group of materials as a separate state of matter. Research and technology developments made from the sixties of the twentieth century resulted in a substantial progress in science and technology in the field.

This work deals with some aspects of the mechanics of granular materials. It is focused on the materials of biological origin used in agro and food technology. The main features of agro and food materials that make them different from mineral materials are strong influence of moisture content on mechanical behaviour and high deformability of granules. These differences bring about certain peculiar behaviours and necessity of adjustments of models of material, experimental techniques and technological solutions.

While presenting this book, our purpose was to focus attention of the reader on what we believe is important for understanding of the mechanical behaviour of granular materials of biological origin. Selection of the presented material was based on direct professional experience of the authors. The main theoretical approaches – from the origins of soil mechanics to micropolar theory and DEM modelling have been addressed. A review of commonly applied experimental methods and material parameters has been presented. Finally, a catalogue of material parameters drawn from laboratory testing of the authors was attached for reference as well as for comparison with results of other laboratories. This “Mechanical Properties of Granular Agro- Materials and Food Powders for Industrial Practice” is composed of two volumes. Part I presents mainly issues relevant for storage and handling, while Part II addresses questions of grinding and agglomeration.

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Authors

1. INTRODUCTION

Physical properties of materials of biological origin influence in great measure equipment and process design as well as processing conditions. The appropriate knowledge and understanding the way they influence the processing course and efficiency, interactions with product quality factors, is necessary for the right selection of processing equipment, process conditions and parameters, process and quality control procedures, and many others present in daily engineering practice.

Comminution is an operation of great importance and one of the most frequent in human activity. Energy, mass, and heat transport and transformations, as physical processes inherent in mixing, drying, pelleting and other manufacturing operations, are crucial for every technology, and conditioned by properties of particles composing a powder, e.g., size, shape, distribution, etc. Simple product's properties as well as modern product engineering depend on comminution results. A large quantity of ground biological materials within their wide diversity of composition, structure, physical and chemical condition, involves special and often unique processing equipment to be used. As the consequence, an indication of the most relevant criteria among material properties to the course of a specific process is still demanding. For years, many research centres have been engaged in activities for discovering areas for better understanding of phenomena occurring in the process of grinding.

A review of literature allows it to be pointed out, that the agglomeration ability of feed materials is not a frequent research interest. There is a lack of research works, where a rather comprehensive analysis and employing various materials would be undertaken. Moreover, research reports dealing with the influence of physical and chemical properties of a specific material on its behaviour during distinct agglomeration stages are missing.

A wide-ranging analysis of the agglomeration technology (compaction, extrusion, pelleting) of biological powdery materials showed process parameters as well as the material ability to compression were considerably depended on physical state, chemical composition, moisture, and temperature of materials processed. Mechanical and rheological properties of materials, as essential to the agglomeration, are governed by all the above. Therefore, parameters of the agglomeration process have to be related to the physical state and composition of the materials that undergo processing.

This brief preview points towards the necessity of categorization of raw feed materials according to their grinding and agglomeration ability. It is also about the importance of physical properties of materials processed to the comminution and agglomeration technology, from the selection of the most adequate processing methods, materials, operating conditions to the overall efficiency.

The determination of degree of the influence of plant materials properties on parameters of grinding, agglomeration, and their grinding and compression ability, along with the quality of final products constituted the main objective of the work. The work was done within the frame of the research project no. 5 S 306 01407.

Chapter I

MATERIAL PROPERTIES IN GRINDING

2. SELECTED ISSUES OF GRINDING RESEARCH

Comminution is a complex process and its mechanism is difficult to describe. Its magnitude, various but vital in each particular case, to every human activity area has caused that different research methods varying in complexity and accuracy, from the techniques used to the models developed, as well as technologies applied, have been introduced. Austin [2, 3] has pointed it out, that grinding theory stayed far behind industrial practice. In the processing of food and agricultural materials, technology advancement is suspected foremost to research works mainly empirical in nature, and rarely explaining the nature of phenomena involved during processing. Hence, the above warrants a development of the adequate process models within regard to properties of processed materials, process parameters, and product's quality.

Aimed at underline the magnitude of material properties to the description and analysis of the grinding process, selected issues were presented in the material-process-product relation. Interfaces occurring in the grinding process, difficulties of measurements and description as well as interpretation of some material physical properties, energy investments, and product features were shortly discussed.

2.1. Material properties

Comminution technology, from the equipment design through compliance to the processing regimes to the efficiency assessment, is determined by properties of materials processed. There are some among the material features, which should be referenced in this place, i.e.

a) mechanical properties – material reaction to the loading (e.g., hardness, brittleness, elasticity, strength),
b) rheological properties – material behaviour related to the flow and stress relaxation),
c) structure,
d) geometrical features.

Material response to mechanical loading, expressed frequently by the stress-strain relation, is particularly important to the course of grinding. It gives also a possibility to interpret it on the classical mechanic background. Profound understanding of material behaviour with the conventional distinction from elastic, plastic or viscous bodies is necessary to the successful analysis of occurring within the process phenomena. Vast and available literature on the subject of mechanical properties inclined us to this short note only. Any attempt to considering the problem of mechanical properties within its complexity in this short review would have to be too cursory.

A quantitative determination of mechanical properties and in cases when that is not directly possible an appropriate qualifying characteristic is necessary to the proper selection of grinding equipment and operating conditions. With this in mind, the first stage for the right selection of grinding conditions is profound understanding of the material properties within their relevancy to the processing and product's quality. The material's mechanical structure may indicate the character of loads resulting from acting machine, to be used to execute the process in the way expected and effectively. Generally, compression forces for brittle materials or the ones having many crack planes are reasonably used. In cases where new crack planes should be created, application of shear forces or the ones resulting from impact is more efficient. Much of plant materials possess fibrous structure, and they are not well processed by compression but well ground within impact, tensile or shear conditions [7, 43, 44]. The interpretation of interaction between the material property and the nature of forces causing fragmentation (compression, tension, shear, tearing, abrasion, impact, and the like) constitutes still an important area of research activities. This is, although, not straightforward task, because in every case the process mechanism is different.

Plant materials belong to the group of materials the most composed within their diversity of structure and chemical composition. They are living organisms, physically unstable, hence any equilibrium in the mechanical meaning of the word, cannot be found. They present variable and different responses to various mechanical and thermal effects. It is a reason that determination of mechanical properties has to deal with many difficulties from proper method selection, samples preparation, to the way that results are analysed and interpreted. Diversity of plant materials and accompanying to that variability of technology, and final products diversity strongly induce, within the research in the area of agricultural and food engineering, occurrence of unique methods, apparatus and parameters. Moreover, they not always are reflected in research works for others materials, i.e., structural materials, nor have sound fundamentals in the material science or classical mechanics.

According to Pfost, among the main materials features having significant influence on the course of grinding, hardness, brittleness, toughness, abrasiveness, thermal and chemical stability, structure along with its homogeneity, moisture, shape uniformity are the most essential [45]. In general, as stated by Brennan *et al.* [7] hard materials need more energy for grinding to be added, what is related to the longer residency time distribution in the working chamber of a machine.

Peleg [44] postulates that particle „mechanical history" and its physical properties like the mechanical ones, i.e., brittleness and strength possess a major influence on the particle fragmentation process. The above properties are not only determined by the kind of processed materials, but also others like shape, structure (chips are not brittle due to materials they are composed are not strong, but due to their shape and structure) must be respected.

Mechanical properties of cereal materials change, regarding to type, variety, maturity and many others [5, 14, 16, 26, 36, 42, 57, 58]. Different parts of cereal kernel, obviously, show dissimilar resistance to mechanical loading. Wheat coat is easily broken in a dry state. Moisture addition changes its response to mechanical loading.

Chemical composition and structure of a cereal kernel exert high influence on the grinding process. Different kernel components show distinct structural and mechanical properties. The kernel endosperm is relatively brittle, whereas the coat is much tougher, and stress values causing it rupture are 10-15 times higher than in the case of the endosperm [27]. Materials, which are difficult to fragment, are those with relatively high fat and fibre content, like oil seeds, oat, etc. Cereals are generally easy broken.

Properties of plant materials are strongly dependent on moisture content. This factor has strong influence equally on properties of an individual structural component and interaction between components of a structure, what subsequently has an important effect on its behaviour during processing. Relative simplicity of control of the moisture and influencing it by conditioning, drying, and the like, and through this inducing a change in material structure and mechanical properties make this parameter very efficient and meaningful for industry practice, and common in research works.

An increase of plant materials moisture is accompanied by some enlargement in plasticity of internal or external material structure [15, 16, 18, 19, 26, 30, 31, 53, 54, 55]. Moisture affects properties of the material's surface, making it less rough [7, 44]. In the case, as for example for a humid cereal kernel, there is a smaller probability to find spaces or planes within a particle body, which would act as stress concentrators or crack initiators [44]. This increase in plasticity, is followed by the loss of brittleness, therefore moist particles are less brittle. This consequence is strongly dependent on the material structure, moisture distribution within the particle body and many others. The increase in particle plasticity is often related to the lower rate of grinding with a lower material predisposition to create fines [7].

An increase of moisture content stimulates a rise of the cohesion forces within particle body and creation of liquid bridges. This is an important issue for inter-particle interactions as well. Fin particles may be adhered to larger ones due to the surface activity. This process leads to formation of new agglomerates. They need to be again fragmented on one side, and their lower mobility influences processes of segregation and classification on the second [44].

The occurrence of water may have negative but also positive impacts on the fragmentation process. Small amounts of water may avoid from excessive fin particles formation, which can generate explosives when mixed with air. An example of water acceptance during fragmentation is corn wet milling.

Moisture, as have being discussed, exerts in a great measure material physical properties and consequently the fragmentation process. Vast literature on the area points at increase in grinding energy requirements for higher moisture levels. Melnikow, for barley kernels of the moisture content above 14%, reports the increase of energy requirement in the range about 6% for every 1% of the increase in kernel moisture. At the same time, the decrease about 3% of the grinding rate was observed.

The increase of moisture content, for wheat grain from 10 to 18%, causes the raise of milling energy requirements of about 100% for mealy kernels and about 75% for vitreous ones. Similar trends were noticed for other cereal grains, but values were strongly dependent on vast number of factors, what had been presented in the mainstream literature. Generally, along with the moisture content, values of the grinding energy consumption related to an augmentation of the moisture increase as well. The highest changes may be observed in the range from 10 to 17%, and often the optimum limit for grinding is proposed to 14% [27]. From the economical perspective and others resulting from product requirements, i.e., separation of distinct structural components, proportion of bran in flour, grinding at both lower and higher moisture levels is frequently performed.

Although, the energy requirements according to moisture fluctuations are well documented, particle size of final product may be a subject of scientific discussion. Correspondingly, to the moisture content, various grains structural components react to the machine tool differently. A mode, intensity and time of tool reaction on a particle being fragmented are factors having obvious reflection in the product property. Some works point at similar particle size for materials largely different in moisture content. This is possible, for example, in the case when size of a final particle is strongly forced by grinder construction elements, i.e., the hammer mill screen. This has been confirmed by the Islam and Matzen, for wheat grinding in the range 8-21% of moisture content [25], and by Łysiak and Laskowski for leguminous seeds [36].

The grindability of a kernel changes with temperature. An increase of the kernels' temperature makes them more hard, involving higher brittleness and better grindability. Grinding probability may increase also at low temperatures, especially below zero in the Celsius scale [24]. Difference in particle size distribution for various temperature levels was also confirmed by Wolf and Pahl [64]. At ambient temperatures, a significant variance was not noticed.

During the comminution process, friction effects are present. Many of the particles are also stressed to the levels not exceeding material strength. In the case, the energy added is transformed to heat. This is a reason of the increase of material temperature, what can have an important influence on the process course, as well as on quality of final products.

In general, behaviour of plant materials exposed to the fragmentation is referred to the moisture in most cases, and this is consistent with industry needs and practical experience. This is, of course, related to the significance of moisture influence on processing, i.e., bran and endosperm separation in wheat milling, what is relatively well recognised, and to the empirical character of many research works.

It is worth a note, that research on physical properties within their variability characteristic for plant materials (variability of objectives, methods, standards, equipment and the like) [9, 14, 18, 22, 23, 32, 51, 56, 66, 67] give a rise to the most frequent reference of grinding parameters to material moisture [10, 13, 29, 35]. Although, it is generally known that higher material hardness is related to higher energy requirements. On the other hand, the same may be observed for the larger plasticity. The conclusion depends on conditions of particle stressing, therefore on the grinder design. Description of the process on the base of material mechanical properties like elasticity, rigidity, strength, brittleness, etc. is rather rare. Importance of the second emphasizes the dependence of mechanical properties mainly on the moisture content.

2.2. Grinding energy

Definition of grinding energy expenditure, for a better understanding of the problem of grinding efficiency, needs the three terms to be distinguished:

a) fracture energy related to unit mass, E_F, which is that actually used for particle size reduction,
b) externally applied energy per unit mass, $E_{A,}$
c) externally supplied energy to the system, E_{EX}.

The two last one are relatively easy to arrive at, but the fracture energy is much more difficult to asses. Special methods and apparatus must be adopted for.

Single particle slow compression and particle bed testing are the methods the most frequent and giving the best results. In both cases, the area under stress-strain curve up to the first breakage, or some others deformations dependently on standard applied, is proportional to fracture energy [47, 50]. For single particle breakage, of the same size and geometry, E_A is always greater than E_F. In a particle bed testing, E_A is much greater because many particles are stressed to levels below that critical for fracture. The associated energy is loss as heat. In the case frictional effect are also considerable. E_A and E_F are net applied energies, and contrary to E_{EX}, do not include mechanical and electrical drive losses.

Energy requirements may be derived when we know at least one of the tree above, but in every case very high differences must be expected. The differences are a reason of very low grinding efficiency. One measure of grinding efficiency may be expressed by the ratio E_F/E_A. or E_F/E_{EX}. Since, E_F may be obtained from uniaxial compression of a single particle it is concept present in common practice.

It is well known that grinding efficiency is far too low, despite of many efforts to reduce the energy losses. Referring fracture energy to free surface energy as present in literature, grinding efficiencies may be rated in the range 0.1 to 1% [52]. The fracture energy based on laboratory tests like the compression yields in efficiency values of 5% to 20%, so still low [47].

In spite of general agreement about the above results, the precise determination of grinding energy expenditures is still missing, and very difficult or impossible to attain. Early attempts, based on increase of material specific surface as an effect of fragmentation and theoretical free surface energy, have not given right values. One of the most contributing to this are inadequacy of methods for surface measurements and difficulties arising in measurements of energy involved in material plastic deformation [47, 60]. Therefore, grinding energy assessment should be based on the minimum energy expenditures, but not on the amount of new surface created [60].

The values justify the energy expenditure parameter, which is frequently used for process description and analysis. They are on the other hand a challenge to design engineers and grinder operators. It seems to be obvious that it is impossible to face the problems without better understanding fracture process mechanisms, clear designing process aims and possibilities for energy costs reductions, and consequently assigning clear research objectives. For that, sources of energy losses, dependent on material properties, machine design, operation and maintenance condition and the like must be identified. Because of low process efficiency and difficulties arising during fracture energy assessment for fundamental studies it is often convenient to adopt energy applied in terms of unit mass or volume. In very special circumstances only, it is possible to consider net fracture energy.

The three following, between the most frequently used methods of the grinding energy assessment have to be referred [47, 50]:

a) single-particle compression,
b) single-particle impact,
c) confined particle bed test.

Ones of the most efficient to the grinding ability determination are relatively easy to execution the experiments on individual particles. This research direction is one of most frequently used for the process interpretation.

2.3. Properties of final products

Any energy expenditure causing breakage must be related to the initial and final particle size conditions.

Characteristic particle size only very rarely may be unambiguously determined. Examples are spheres or cubes, thus the particles of regular geometry. In practice, shape of an individual particle is not regular, and hence more than one way may be applied to determine its characteristic diameter. There are, basically, three following groups of methods to determine the characteristic size:

a) size of a particle, for first group, is related to the size of an equivalent sphere that would have the same property as particle itself, such as volume, etc.
b) second group uses the diameter of a circle that would have the same property as projected outline of the particles,
c) third group is associated with a linear dimension as measured my microscope.

Measurement methods used in modern particle size analysers base on different particle physical properties (microscopy, laser diffraction, sedimentation, NIR) hence, their results are not always comparable. The differences in results of size or surface assessment are often related to particle shape, which definition is complex as well.

Quantitative comparisons of feed and ground material are most commonly based on particle size distribution or values of specific surface created. An important aspect for the right material characterisation is method of expressing of the particle distribution. There are three or four types of size distribution: by number, by length, by surface, by mass or volume. Density distribution by mass is the most frequently used method. There are additionally many average sizes which can be defined for a given size distribution. The three most important are: the mean diameter, the median and the mode.

Size distribution of fragmented particles depends on a variety of factors. Material properties, grinding methods, or time and intensity of a machine action have to be emphasised.

Heywood presented the effect of time of grind on product size distribution. His experiment shows a change from multimodal to mono-modal distribution of particles with grinding time rise [47]. In respect to that, a material description only with one average size is sometimes questioned.

Increase in specific particle surface is a common way in existing descriptions of the grinding process. Interpretation of the results due to variability of the methods used for the parameter assessment makes often-necessary comparisons difficult. Hence, one may state that direct comparisons are possible when the same methods and conditions were applied. It is necessary to note that the same value of specific surface for two quite different size distributions can be obtained [37, 40]. Moreover, the heterogeneity of structure of plant materials induces some shortcomings to be applied in every particular case.

Another way of expressing size distribution is application of mathematical functions. The most common are lognormal distribution, distributions of Rosin-Rammler-Bennett (RRB), Gaudin-Schuhmann, Gaudin-Meloy, Broadbent-Callcott or Weibull [43-48]. The „goodness of fit" is a criterion deciding the selection the most appropriate distribution in general. Some others, like in a Weibull distribution example, may be directly related to the fracture mechanism to interpret particle size changes during fragmentation. There exist also complex mathematical equations including material properties, like shape or crack planes [47].

Some measurements' difficulties, as well as the ways used for the distribution expressing and interpretation, and their meaning were shortly discussed by Laskowski and Łysiak [37, 38].

There is reasonable to state that the selection of the most adequate method fore size description must be the compromise between the model accuracy and its complexity. This implies also the necessity of development of a better approach to represent material changes during fragmentation.

2.4. Energy laws in grinding process modelling

Grinding energy and properties of feed and final products are main parameters used for the process modelling. Much research works have treated about the energy expenditure corresponding to the changes of particle size [1, 45, 49, 65]. Four main directions in the process modelling are followed. First concentrates on fracture mechanics and theories of crack initiation and propagation within a particle [17, 47, 63]. Second, since two century, deals with energy laws, describing the relation between fracture energy and particle sizes [2, 6, 29]. Third deals with relations between various parameters, e.g., machine design, process condition on energy requirements, output and efficiency, quality of products, etc., within very vast range of machine types, and materials processed [4, 12, 20, 21, 24, 28, 39,]. Finally, fourth is associated with the kinetic modelling of changes in particle size distribution, and mass flow during grinding, noted as the population balance modelling [3, 44, 61, 62].

Theoretical study postulated that the energy dE expended to the dx change of particle size might be expressed in the form of the Walker equation [1, 6, 43].

$$\frac{dE}{dx} = -\frac{K}{x^n} \tag{1}$$

where K and n are constants dependent on material properties and a grinding machine.

The above general equation, for $n = 2$, has the following form:

$$E = K(\frac{1}{x_2} - \frac{1}{x_1}) \tag{2}$$

where x_1 and x_2 are characteristic dimensions of the feed and product respectively.

This equation presents Rittinger's law, who postulated that the energy expenditure during the fragmentation process is proportional to the new surface formed. The Rittinger's law proved to be more adequate for milling processes where large increase in new surface takes place [2, 41, 43, 47].

Kick stated that for any unit mass of material the energy required to produce a reduction ratio is constant, and independent on particle size. The energy is proportional to the grinding ratio, and n in the Walker equation assumes value one. Hence:

$$\frac{dE}{dx} = -\frac{K}{x} \tag{3}$$

or $E = K \ln x_1/x_2$, where x_1/x_2 is the grinding ratio.

Contrary to the Rittinger's law, the Kik's theory better expresses crushing and grinding processes where most of the energy is absorbed for particle shattering along existing crack planes or heterogeneity [2, 41, 43, 47].

For $n = 1.5$ we obtain Bond's law, who concluded that the work input to break a particle of dimension x_1 lies between x_1^3 and x_1^2, a compromise between Rittinger and Kick. In reduction a fixed size, x_1 to a product size, x_2 the energy might be expressed as:

$$E = 2K\left(\frac{1}{\sqrt{x_2}} - \frac{1}{\sqrt{x_1}}\right) \tag{4}$$

where: $2K = 10W_i$ (Bond work index) – reflects material properties.

This equation, called „third grinding law", well describes processes of fine grinding [2, 41, 43, 47].

Another formula was presented by Hukki. According to him, Rittinger's and Kick's constants depend on particle size [1].

$$dE = K\frac{dx}{x^{f(x)}} \tag{5}$$

Charles (1957) also incorporated a variable exponent into the energy equation but in the context of the size modulus of the Schuhmann distribution plot. It has the form:

$$E = \frac{c}{(r-1)(m-r-1)}k^{1-r} \tag{6}$$

where c is a constant, m is the Schuhmann plot modulus, k is the particle size modulus, and r is the grinding ratio. The law did not find any practical application due to the presence of important shortcomings [7, 47].

Simple relationships, others than the above cited, have been advocated [8, 27, 41, 47] but the same shortcomings apply.

Review of the laws was presented by Hukki [6, 47]. He stated that no one of them find the applicability for the full range of particle sizes. More, they were found to be inadequate in practical circumstances. The shortcomings incorporated in, demand next research works to be done.

One alternative has been a pragmatic assessment of the easy and difficulty with which a material is reduced in size, i.e., its grindability [47]. Many expressions have been proposed over the years, but two have come into prominence, i.e., Hardgrove index and Bond work index. Because of specific measurement conditions, the application of the two indexes to the grinding of plant materials is not directly possible.

In summary, a development of the grinding process model reflecting the interfaces between material properties, process parameters along with product features should be supported [11].

3. PHYSICAL PROPERTIES OF MATERIALS. METHODS AND PROCEDURES DESCRIPTION

3.1. Primary physical properties

The measurement procedures described underneath were used for every case and for every material (kernel, seed or powder) when they are referred.

3.1.1. Measurement of material moisture

Material moisture was determined via the convective oven method according to the Standard PN-86/A-74011. Three glass dishes filled with 5 g samples of course ground material were placed into a universal convective oven, type SUP-4, previously re-heated to 105°C. They were being dried for 3 hours, and subsequently weighed with the accuracy 0.1 mg on an electronic balance, type Europe 60.

Wet basis moisture content (designated w in the text) is described by the percentage equivalent to the ratio of the weight of water, W_w, to the total mass of the material sample, W_t, and was determined using the following formula:

$$w = \frac{W_w}{W_t} \cdot 100\% = \frac{W_w}{W_w + W_d} \cdot 100\% \tag{7}$$

where W_d is weight of sample dry mass.

Average moisture content was calculated from three individual measurements.

To obtain the moisture levels required, the appropriate amount of water, derived from the mass balance calculations, was added to material samples, or removed by drying at 40°C temperature. Afterwards, the tightly closed samples were stored for over 48 hours at ambient temperatures.

3.1.2. Measurement of bulk density

The measurement of the bulk density of powders is so fundamental to their storage, processing and distribution that it does merit any particular consideration. The bulk density is the mass of particles that occupies a unit volume of a vessel.

Bulk density of the materials used in the research was determined according to the Standard PN-73/R-74007.

A cylindrical cup of volume V, equal to 250 cm^3 was carefully filled with a material sample through the stationary chute. The excess powder was skimmed from the top of the cup using the sharp edge knife. Weight of the material sample in the cylinder, W_s, was then determined on an electronic balance WPE 300, with the accuracy of 0.01 g. The bulk density (designated ρ_n in the text) was calculated from the equation:

$$\rho_n = \frac{W_s}{V} \tag{8}$$

Average value of the material bulk density was calculated from three repetitions.

3.1.3. Measurement of tapped density

Tapped density (also called tap bulk density or packed bulk density), as is implied by its name, is the bulk density of a powder which has been settled into a closer packing than existed in the poured state by tapping, jolting or vibrating the measuring vessel.

This parameter was determined according to the Standard PN-73/R-74007 on a Backer–Rosenmuller shaker. A material sample was placed in a scaled glass cylinder of volume equal to 500 cm^3, and then shaken for 10 minutes, at frequency of 150 per minute. After had been tapped, the volume occupied by the material, V was read out from a scale. Weight of the material sample, W_s, was then determined on an electronic balance, type WPE 300, with the accuracy of 0.01 g. The tapped density of the material (designated ρ_v in the text) was calculated in the analogous way to the bulk density. The measurements were performed in three repetitions.

3.1.4. Measurement of 1000 kernel weight

The measurements ware made according to the Standard PN-68/R-74017. Thousand randomly chosen kernels (seeds) with the help of a seed counter, type LN-3, were weighed at the accuracy of 0.01 g on a balance WPE-300. The measurements were done in three repetitions.

3.1.5. Measurement of angle of slide

The angle of slide is the minimum angle to the horizontal of a flat, inclined, surface that will allow bulk solid to flow from rest under its own weight.

A bakelite plate was steeply inclined, until majority of the material started to slide relative to the plate. The inclination angle was read out with precision to 1 deg. Average value of the angle of slide (designated α_z in the text) based on three repetitions.

3.1.6. Measurement of angle of repose

The angle of repose, a rough powder flowability indicator, is defined as the angle of the free surface of a pile of powder to the horizontal plane. In order to measure this parameter, the device presented in Figure I-1 was used.

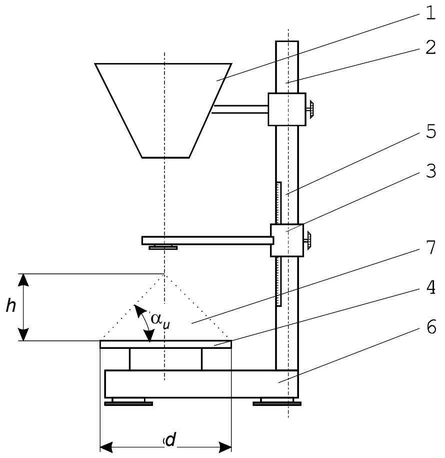

Fig. I-1. Device for the determination of angle of repose: 1 – cone chute, 2 – guide bar, 3 – positioner, 4 – steel plate of known diameter, 5 – millimeter scale, 6 – stand, 7 – material

The material was allowed to fall a constant height of 50 mm approximately through the stationary chute onto a flat steel plate of known diameter *d*. Height, *h*, of the formed pile was measured with a moving positioner. The angle of repose, α_u was determined from the following equation:

$$\alpha_u = arctg\frac{2h}{d} \tag{9}$$

The measurements were made in three replications.

3.2. Mechanical properties

3.2.1. Equipment description

Studies on the resistance characteristics were carried out using methods evaluated in the Department of Equipment Operation and Maintenance in Food Industry of the Agricultural University of Lublin. The measurements were taken on a universal testing machine Instron 4302 (Fig. I-2).

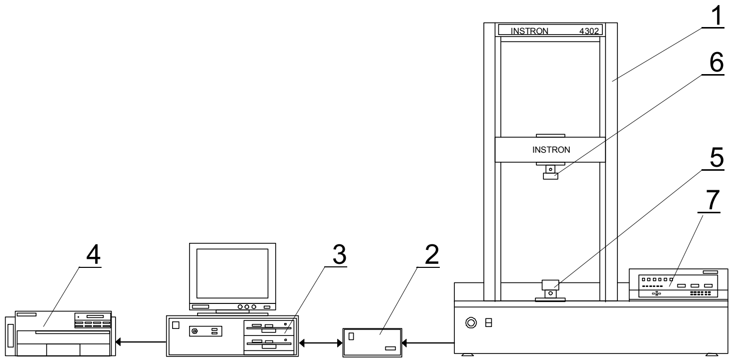

Fig. I-2. View of the device for testing of mechanical properties: 1 – universal machine Instron, 2 – analog-digital transducer, 3 – PC computer, 4 – printer, 5 – bottom plate, 6 – upper moving plate

Changes in the loading force in relation to the kernel (seed) deformation were recorded by means of a computer system with the measuring frequency of 200 Hz. Adjusted computer software, for data registration and analysis was developed in the Department.

3.2.2. Operating conditions and parameters of compression testing

Wheat, barley, rye, and four leguminous seeds were used for the compression testing (Tab. I-1).

Table I-1. List of the raw materials employed for the determination of mechanical properties

Material	Variety or cultivar
Wheat	Alkora, Delta, Gółka, Henika, Jara, Jota, Kadett, Liwilla, Omega, Ostka, Panda, Sawa, Sigma
Barley	Ars, Edgar, Klimek, Kos
Rye	Amilo, Dańkowskie Nowe, Dańkowskie Złote, Warko
Leguminous	Faba bean cv. Nadwiślański, lupine cv. Emir, pea cv. Fidelia, vetch cv. Szelejewska

The wheat cultivars originated from RZD Felin, whereas the others materials from Polish Stocking Company „Centrala Nasienna”, from Lublin. The determinations were curried out for chosen grain size features, and at distinct moisture content levels according to Table I-2.

Mechanical properties of the wheat cultivars were determined for five kernel fractions. For the others, the most favoured size fraction (with the highest mass percentage) was employed.

Table I-2. Moisture content and size fraction of the kernels (seeds) used in the compression testing

Material	Moisture (%)	Size fraction (mm)
Wheat	11; 14; 15.5; 17; 18.5	<2.25-2.7); <2.7-2.9); <2.9-3.1); <3.1-3.3); <3.3-4.0>
Barley	10; 12; 14; 16; 18	<2.5-2.9>
Rye	10; 12; 14; 16; 18	<2.3-2.7>
Faba bean	10; 12; 14; 16; 18	<7.0-7.4>
Pea	10; 12; 14; 16; 18	<5.0-5.5>
Lupine	10; 12; 14; 16; 18	<5.0-5.5>
Vetch	10; 12; 14; 16; 18	<3.4-4.0>

Individual seeds were weighted (with the accuracy of 0.1 mg) and their basic dimensions were determined, i.e., thickness, width and length (with the accuracy of 0.01 mm). They were then placed at the bottom plate of the resistance machine. The cereals kernels were situated in the position with the crease towards the bottom fixed machine plate. For the leguminous seeds, the plane splitting two seed cotyledons was approximately parallel to the loading machine plates, and perpendicular to the direction of loading. The compressive load was acting along kernel's (seed) thickness. The compression rate of 10 mm min^{-1} was adjusted. The measurements were carried out until the constant distance between the plates of 0.5 mm was achieved, according to Janiak, and Janiak and Laskowski [26, 33]. Measurements were made in 50 repetitions for each material and moisture level.

An example of the load-deformation curve (compression characteristic), recorded during an experiment was presented in Figure I-3. The values of compressive loads and corresponding to them deformations at the material rupture point (point 1; F_1, Δh_1 respectively), and at the collapse threshold (point 2; F_2, Δh_2 respectively) were determined for each individual curve.

An area under the compression curve allowed energy inputs during the compression to be established. Determined from the characteristics, strain energy up to the rupture point and overall crushing energy up to the collapse threshold were denoted L_1 and L_2 respectively. The material apparent stiffness, $tg\alpha$, was determined in the initial linear range of the compression characteristic, and expressed in N mm^{-1} unit.

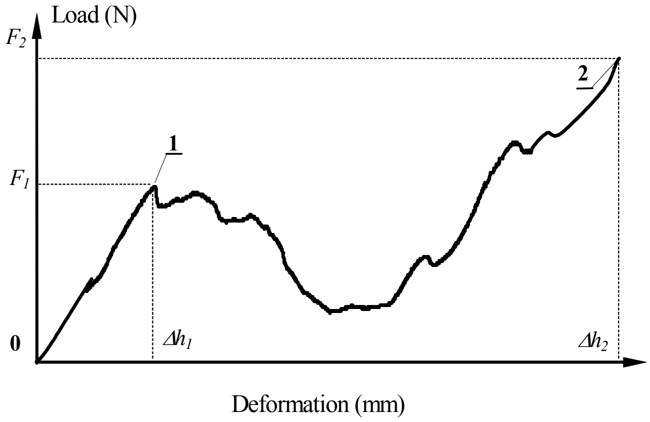

Fig. I-3. Compression curve

A list of the parameters established in the compression experiments comprises:

F_1 – force at the rupture point,

F_2 – force at the collapse threshold,

Δh_1 – kernel deformation up to the rupture point,

$tg\alpha$ – apparent stiffness (the increase in load per the increase in deformation for the linear range of the compression characteristic),

L_1 – strain energy up to the rupture point

L_2 – crushing energy up to the collapse threshold,

L_{j1} – specific strain energy up to the rupture point,

L_{j2} – specific crushing energy up to the collapse threshold.

4. GRINDING. METHODS AND PROCEDURES DESCRIPTION

4.1. Equipment description

Grinding experiments were curried out on a laboratory hammer mill, type Polymix Micro Hammermill. The grinder was equipped with a computer system that allowed grinding energy consumption to be recorded and analysed (Fig. I-4).

The hammer mill was connected to the power supply through an analogue/digital wattmeter type P7, produced by MERAZET. Signal from the analogue output of the wattmeter (in the range 0-10 V DC) was converted by a digital transducer and directed to the PC. Data recording software was developed in the Department of Equipment Operation and Maintenance in Food Industry [34].

Some characteristics of the grinder were as follows: power supply single-phase 220 V, 50 Hz; output 100 W; hammer speed 7800 RPM.

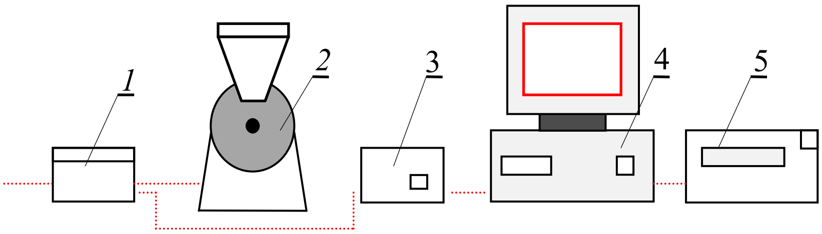

Fig. I-4. Experimental set-up for grinding tests; 1 – analogue/digital wattmeter type P7, 2 – hammer mill, 3 – analogue-digital transducer, 4 – PC computer, 5 – printer

4.2. Operating conditions and parameters of grinding

The externally supplied energy to the hammer mill, necessary to grind a material sample, was the main parameter derived from the grinding experiments. The measurement of the energy based on the electrical power requirements during one grinding test. An example of the electric power characteristic recorded in the course of one grinding experiment was presented in Figure I-5.

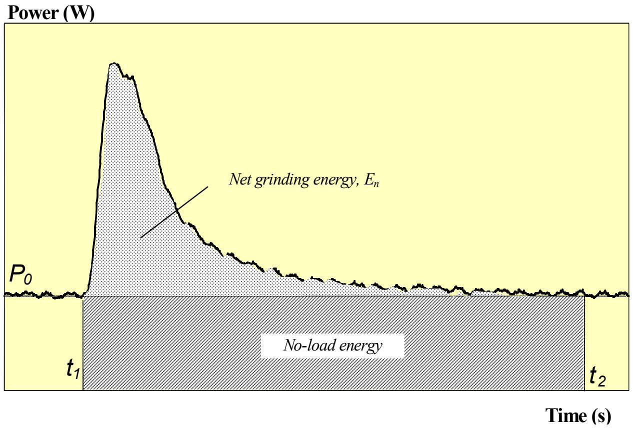

Fig. I-5. Power requirement, *P(t)* during grinding test; t_1 to t_2 – grinding time interval

In general, energy losses in the process of grinding are dependent on a vast number of factors. This also implies a difficulty in the assessment of this parameter following a non-debatable procedure. Respecting the importance of some shortcomings, the net power requirement was computed as the difference between the total power and the no-load power requirements during one grinding test; this means, electrical and drive losses were not included in the resulted grinding energy value, E_n [6]. The specific grinding energy consumption, (denoted E in the text) related to the mass of ground sample, m, was determined from the equation:

$$E = \frac{E_n}{m} \tag{10}$$

Different material moisture levels were attained as given in the experimental program, i.e., 10, 12, 14, 16, and 18%. Small batch samples of 2 g (±0.1) weight, for each material and moisture content, were ground applying three different in the hole size screens, i.e., 1, 1.5, and 2 mm diameter. Subsequently, the specific energy consumption, E, was determined according to the above described procedures. The experiments were made in 15 repetitions for each material, moisture content level, and screen mesh size applied.

The ground materials were subsequently submitted to the particle size analysis. A sieving technique was used, applying a SZ-1 apparatus produced by Zakład Badawczy Przemysłu Piekarskiego, from Bydgoszcz. The following screen apertures were employed: 0.09, 0.1, 0.12, 0.2, 0.25, 0.315, 0.4, 0.5, 0.63, 0.8, 1, 1.25, 1.6, and 2 mm.

The measurements were made for samples that had been composed of all 15-batch tests (achieved within the same conditions, i.e., material, moisture, and screen size). As a result, the sample of mass about 30 g from 15 individual tests was analysed.

Mean particle size, $d_{ś}$, was computed according to the equation:

$$d_s = \frac{\sum_{i=1}^{n} d_i P_i}{100} \tag{11}$$

where: d_i – mean diameter of particles retained on i sieve (mm), P_i – percentage by mass of particles retained on i sieve, and n number of sieves used.

5. INFLUENCE OF MATERIAL PROPERTIES ON GRINDING ENERGY

5.1. Influence of material moisture

One of the most essential properties of biological origin materials, and simultaneously demonstrating very high relevance to grinding operations, is moisture content. As have been noted before, this feature due to very important significance for practice is very frequent in many research works. One has to underline also that it is decisive to the rheological state of any biological material.

Results of the experiments carried out are presented in Tables III-32 to III-40**,** i.e., specific energy consumption and mean particle size of final products within the frame of the experimental program.

For the four cultivars of barley used in the studies, statistical analyses showed that the most adequate, and at the same time simple relation describing moisture impact on grinding energy expenditures, is a linear one. Values of equations' parameters and correlation coefficients are listed in Table I-3.

Table I-3. Regression equation to predict grinding energy consumption, E (kJ kg^{-1}), as a function of moisture, w (% w.b.), for barley cultivars

Material	Screen mesh size (mm)	Equation form	*a*	*b*	Corr. Coeff. *R*	p-value
Barley, cv. Ars	1.0	$E = aw + b$	9.29	48.56	0.927	0.00
	1.5		6.84	39.06	0.961	0.00
	2.0		4.64	40.32	0.962	0.00
Barley, cv. Edgar	1.0	$E = aw + b$	7.31	84.85	0.910	0.00
	1.5		3.74	89.06	0.908	0.00
	2.0		2.27	80.03	0.843	0.00
Barley, cv. Klimek	1.0	$E = aw + b$	9.47	72.11	0.887	0.00
	1.5		5.80	76.61	0.930	0.00
	2.0		5.33	48.64	0.905	0.00
Barley, cv. Kos	1.0	$E = aw + b$	10.22	25.67	0.936	0.00
	1.5		7.16	25.42	0.921	0.00
	2.0		4.97	26.64	0.964	0.00

Values of the parameter *a* (slope of a linear regression) decrease while the mesh screen size increases; this was confirmed by applying Tukey's procedure. Therefore, the magnitude of moisture influence on the grinding energy is more important when the grinding ratio is to be higher (smaller final particles size).

Larger amount of water and the resultant increase in the plasticity of kernel is a reason of superior energy requirements for the grinding needs. Interactive influence of cultivar, moisture, and screen size on the grinding energy was noticed. Significant differences concerning the energy requirements were also observed between the cultivars. Between them, the highest energy inputs were necessary for cv. Klimek, as oppose to cv. Kos. The lowest energy changes, associated to the increase of moisture, were observed for cv. Edgar.

The grinding experiments done on rye kernels and leguminous seeds showed, that observed energy increase in a function of the material moisture might be estimated by a polynomial equation of degree 2. The results corresponding to this are given in Tables I-4 and I-5.

Table I-4. Regression equation to predict grinding energy consumption, E (kJ kg^{-1}), as a function of moisture, w (% w.b.), for rye cultivars

Material	Screen mesh size (mm)	Equation form	*a*	*b*	*c*	Corr. coeff. *R*	p-value
Rye cv. Amilo	1.0	$E = aw^2 + bw + c$	0.33	–2.27	97.38	0.964	0.00
	1.5		0.02	–5.36	22.21	0.949	0.00
	2.0		0.05	–3.34	20.41	0.932	0.00
Rye cv. Dańkowskie Nowe	1.0	$E = aw^2 + bw + c$	–	3.02	75.24	0.852	0.00
	1.5		0.54	–10.76	128.5	0.941	0.00
	2.0		0.40	–7.42	89.75	0.956	0.00
Rye cv. Dańkowskie Złote	1.0	$E = aw^2 + bw + c$	0.36	–6.08	134.7	0.913	0.00
	1.5		0.36	–6.70	107.9	0.953	0.00
	2.0		0.50	–10.48	114.5	0.939	0.00
Rye cv. Warko	1.0	$E = aw^2 + bw + c$	0.90	–18.61	194.6	0.978	0.00
	1.5		0.83	–17.39	163.2	0.966	0.00
	2.0		0.68	–14.40	125.3	0.956	0.00

Similarly, to the previous observations, also for rye, higher changes in the grinding energy consumption relatively to the increase in material moisture are characteristic when it is being ground at smaller screen mesh size. The interfaces within the applied conditions (cultivars, moisture content, and screen size) must be also respected. Between the rye cultivars used, the highest energy inputs were required to grind cv. Amilo, and the lowest for cv. Dańkowskie Nowe.

En essence, the interfaces between material moisture and the grinding energy depend also on the kind of material in question, i.e., on its physical property. The lowest influence of the moisture content of raw materials employed in our experiments was reported for rye, and the largest for lupine. The general relationship, $E = f(w)$, has a linear character for barley and quadratic for rye and pulses.

Table I-5. Regression equation to predict grinding energy consumption, E (kJ kg^{-1}), as a function of moisture, w (% w.b.), for leguminous seeds

Material	Screen mesh size (mm)	Equation form	*a*	*b*	*c*	Corr. coeff. *R*	p-value
Faba bean cv. Nadwiślański	1.0	$E = aw^2 + bw + c$	2.92	–73.5	455.5	0.955	0.00
	1.5		3.02	–69.7	471.6	0.946	0.00
	2.0		3.13	–65.4	479.1	0.957	0.00
Pea, cv. Fidelia	1.0	$E = aw^2 + bw + c$	2.05	–45.9	374.5	0.951	0.00
	1.5		1.73	–38.9	269.1	0.948	0.00
	2.0		2.45	–58.2	331.2	0.941	0.00
Lupine, cv. Emir	1.0	$E = aw + b$	37.9	–146	–	0.926	0.00
	1.5		29.8	–151	–	0.919	0.00
	2.0		32.4	–242	–	0.919	0.00
Vetch cv. Szelejewska	1.0	$E = aw^2 + bw + c$	1.22	–23.1	172.1	0.950	0.00
	1.5		0.65	–12.6	100.9	0.949	0.00
	2.0		1.22	–27.9	183.6	0.956	0.00

Values of the mean particle size of the ground raw materials in relation to their moisture and the screen mesh size used are presented in Table I-6.

Table I-6. Particle mean size of ground raw materials, $d_{ś}$ (mm), in relation to their moisture, w (% w.b.), and screen mesh size, s (mm)

Material	Equation form	*a*	*b*	*c*	Corr. Coeff. *R*	p-value
Barley cv. Ars	$d_{ś} = aw + bs + c$	0.0021	0.182	0.144	0.995	0.00
Barley cv. Edgar		0.0031	0.178	0.149	0.993	0.00
Barley cv. Klimek		0.0013	0.183	0.180	0.990	0.00
Barley cv. Kos		–	0.169	0.206	0.993	0.00
Barley cv. Amilo		–0.003	0.181	0.229	0.994	0.00
Rye cv. Dańkowskie N.		–0.001	0.194	0.162	0.993	0.00
Rye cv. Dańkowskie Z.		–	0.191	0.155	0.984	0.00
Rye cv. Warko		–0.002	0.201	0.178	0.988	0.00
Faba bean cv. Nadwiślański		–0.007	0.166	0.247	0.962	0.00
Pea cv. Fidelia		–0.004	0.185	0.196	0.963	0.00
Lupine cv. Emir		–0.008	0.215	0.277	0.983	0.00
Vetch cv. Szelejewska		0.003	0.186	0.118	0.995	0.00

The variability, which may be observed from Table I-6, makes it difficult to conclude on the moisture influence on the particle mean size in an unambiguous way. The parameter *a*, acquires both positive as well as negative values. Whatever, its low values allow little influence to be stated. This may be explained by a large, if not decisive, impact on the final particle size induced by the screen of hammer mill.

The influence of material moisture on the grinding energy expenditures related to a change in particle dimensions (particle mean size), was presented by the formulae $E = k\, d_{\acute{s}}^{\,n}$ (k, n – constants). The results corresponding to this are listed in Tables I-7 to I-9. The above function has been shown to describe the experimental data with high accuracy, what was confirmed by high values of correlation coefficients.

Table I-7. Relationships between specific grinding energy, E (kJ kg^{-1}), and mean particle size, $d_{\acute{s}}$ (mm), for ground barley

Material	Moisture (%)	Equation form	*k*	*n*	Corr. coeff. *R*	p-value
Barley cv. Ars	10	$E = k\, d_{\acute{s}}^{\,n}$	36.61	–1.32	–0.972	0.00
	12		43.20	–1.27	–0.981	0.00
	14		52.13	–1.14	–0.983	0.00
	16		52.92	–1.31	–0.974	0.00
	18		57.13	–1.30	–0.983	0.00
Barley cv. Edgar	10	$E = k\, d_{\acute{s}}^{\,n}$	40.50	–1.41	–0.985	0.00
	12		53.96	–1.15	–0.989	0.00
	14		54.18	–1.21	–0.984	0.00
	16		57.10	–1.26	–0.987	0.00
	18		49.86	–1.53	–0.979	0.00
Barley cv. Klimek	10	$E = k\, d_{\acute{s}}^{\,n}$	44.78	–1.43	–0.985	0.00
	12		55.58	–1.28	–0.989	0.00
	14		56.30	–1.40	–0.984	0.00
	16		62.96	–1.33	–0.987	0.00
	18		57.49	–1.58	–0.979	0.00
Barley cv. Kos	10	$E = k\, d_{\acute{s}}^{\,n}$	30.92	–1.50	–0.978	0.00
	12		34.92	–1.47	–0.968	0.00
	14		39.96	–1.46	–0.981	0.00
	16		42.62	–1.47	–0.975	0.00
	18		45.43	–1.60	–0.972	0.00

Table I-8. Relationships between specific grinding energy, E (kJ kg^{-1}), and mean particle size, $d_ś$ (mm), for ground rye

Material	Moisture (%)	Equation form	k	n	Corr. coeff. R	p-value
Rye, cv. Amilo	10	$E = k\,d_ś^{\,n}$	26.21	–1.45	–0.990	0.00
	12		24.70	–1.53	–0.989	0.00
	14		38.70	–1.23	–0.987	0.00
	16		39.53	–1.24	–0.981	0.00
	18		44.53	–1.25	–0.978	0.00
Rye, cv. Dańkowskie Nowe	10	$E = k\,d_ś^{\,n}$	22.50	–1.41	–0.989	0.00
	12		25.02	–1.44	–0.985	0.00
	14		27.04	–1.34	–0.994	0.00
	16		33.44	–1.23	–0.983	0.00
	18		43.42	–1.04	–0.966	0.00
Rye, cv. Dańkowskie Złote	10	$E = k\,d_ś^{\,n}$	26.75	–1.27	–0.972	0.00
	12		27.54	–1.38	–0.989	0.00
	14		26.21	–1.45	–0.990	0.00
	16		33.41	–1.27	–0.991	0.00
	18		40.07	–1.18	–0.983	0.00
Rye, cv. Warko	10	$E = k\,d_ś^{\,n}$	19.94	–1.55	–0.993	0.00
	12		27.22	–1.34	–0.987	0.00
	14		26.86	–1.43	–0.994	0.00
	16		29.81	–1.47	–0.993	0.00
	18		45.32	–1.18	–0.986	0.00

Table I-9. Relationships between specific grinding energy, E (kJ kg^{-1}), and mean particle size, $d_ś$ (mm), for ground leguminous seeds

Material	Moisture (%)	Equation form	k	n	Corr. coeff. R	p-value
Faba bean cv. Nadwiślański	10	$E = k\,d_ś^{\,n}$	19.94	–1.29	–0.931	0.00
	12		27.22	–1.16	–0.931	0.00
	14		26.86	–1.53	–0.959	0.00
	16		29.81	–1.00	–0.934	0.00
	18		45.18	–0.64	–0.800	0.00
Pea cv. Fidelia	10	$E = k\,d_ś^{\,n}$	9.07	–1.98	–0.984	0.00
	12		10.76	–1.86	–0.985	0.00
	14		16.52	–1.67	–0.983	0.00
	16		22.46	–1.58	–0.983	0.00
	18		67.54	–0.78	–0.900	0.00
Lupine cv. Emir	10	$E = k\,d_ś^{\,n}$	34.27	–2.29	–0.982	0.00
	12		32.98	–2.44	–0.960	0.00
	14		87.26	–1.54	–0.977	0.00
	16		162.8	–1.00	–0.929	0.00
	18		193.1	–0.93	–0.890	0.00
Vetch cv. Szelejewska	10	$E = k\,d_ś^{\,n}$	9.50	–1.72	–0.979	0.00
	12		9.83	–1.87	–0.980	0.00
	14		10.37	–2.05	–0.982	0.00
	16		16.09	–1.92	–0.976	0.00
	18		30.46	–1.52	–0.947	0.00

5.2. Influence of material resistance parameters

The analysis of the moisture influence on grindability of feed materials presented in the previous chapter shows various implications of this factor to material behaviour in the course of grinding. Therefore, an application to the process description of mechanical properties of materials processed might be advantageous, and give some insight into their fracture process.

The undertaken analyses comprised 12 materials, within the three distinguished groups as previously (barley, rye, and leguminous seeds). They based on average values of the resistance parameters (from 50 individual tests), specific grinding energy consumption (from 15 individual tests), and particle size of ground products. Results, mainly in form of linear regression equations, are demonstrated in following tables and figures. The figures include only relationships significant at the level 0.05.

Table 1-10. Correlation matrix between grinding energy consumption and resistance parameters of barley kernels

Parameter	Specific grinding energy/screen size (mm)			Mean particle size
	1.0	1.5	2.0	
h_1	0.728	0.695	0.644	0.5185
	p = 0.000	**p = 0.001**	**p = 0.002**	**p = 0.019**
$tg\alpha$	–0.377	–0.325	–0.249	–0.247
	p = 0.101	p = 0.161	p = 0.288	p = 0.293
F_1	–0.030	0.017	0.111	–0.152
	p = 0.897	p = 0.943	p = 0.639	p = 0.521
F_2	0.774	0.804	0.782	0.609
	p = 0.000	**p = 0.000**	**p = 0.000**	**p = 0.004**
L_1	0.599	0.612	0.595	0.303
	p = 0.005	**p = 0.004**	**p = 0.006**	p = 0.193
L_2	0.781	0.810	0.802	0.534
	p = 0.000	**p = 0.000**	**p = 0.000**	**p = 0.015**
L_{j1}	0.488	0.496	0.482	0.260
	p = 0.029	**p = 0.026**	**p = 0.031**	p = 0.268
L_{j2}	0.715	0.744	0.732	0.538
	p = 0.000	**p = 0.000**	**p = 0.000**	**p = 0.014**

bold type marks relations significant at 0.05.

For barley, the specific grinding energy was significantly related to the kernel deformation up to the rupture point, strain energy and specific strain energy inputs until rupture occurs, and specific crushing energy expenditures up the collapse threshold, i.e., overall specific energy expenditures in the crushing test

(Tab. I-10). Any increase in the values of the above compression parameters induced larger energy requirements for grinding. No relevancy of the rapture load, nor the kernel's apparent stiffness to the grinding energy was confirmed.

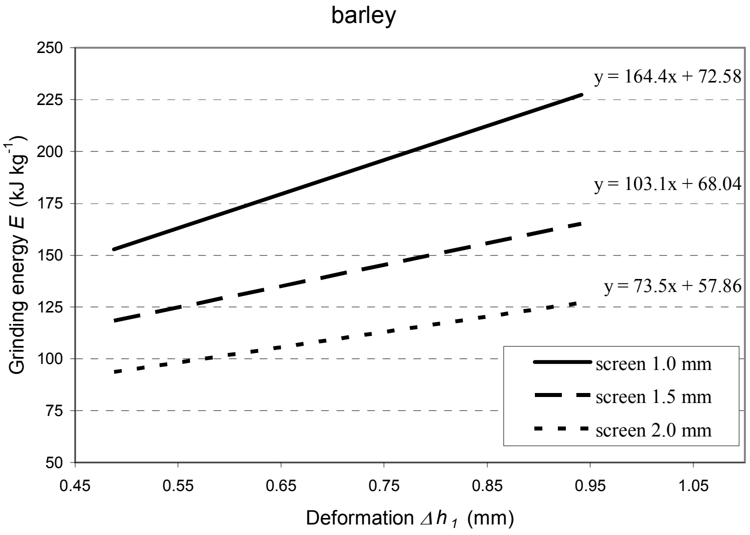

Fig. I-6. Deformation at rupture versus grinding energy consumption for barley kernels

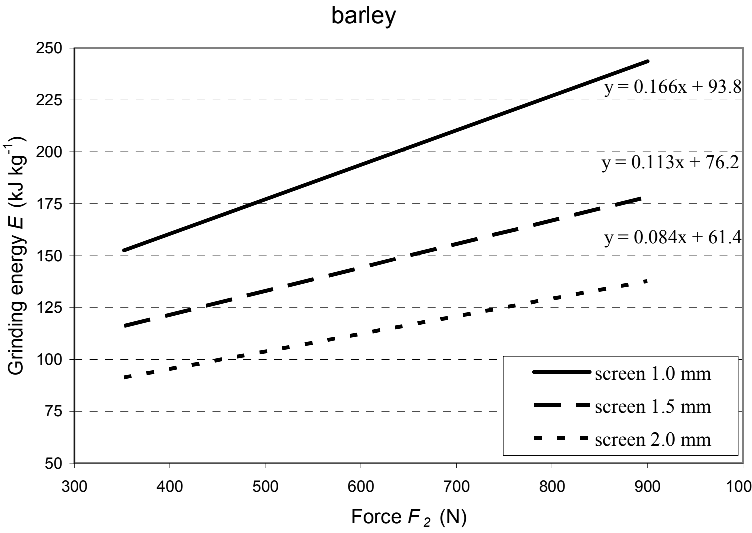

Fig. 1-7. Load at the collapse threshold versus grinding energy consumption for barley kernels

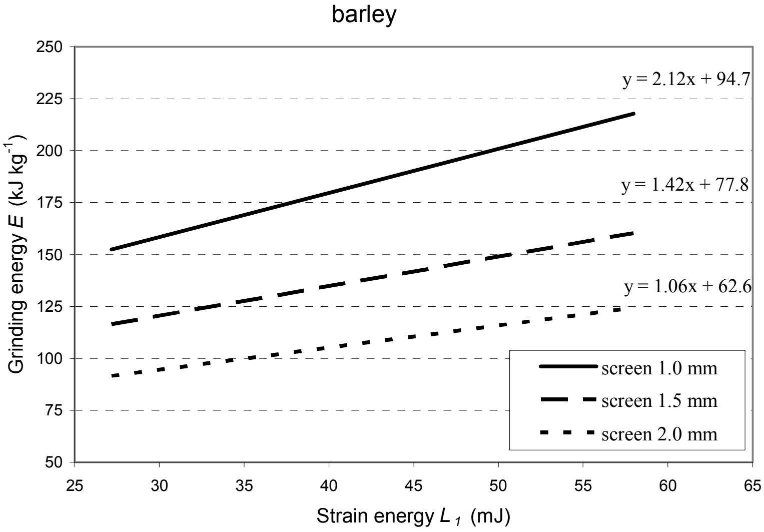

Fig. I-8. Strain energy up to rupture versus grinding energy consumption for barley kernels

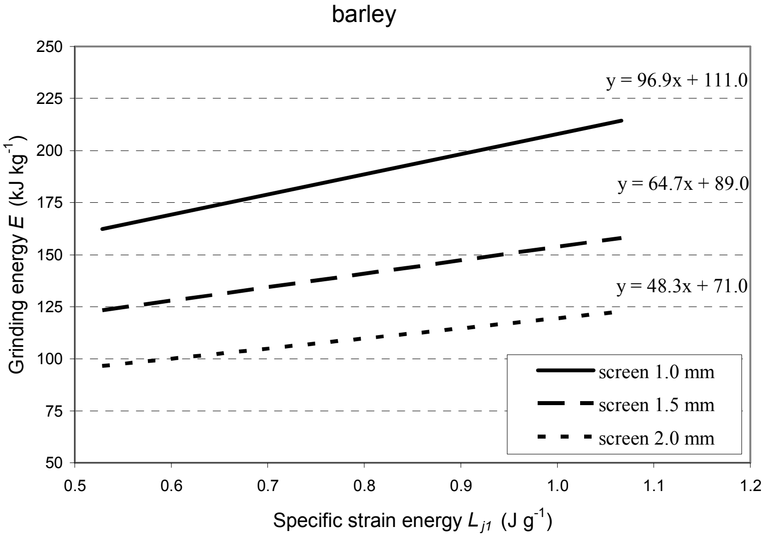

Fig. I-9. Specific strain energy up to rupture versus grinding energy consumption for barley kernels

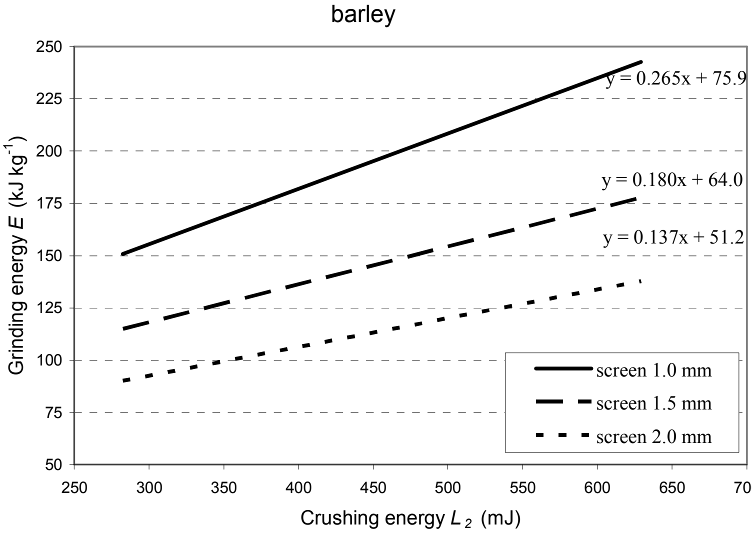

Fig. I-10. Crushing energy up to the collapse threshold versus grinding energy consumption for barley kernels

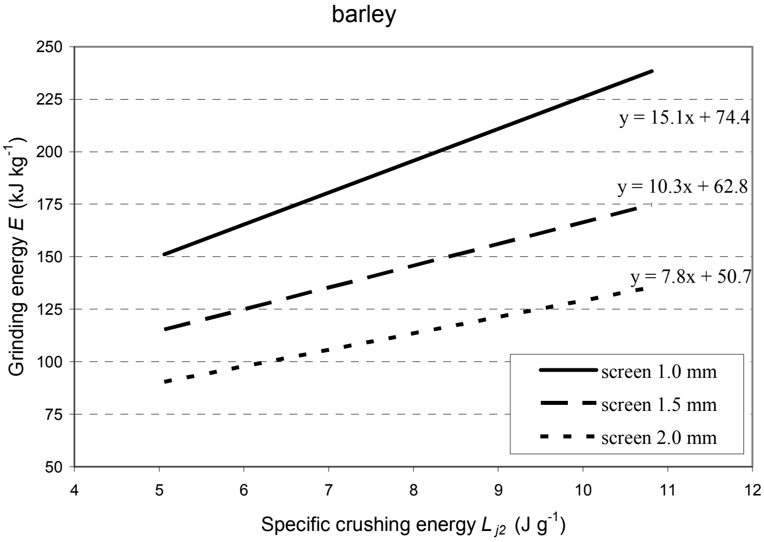

Fig. I-11. Specific crushing energy up to the collapse threshold versus grinding energy consumption for barley kernels

Table I-11. Correlation matrix between grinding energy consumption and resistance parameters of rye kernels

Parameter	Specific grinding energy/screen size (mm)			Mean particle size
	1.0	1.5	2.0	
h_1	0.658 **p = 0.002**	0.731 **p = 0.000**	0.709 **p = 0.000**	–0.288 p = 0.218
$tg\alpha$	–0.864 **p = 0.000**	–0.853 **p = 0.000**	–0.830 **p = 0.000**	0.289 p = 0.216
F_1	–0.653 **p = 0.002**	–0.630 **p = 0.003**	–0.589 **p = 0.006**	0.239 p = 0.309
F_2	–0.006 p = 0.978	–0.047 p = 0.844	–0.039 p = 0.867	–0.291 p = 0.212
L_1	0.226 p = 0.336	0.277 p = 0.237	0.288 p = 0.217	–0.027 p = 0.910
L_2	0.413 p = 0.070	0.393 p = 0.086	0.391 p = 0.087	–0.413 p = 0.070
L_{j1}	0.189 p = 0.423	0.218 p = 0.356	0.220 p = 0.350	0.124 p = 0.600
L_{j2}	0.475 **p = 0.034**	0.430 p = 0.058	0.418 p = 0.066	–0.319 p = 0.170

bold type marks relations significant at 0.05.

In the case of rye, the parameters of crushing test corresponding to the material rupture event showed to be the best correlated to the grinding energy requirements. The increase in the strain energy at rupture led to higher values of the grinding energy consumption. The apparent stiffness coefficient, as opposite to the results for barley, proved to be significant to grinding. An increase in the material stiffness induces lower energy expenditures for grinding. The grinding energy was inversely related to the load at kernel rupture. The crushing energy inputs, neither the strain energy nor the overall crushing energy, were related to the grinding energy requirements.

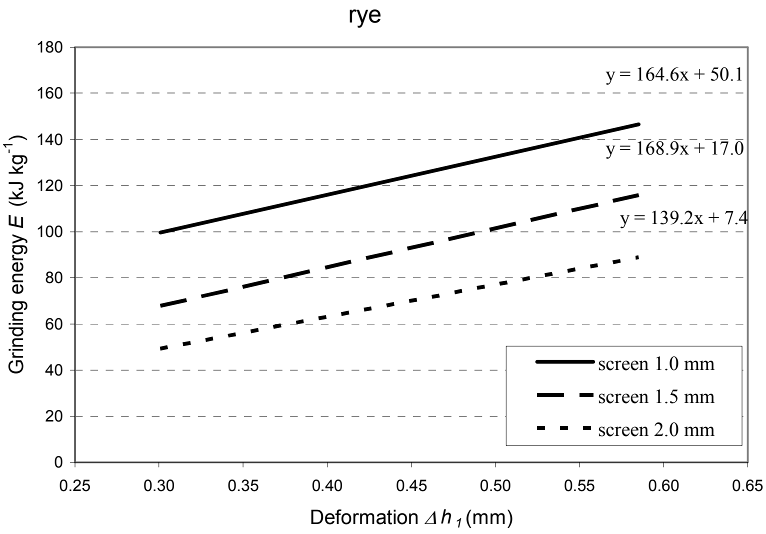

Fig. I-12. Deformation at rupture versus grinding energy consumption for rye kernels

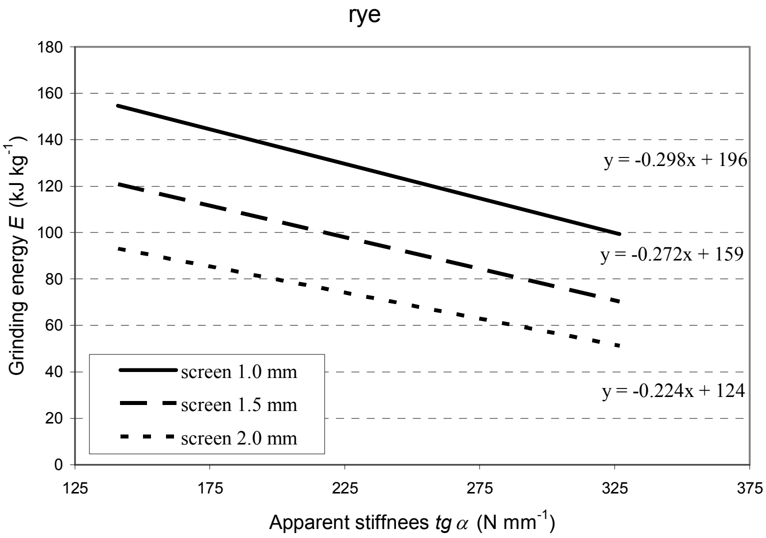

Fig. I-13. Apparent stiffness versus grinding energy consumption for rye kernels

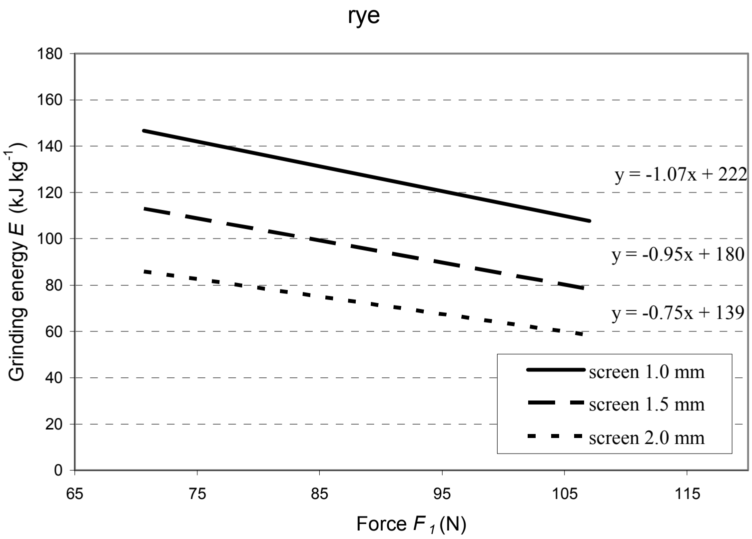

Fig. I-14. Load at rupture versus grinding energy consumption for rye kernels

Table I-12. Correlation matrix between grinding energy consumption and resistance parameters of leguminous seeds

Parameter	Specific grinding energy/screen size (mm)			Mean particle size
	1.0	1.5	2.0	
h_1	0.783	0.831	0.872	–0.178
	p = 0.000	**p = 0.000**	**p = 0.000**	p = 0.451
$tg\alpha$	–0.471	–0.488	–0.553	0.136
	p = 0.036	**p = 0.029**	**p = 0.011**	p = 0.566
F_1	–0.139	–0.088	–0.131	–0.259
	p = 0.558	p = 0.712	p = 0.581	p = 0.269
F_2	0.011	0.103	0.095	–0.553
	p = 0.961	p = 0.665	p = 0.689	**p = 0.011**
L_1	0.275	0.346	0.329	–0.324
	p = 0.240	p = 0.135	p = 0.156	p = 0.163
L_2	0.090	0.189	0.182	–0.585
	p = 0.705	p = 0.424	p = 0.441	**p = 0.007**
L_{j1}	0.742	0.670	0.653	0.729
	p = 0.000	**p = 0.001**	**p = 0.002**	**p = 0.000**
L_{j2}	0.635	0.668	0.638	–0.005
	p = 0.003	**p = 0.001**	**p = 0.002**	p = 0.983

bold type marks relations significant at 0.05.

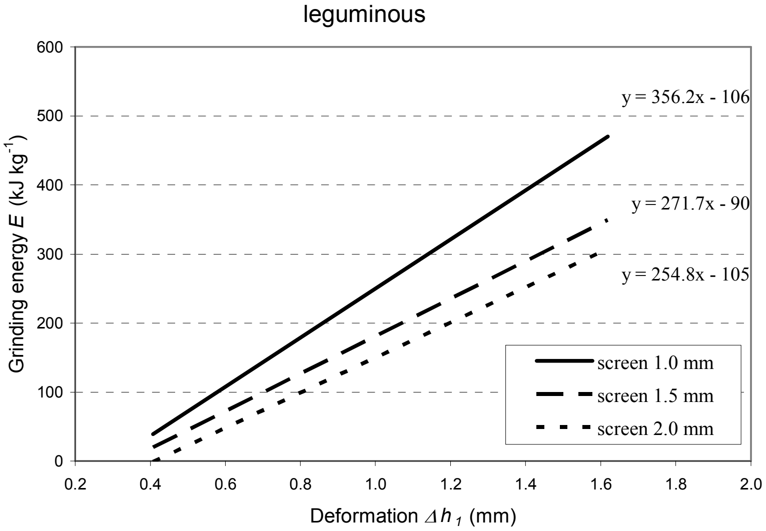

Fig. I-15. Deformation at rupture versus grinding energy consumption for leguminous seeds

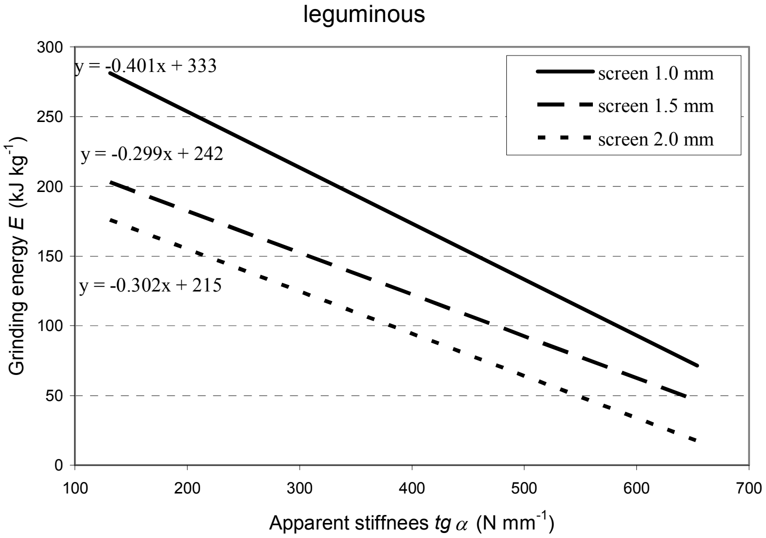

Fig. I-16. Apparent stiffness versus grinding energy consumption for leguminous seeds

For the group of pulses, the grinding energy has shown to be significantly related to the deformation up to the seed rupture point, seed stiffness, and both specific strain and specific crushing energy inputs. Lack of any relevance for the other parameters is bound to be related to the differences in seeds geometry, mainly size, what had an obvious effect on the compression testing results as well as the performed analyses.

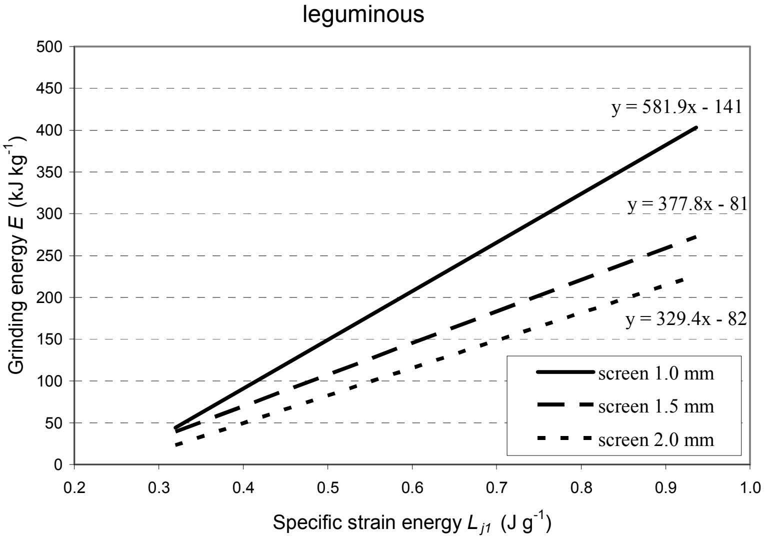

Fig. I-17. Specific strain energy up to rupture versus grinding energy consumption for leguminous seeds

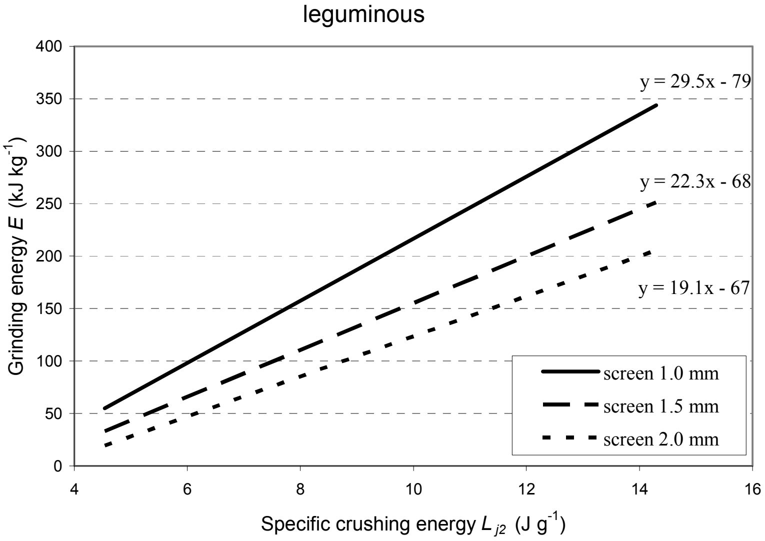

Fig. I-18. Specific crushing energy up to the collapse threshold versus grinding energy consumption for leguminous seeds

Table I-12. Correlation matrix between grinding energy consumption and resistance parameters (all 12 materials included)

Parameter	Specific grinding energy/screen size (mm)			Mean particle size
	1.0	1.5	2.0	
h_1	0.754	0.766	0.783	–0.114
	p = 0.000	**p = 0.000**	**p = 0.000**	p = 0.385
$tg\alpha$	–0.310	–0.356	–0.393	–0.102
	p = 0.016	**p = 0.005**	**p = 0.002**	p = 0.437
F_1	0.058	0.063	0.034	–0.304
	p = 0.660	p = 0.630	p = 0.794	**p = 0.018**
F_2	0.137	0.172	0.167	–0.524
	p = 0.294	p = 0.187	p = 0.201	**p = 0.000**
L_1	0.339	0.356	0.346	–0.354
	p = 0.008	**p = 0.005**	**p = 0.007**	**p = 0.005**
L_2	0.180	0.223	0.220	–0.561
	p = 0.169	p = 0.087	p = 0.090	**p = 0.000**
L_{j1}	0.541	0.527	0.504	0.571
	p = 0.000	**p = 0.000**	**p = 0.000**	**p = 0.000**
L_{j2}	0.634	0.632	0.606	–0.014
	p = 0.000	**p = 0.000**	**p = 0.000**	p = 0.912

bold type marks relations significant at 0.05.

Statistical analyses, in which all 12 materials from the three groups were included, have confirmed significant contribution to the grinding energy consumption of the following parameters: deformation at the rupture point (also observed for each group separately), kernel (seed) apparent stiffness (in spite of lack of significance at 0.05 level for rye), strain energy up to the rupture point, and both specific energies up to the kernel (seed) rupture and collapse threshold.

Larger amounts of the grinding energy were required for the materials, for which larger deformations at failure and at the same time lower stiffness were characteristic. Material was more difficult to grind, when also more energy inputs were involved in its crushing experiments. Any relevancy of loads at the rupture point nor loads at the collapse threshold on the grinding energy expenditures was not confirmed.

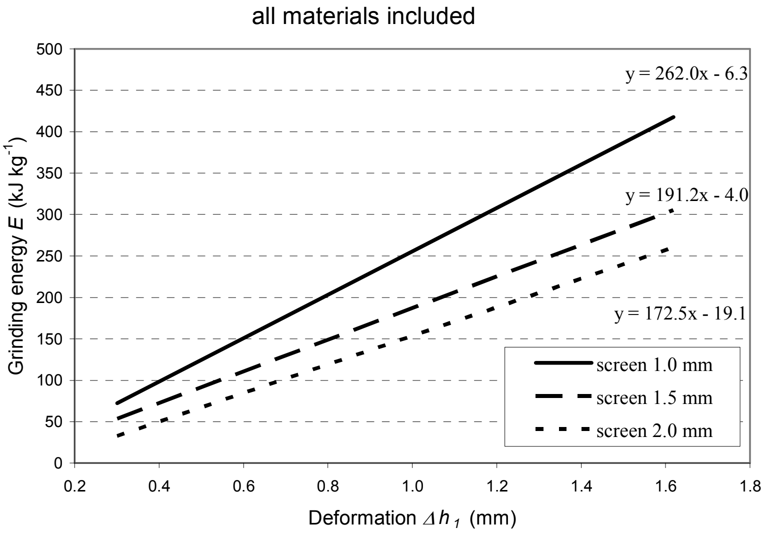

Fig. I-19. Deformation at rupture versus grinding energy consumption (all 12 materials included)

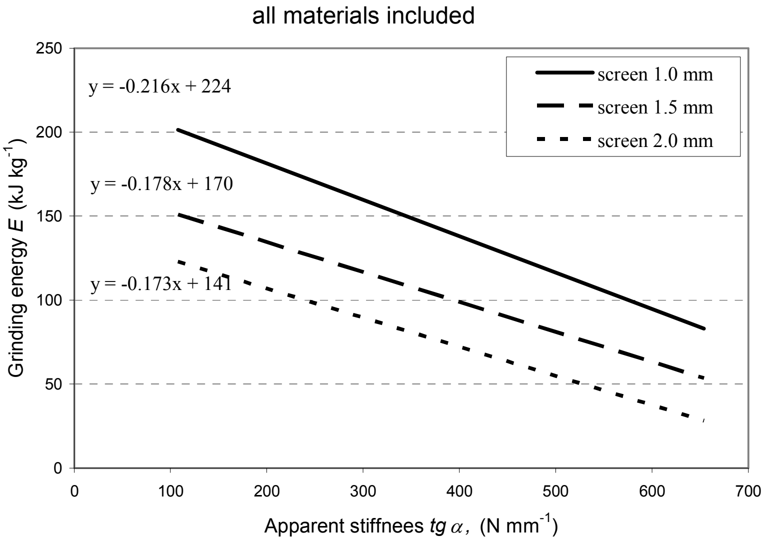

Fig. I-20. Apparent stiffness versus grinding energy consumption (all 12 materials included)

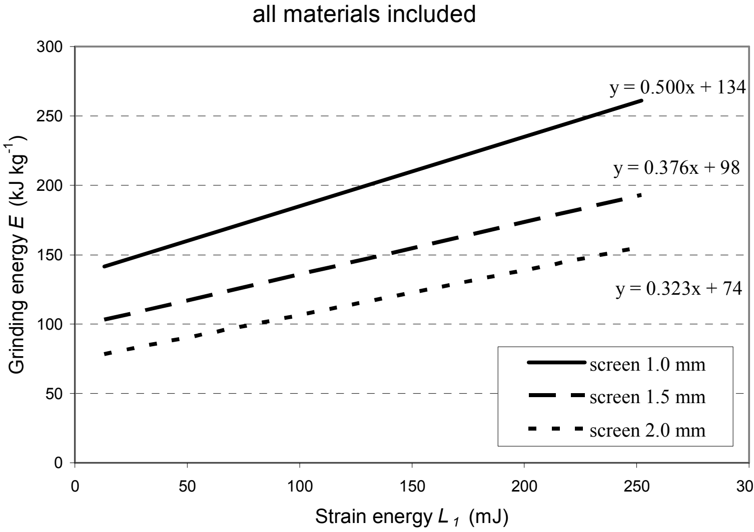

Fig. I-21. Strain energy versus grinding energy consumption (all 12 materials included)

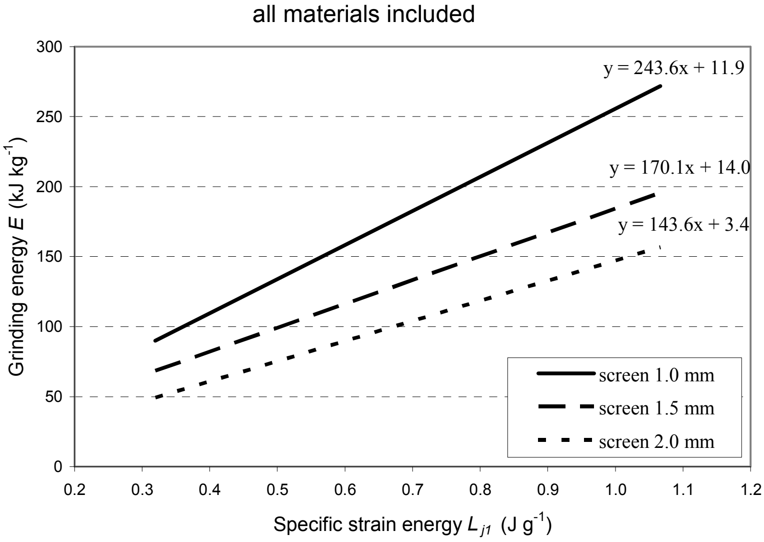

Fig. I-22. Specific strain energy versus grinding energy consumption (all 12 materials included)

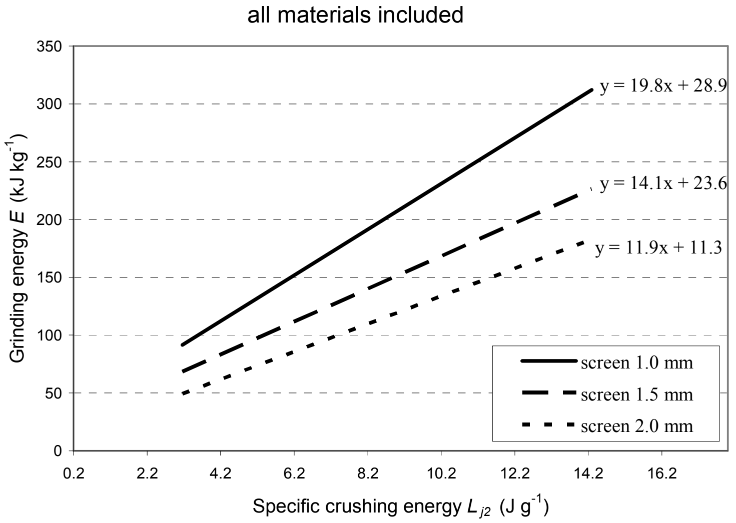

Fig. I-23. Specific crushing energy versus grinding energy consumption (all 12 materials included)

6. CONCLUSIONS

The influence of material moisture content on the course of grinding was visible especially when analysing energy expenditures. For that case, its relevancy may be expressed by linear or quadratic equations, depending on the kind of material in question. Between the materials used, linear increase was observed for barley and lupine, and quadratic for the others.The lowest influence of moisture, in the studied range, was observed for rye and the largest for the leguminous seeds (particularly for lupine). For the latter materials, the moisture exceeding 14% induced relatively high increase in the grinding energy requirements.

Effect of moisture content on the grinding energy consumption relative to the change in size of a particle submitted to fragmentation might be well described by an exponential equation of general form $E = k d_{ś}^{n}$.

A material property is more or less induced by its moisture. The magnitude of this influence depends on a variety of factors, and therefore, and especially for a better understanding of the grinding process mechanism, other material features must focus more attention. Among them, the mechanical behaviour is of great importance.

The uniaxial experiments done on individual particles, showed some relevancy to the energy requirement during grinding. Between the parameters obtained from the compression testing, the highest influence on the grinding energy was observed for the kernel (seed) deformation up to rupture (failure), and its apparent stiffness. An increase of deformation until failure occurs, in every case, resulted in higher energy requirements for grinding. Second parameter of high magnitude to grinding is the material stiffness. It showed to be, inversely related to the grinding energy consumption. Its magnitude was especially important to the grinding of pulses, which undergo relatively high increase in plasticity because of moisturizing.

The failure load has proved to be insignificant to the grinding energy requirements assessment within the frame of the pursued experimental program.

A lack of direct significance of strain energy inputs as necessary to provoke a failure, together with the confirmed significance of the two above-mentioned factors, allows state, a description that is more complex should be used. To avoid some observed discrepancy, geometrical features of the particles under compression have to be integrated to the description as well. This seems, however, to be not easy task while dealing, but not only, with materials of biological origin. Their complex mechanical behaviour warrants continuous research necessary for discovering the nature of phenomena observed in industrial practice.

7. REFERENCES

1. **Albera F.:** La Modelisation du Brayage en Mineralurgie. These de Docteur de l'Universite D'Orleans, 1987.
2. **Austin L.G.:** A Commentary on the Kick, Bond and Rittinger Laws of Grinding. Powder Technology, 7, 315-317, 1973.
3. **Austin L.G.:** Introduction to the Mathematical Description of Grinding as a Rate Process. Powder Technology, 5, 1-15, 1971.
4. **Bieliński M.:** Classification of grinders design according to material properties (in Polish). III ICCE Conference „Ecologic Crumblers – Crumblers Engineering, Bydgoszcz, 144-153, 1993.
5. **Biskupski A.:** Technological properties and suitability of new cereals varieties for food industry (in Polish). Przemysł Spożywczy, 12, 448-451 1979.
6. **Boss J.:** Study on grinding energy of cereal grains (in Polish). Przegląd Zbożowo-Młynarski, 6, 3-7, 1986.
7. **Brennan J.G., Butters J.R., Covell N.D., Lilly A.E.:** Food Engineering Operations. ASPL, Londyn, 1976.
8. **Chwiej M.:** Machinery for food industry. Machines and apparatus (in Polish). PWN, Warszawa, 1977.
9. **Cook J., Baker K.:** Compression Test of Food Materials of Convex Shape. Agricultural Engineers Yearbook, 386-389, 1974.
10. **Csermely J., Bölöni I.:** Grinding Wet Corn. Hungarian Agricultural Research, 1, 16-22, 1995.
11. **Dexter J.E.:** Practical applications of milling research. 10th International Cereal and Bread Congress, Porto Carras, Chalkidiki, Greece, June, 1996.
12. **Doehlert D.C., Moore W.R.:** Composition of Oat Bran and Flour Prepared by Three different Mechanisms of Dry Milling. Cereal Chem., 74, 4, 403-406, 1997.
13. **Flizikowski J.:** Research and Design Fundamentals of Multiple Disc Shredders (in Polish). Rozprawy 42, Bydgoszcz, 1990.
14. **Frontczak J.:** Determination methods and analysis of physical properties of maize kernels (in Polish). Zeszyty Nauk. AR Wrocław, 61, 0-47, 1987.

15. **Frontczak J.:** Test Result Interpretation Methods Comparison at Determination of Corn Grain Strength in Respect to Grain Moisture Content. Zesz. Probl. Post. Nauk Roln., 389, 49-58, 1991.
16. **Frontczak J.:** Mechanical properties' variability of selected maize cultivars (in Polish). Zeszyty Nauk. AR Wrocław, 156, 7-20, 1985.
17. **Fuerstenau D.W.:** Grinding Aids. 7th European Symposium on Comminution, 109-126, 1990.
18. **Gąsiorowski H., Kołodziejczyk P.:** Micro-hardness of rye kernel (in Polish). Przegląd Zbożowo-Młynarski, 5, 9-19, 1990.
19. **Gąska R., Kolowca J.:** Effect of cereal grain moisture on its mechanical damages (in Polish). Zesz. Probl. Post. Nauk Roln., 202, 209-217, 1978.
20. **Grochowicz J.:** Studies on Hammer Mill Working Process (in Polish). Zesz. Probl. Post. Nauk Roln., 225, 205-212, 1980.
21. **Grochowicz J., Laskowski J.:** Analysis of Factors Influencing Working Parameters of Hammer Mills (in Polish). Biul. Inf. Przem. Pasz., 1, 4-6, 1 978.
22. **Grochowicz J., Nadulski R.:** The Methods for Studying and Determining Physical Properties of Some Leguminous Plants. Zesz. Probl. Post. Nauk Roln., 399, 91-102, 1993.
23. **Grochowicz J., Nadulski R.:** Determination of some mechanical properties of horse bean (in Polish). Zesz. Probl. Post. Nauk Roln., 354, 67-71, 1989.
24. **Heidenreich E., Schultz F.:** Comminution of Grain in Hammer Mills. 7th European Symposium on Comminution, 917-922, 1990.
25. **Islam M. N., Matzen R.:** Size Distribution Analysis of Ground Wheat by Hammer Mill. Powder Technology, 54, 235-241, 1988.
26. **Janiak G.:** Energy for wheat kernel crushing process (in Polish). PhD Thesis, AR w Lublinie, 1994.
27. **Jankowski S.:** Introduction to flour and groat technology (in Polish). WTT, Warszawa, 1981.
28. **Kalwaj J.:** Analysis of factors influencing energy consumption in hammer mills (in Polish). III ICCE Conference „Ecologic Crumblers – Crumblers Engineering, Bydgoszcz, 221-224, 1993.
29. **Kiryluk J.:** Effect of moisture content of pea and horse bean groats on their milling properties (in Polish). Przegląd Zbożowo-Młynarski, 27-29.
30. **Kolowca J.:** Study on the resistance of cereal grains (in Polish). Zeszyty Naukowe, WSR, Kraków, 77, 49-59, 1973.
31. **Kolowca J., Ryś S., Ślipek Z.:** Problems in measurement and description of some physical properties of cereals (in Polish). Zesz. Probl. Post. Nauk Roln., 258, 409-415, 1983.
32. **Koper R.:** Modern research methods for determination of mechanical properties of cereal grains (in Polish). Zesz. Probl. Post. Nauk Roln., 320, 29-41, 1987.
33. **Laskowski J. Janiak G.:** Procedure of determination strength factors of grain for processing (in Polish). Biul. Nauk. Przem. Pasz., 1, 45-58, 1996.
34. **Laskowski J., Łysiak G.:** Experimental Set-up for Grinding Process Testing of Biological Raw-materials (in Polish), Postępy Techniki Przetwórstwa Spożywczego, ½. 6, 55-58, 1997.
35. **Laskowski J., Łysiak G.:** Relationships between Resistance Characteristics of Barley Kernels and Energy Consumption during Grinding on Hammer Mill. Int. Agrophysics, 11, 265-271, 1997.
36. **Laskowski J., Łysiak G.:** Study on the mechanical properties and the disintegration process of legume seeds (in Polish). Problems of Agricultural and Forest Engineering, Proceedings of the IV International Conference, Warszawa, 206-211, 1997.
37. **Laskowski J., Łysiak G.:** Analysis of methods of the particle size distribution assessment of ground cereals (in Polish). Inżynieria Rolnicza, 2, 37-46, 1999.
38. **Laskowski J., Łysiak G., Dziki D.:** Effect of moisture content and species of cereals on particle size distribution in ground grain evaluated by laser diffraction (in Polish). Inżynieria Rolnicza 4(15), 27-34, 2000.
39. **Lewinski J., Mazela A.:** The Analysis of the Impact of a Single Particle on the Hammer of a Hammer Crusher. Aufbereitungs Technik, 10, 605-610, 1985.
40. **Łysiak G.:** Influence of physical properties of plant materials on the course of grinding (in Polish). PhD Thesis, Akademia Rolnicza, Lublin, 1997.

41. **Nowak A.:** Theoretical Basis of Solids Comminution (in Polish). Prace Nauk. Bad. Inst. Masz. Spoż. Warszawa, 1972.
42. **Obuchowski W.:** Wheat grain hardness, technological significance and factors influencing this feature (in Polish). Roczniki AR Poznań, Rozprawy Naukowe, 152, 1-56, 1985.
43. **Ortega-Rivas E.:** Food Powders. Aspen Publishers, Inc, USA, 2001.
44. **Peleg M.:** Disintegration and Segregation. Kinetics of Dry Food Particulates. Physical Chemistry of Food, Marcel Dekker, New York, 531-571, 1992.
45. **Pfost H.B.:** Grinding and Rolling. Feed Manufacturing Technology, 68-77, 1970.
46. **Popplewell L.M., Peleg M.:** Theoretical Kinetic Model for Particulates Disintegration Processes that Result in Bimodal Size Distributions. Powder Technology, 70, 21-30, 1992.
47. **Prasher C.L.:** Crushing and Grinding. Process Handbook. London, 1987.
48. **Scarlett B.:** Particle Size and Shape the Motor for Comminution Research. 7th European Symposium on Comminution, 79-88, 1990.
49. **Schubert H.:** On the Energy Utilization in Comminution. Aufbereitungs Technik, 34, 495-501. 1993.
50. **Schönert K.:** The Influence of Particle Bed Configurations and Confinements on Particle Breakage. 8th European Symposium on Comminution, 1, 7-26, 1994.
51. **Shelf L., Mohsenin N.N.:** Evaluation of the Modulus of Elasticity of Wheat Grain. Cereal Chem., 44/4, 392-402, 1967.
52. **Stairmand C.J.:** The Energy Efficiency of Milling Processes. A Review of Some Fundamental Investigations and Their Application to Mill Design. 7th European Symposium on Comminution, 1-17, 1975.
53. **Staszczak Z.:** Investigations of the Rheological Properties of Wheat Grain. Zesz. Probl. Post. Nauk Roln., 203, 225-234, 1978.
54. **Szot B.:** Factors determining wheat grain resistance to loading (in Polish). Zesz. Probl. Post. Nauk Roln., 258, 437-448, 1983.
55. **Szot B., Grundas S.:** Issues of changeability of some physical properties of cereal grains (in Polish). Zesz. Probl. Post. Nauk Roln., 202, 219-243, 1978.
56. **Szot B., Grundas S., Grochowicz M.:** The method of determination of cereal grain resistance to mechanical deformations (in Polish). Zesz. Probl. Post. Nauk Roln., 402, 197-203, 1992.
57. **Szot B., Stępniewski A.:** Mechanical Resistance of Various Cereals Grains to Static Loads. Zesz. Probl. Post. Nauk Roln., 389, 111-119, 1991.
58. **Szot B., Stępniewski A., Rybczyński R.:** Variability of Winter Wheat Grains Resistance to Static Loads. Zesz. Probl. Post. Nauk Roln., 399, 255-259, 1993.
59. **Ślaska-Grzywna B.:** Investigation on basic indicators of grinders work quality in small feed manufactures (in Polish). Biul. Inf. Przem. Pasz., 4, 26-28, 1981.
60. **Tavares L.M. King R.P.:** Single-particle fracture under impact loading. J. Miner. Process., 54, 1–28, 1998.
61. **Tschorbadjiski I., Schallnus H., Schwedes J.:** Modelling of Comminution in Hammer Mills – part 1. Aufbereitungs Technik, 10, 555-562, 1987.
62. **Tschorbadjiski I., Schallnus H., Schwedes J.:** Modelling of Comminution in Hammer Mills – part 2. Aufbereitungs Technik, 12, 699-703, 1987.
63. **Weichert R.:** Fracture Physics in Comminution. 7th European Symposium on Comminution, 3-20, 1990.
64. **Wolf Th., Pahl M.H.:** Cold-Grinding of Spices in Impact Mills. 7th European Symposium on Comminution, 1, 923-939, 1990.
65. **Yashima S., Kanda Y., Sano S.:** Relationship Between Particle Size and Fracture Energy or Impact Velocity Required to Fracture as Estimated from Single Particle Crushing. Powder Technology, 51, 272-282, 1987.
66. **Zoerb G.:** Instrumentation and Measurement Techniques for Determining Physical Properties of Farm Products. Trans. ASAE, 10, 100-113, 1967.
67. **Zoerb G.C., Hall C.W.:** Some Mechanical and Rheological Properties of Grain. Journal of Agric. Eng. Res., 5/1, 28. 1960.

Chapter II

MATERIAL PROPERTIES IN AGGLOMERATION

8. SELECTED ISSUES OF AGGLOMERATION RESEARCH

Feed materials during agglomeration processes are exposed to mechanical forces causing their density changes. The changes in material density as well as process parameters depend on characteristics of equipment employed, and physical and chemical properties of a mixture. Therefore, distinct feed components are characterised by their unique compression ability, being their natural property [21].

The ability to agglomeration of different feed mixture components was a research interest of few workers. More, it has been characterised rather in a very descriptive manner. Experiments of Laskowski [21] show, that the course of compression process is related to material's properties and its chemical composition. This ability might be characterised by material's density changes, based on an extrusion characteristic or by the energy consumption during extrusion.

Literature on the subject [1, 2, 5, 7-14, 16, 17, 21, 23, 24, 26, 46, 50, 54-57, 62] emphasizes the importance of studies with the focal point on the determination of influence of physical and chemical properties of raw materials on the course of agglomeration processes, as well as on processing outcomes.

8.1. Influence of chemical composition on agglomeration processing

Chemical composition of feedstuffs determines their nutritional value (a kind and proportion of nutritional substances) and functionality. With this in mind, some contribution of the following constituents needs to be referred for a good understanding.

Protein. Influence of proteins presence was the subject of works performed by Fredrich and Robohm [7], Korol [19], Tregret [58], Reiders and Bostelare [52]. Results of them point out, that some occurrence of proteins in a mixture is associated with a higher pellet's strength and better performance of a processing machine. This may be explained by a plastifying effect, resultant from the protein gelatinisation, and caused by the temperature increase from conditioning operation or friction effects.

Starch. According to Wellin [61] and Reinders [52] starch presented in a processed mixture has an advantageous effect on the process performance and product strength due to the response to warming resulted from conditioning operations. Denaturation of starch, initially, facilitates adhesion between particles.

The sticky consistency, what becomes characteristic to some starch granules, makes the process of compression easier to perform. Friction forces between particles of a mixture, and between particles and die walls diminish also.

Fat. Fat is one of the mixture components demonstrating a crucial influence on agglomeration processing. Generally, it is accepted that some addition of this component to a feedstuff results in a decrease of the specific energy expenditures for granulation. This is also accompanied by smaller pellet cohesiveness [1, 4, 7, 11, 17, 21, 26, 60, 58]. It is necessary, in this place, to make the distinction, resulting from the fat's origin, between this naturally bound together with a component, and that added to a feedstuff. David and Lefumeux [4] postulate that during the mixture pressing, the former type migrates towards the granule surface, where it acts as a lubricant, giving rise to an increase in the machine output. According to the authors, the materials with fat percentage lower than 1% are more difficult to compact. A low or unsatisfactory pellet consistency is obtained for the percentage of fat higher than 5 percent. Wellin [61] illustrates that addition of fat in the amount only of one percent, might cause a shift to the unsatisfactory process results. According to him, the percentage of this component between 1 to 3% is mostly favoured. Laskowski and Melcion [25], Laskowski and Skonecki [27], Laskowski *et al.* [26] studied consequences of the rapeseeds addition in wheat mixtures. They stated that low amount of fat in a mixture contributes to the decrease in forces, pressures and energy requirements for distinct compression process stages. A lower pellet consistency, in the range of the rapeseed addition about 5 to 7.5%, was also observed. In industrial practice, the percentage of fat in a feed mixture is generally lower than 4 to 6%.

Fibre. Raw materials with a relatively high amount of fibrous matter have, generally, low density and rather high elasticity. These two parameters are of great importance, and affect any mixture ability to agglomeration or pelleting. They must be under control, already at the moment of mixture composing. David and Lefumeux [4] show that fibrous matter induces lower machine output as well as lower pellet durability. The size of fibrous particles in a view of pelleting was the subject of research conducted by Reinders and Bostelare [52], Tregret [58], Hejft [16, 17]. Relatively long particles influenced advantageously the pellet strength, but inversely the machine output. On the other hand, too short particles might result in higher pellet ability to fracture during handling. One of the most important advantages of the fibrous materials occurrence, as a component of feedstuffs, is their ability to the absorption of water, oil, and molasses.

8.2. Influence of material physical properties on agglomeration processing

Among material physical properties, the particle size, moisture as well as temperature within their relevance to agglomeration processing are most widely discussed in the subject literature. According to many workers, size and shape of an individual particle of a feed mixture have a significant influence on pelleting conditions and process results. Tylżanowski [59] states that the average particle size should not be higher than half a pellet diameter if this is smaller than 5 mm. For larger pellet diameters, the particle size should be lower than 3 mm.

The particle size of straw as a component of a feed mixture was analysed by Hejft [16, 17]. He illustrated that smaller particle sizes contribute to an increase in the density of pellets, their durability and strength. Numerous authors state that with some increase in the grinding ratio (decrease in particle size) a better material ability to the granulation might results [4, 51, 59, 61]. Smaller particles are more favoured during conditioning operations, because their larger value of the specific surface plays a part in beneficial impact on water and heat migration necessary for starch gelatinisation. David and Lefumeux [4] show, additionally, that too small particle size might impose too extensive starch gelatinisation, and having place before a compressed material is moved to a die.

The distribution of particle sizes, especially for the smaller ones, is also pertinent to the agglomeration ability as stated by Melcion [48]. The latter is higher when the distribution of particles around the mean size is relatively small. Brudka [1] and Tylżanowski [59] confirm some significance of the adequate grinding for agglomeration needs. When this condition is not tolerably well respected, an increase in the energy expenditure for pressing might result.

More detailed analysis of the particle size effect was given by Mac Mahon and Payne [47]. They state, as the most preferred, the following distribution of particle sizes: max 1% of particles larger than 3.35 mm; up to 5% above 2 mm size, to 20% above 1 mm, 30% above 0.5 mm, 25% above 0.25 mm, and not less than 20% of particles smaller than 0.25 mm (thus about 74% particles of size below the 1.0 mm aperture size).

Moisture content, what is well known, influences practically all physical properties of raw materials, every operation in agglomeration technology, as well quality of final products. Tylżanowski [59] states that the change of moisture already about of 1% may cause processed mixture tend to be too dry or too moist for granulation needs, resulting in the subsequent consequences to the routine operation of a pelleting mill. More, Melcion [49] postulates that one moisture level advantageous for some unit operations or process stages may not be preferred in others. The influence of moisture content on compression process parameters including compression pressure, work inputs for distinct compression stages (phases), as well as some indices of the material ability to agglomeration was confirmed in experiments accomplished by Laskowski and co-workers [27-35, 42].

When concerned about moisture of plant materials, one have to distinguish between the water bound by tissues and cells of a plant (changing with material, season, etc.) and free water added (introduced during tempering, conditioning and the like). Moisture of any mixture employed to granulation varies in a wide range, but it increases about 0.5 to 3 percent, only as the result of conditioning [11, 21]. Reinders and Bastelaere [52] state that after the conditioning operations moisture of a mixture should be near 15 to 15.5 percent of water content. According to Wellin [61], the most favoured to the granulation are mixtures of the moisture content from 13 to 17%. The differences are obviously reasoned by various processing conditions, as well as differences in composition of processed feedstuffs.

When analysing the literature data dealing with levels of temperature adequate for granulation, similar variability may be observed. The temperature of granulated material results mainly from the conditioning process. It is generally accepted, that the temperature range from 80 to 90ºC is most favoured (60-70ºC for feedstuffs rich in proteins). It is worth a note, that temperature of processed mixtures has an important impact on the energy consumption, pelleting press output, and properties of final products [11]. Some changes in compression parameters' values in relation to the temperature of materials of biological origin were presented in some works of Laskowski and Skonecki [37, 39, 40].

This very short preview of literature data let us to conclude that physical properties and chemical composition of feed mixtures have a different implication to the course and results of agglomeration. In essence, physical properties of a material employed to agglomeration determine its ability to this kind of treatment, energy expenditures and quality of final products. This note was confirmed in own authors' research works [27-32, 35, 41, 42]. Therefore, any continuation of research on the presented subject, and particularly dealing with the material properties appears to be worthwhile, if not necessary.

8.3. Criteria for the agglomeration ability assessment

The agglomeration ability may be defined and assessed in more than one way, dependently on subjective needs [4, 6, 7, 17, 18, 21, 27-33, 36, 38-40, 42, 47, 59]. A material has high agglomeration ability when the two following conditions are accomplished. First, low pressures are needed to form a compacted structure. Second, the compact is of expected quality, i.e., high durability.

Drzymała [6] gave a few agglomeration ability values for some non-feed materials. They expressed relationship between the specific pressure of compression and the piston displacement (the higher displacement of the piston for the same pressure the better agglomeration ability), and employed some compacting ability indices related to agglomerate structure, hardness testing, etc.

Another way of the agglomeration ability assessment was presented by Kłassien and Griszajew [18]. In their research, done for products of chemical industry (i.e., fertilizers), they introduced some coefficients of material ability to agglomeration, and a coefficient expressing the agglomerate ability to shape retention, as useful tools, for the right selection of the most adequate agglomeration method. They have shown, proposed coefficients be dependent on material properties, i.e., particle size and distribution, friction coefficients, cohesiveness, temperature, moisture, etc. These research works were especially helpful, and have been continued in own authors' research dealing with the materials of biological origin [28, 29, 31, 38]. For these materials, the assessment of ability to agglomeration was not a frequent research subject.

David and Leufumeux [4] as Mac Mahon and Payne [47] tried to express the ability to granulation for different materials. The procedure proposed by them composed of the following individual indices: a) chemical composition analysis, including moisture, percentage of protein, fibre and fat; b) ability to compression, i.e., ratio of the formed compact weight to the power requirements which is expressed in the five degree scale from very inadequate to very good compression ability; c) abrasiveness of products in the four degree scale based on the abrasion intensity of a die; d) finally, the influence of products on friction and cohesiveness – descriptively.

An interesting, though a descriptive characteristic also, was proposed Mac Mahon and Payne [47]. They introduced for every product five following criteria: pellet quality coefficient (between 0 and 10); coefficient of press performance (0-10); product abrasiveness (0-10); the maximum percentage of a component in a mixture (in %); and finally a percentage of protein, fat and cellulose (Tab. II-1).

Table II-1. Criteria and indices for the agglomeration ability assessment of some cereals, according to Mac Mahon and Payne [47]

Material	Pellet quality (0-10)	Press performance (0-10)	Product abrasiveness (0-10)	Protein (%)	Fat (%)	Cellulose (%)	Bulk density (kg m^{-3})
Maize	5	7	6	9	3.5	2.5	610
Barley	5	6	5	10	1.5	4.9	480
Wheat	8	6	3	11	1.5	2.5	540
Oat	2	3	7	10.5	4.5	10.5	620
Rice	2	3	9	13	1.4	12	710

A different conception, based on six-degree scale, was proposed by Tylżanowski [59] (Tab. II-2).

Table II-2. Agglomeration ability of some feed powders according to Tylżanowski [59]

Material	Range	Reason of inadequacy or note
Corn meal	+++++	
Wheat meal	+++++	
Rye meal	++++	
Barley meal	+++++	
Oat meal	++++	low density and high bran amount
Wheat bran	+++++	
Peanut meal	++	
Soybean meal	++++	
Rapeseed meal	+++	
Dried beet pulp	+++	
Dried potato pulp	+++	
Dry green plant matter	++	only with water addition
Meat and bone meal	+++	
Fish flour (greasy)	+++	
Fish flour	+++	
Milk powder	+	only as a component
Feed phosphate	+	only as a component

The presented review allows a lack of the experiments appreciably quantifying the ability of feed materials to agglomeration to be underlined. Moreover, the adequate quantitative criteria, which are of great importance, are also missing. These both induce the necessity of continuous research.

Many years of own research works have given a basis to develop a method for more comprehensive analysis of the agglomeration mechanism [21, 27, 28, 29, 38, 23, 44]. In order for the agglomeration ability assessment, we based on material density changes under confined compression. Unlike in some early description of the agglomeration process, we assumed that the material agglomeration ability may be described by material density changes caused by the applied compression pressure, or by the energy inputs (i.e., specific work of compression), related to the density increase of processed material. Hence, for the assessment of the agglomeration ability criterion, the two following indices were proposed: the coefficient of material ability to compression (or compression ability coefficient) and a coefficient associating compression energy expenditures and a resultant material density increase. This method was also employed in the experiments done for the needs of this research.

Research works performed for cereals and legume seeds showed, that higher aptitude to the agglomeration was induced by an increase in moisture and temperature of processed materials [33, 36, 37, 39, 40, 42].

A specific compression energy expenditure corresponded to the resultant material density change was postulated by Hejft and co-workers [17] to be a good indicator of the material agglomeration aptitude. The mentioned coefficients have to be determined experimentally. The compression energy may be effectively assessed basing on a compression pressure-specific volume relation (curve) obtained from a simple compression experiment. The compression energy may be derived from the relation presented by Czaban and Kamiński [3], adapting the model of plastic body and respecting Green's condition.

Authors' research works showed the material compression ability depended on material mechanical properties [32, 53], which might be determined according to the procedure presented by Laskowski and Janiak [22].

9. AGGLOMERATION. METHODS AND PROCEDURES DESCRIPTION

9.1. Material and methods

Three following experimental stages constitute research done in the view of the identification of material relevancy to agglomeration processing, i.e., confined compression testing, extrusion testing and granulation (Tab. II-3).

The confined compression experiments were executed with the help of two types of presses, i.e., hydraulic press type ZD40, and universal machine Instron 4302. The former press was also adapted for the extrusion testing. The laboratory pelletmill type CLM, hold at CLPP feed manufacturer in Motycz was used in the granulation experiments.

The sort of 52 raw materials presented in Table II-3 was included in the experiment program. The samples no. 1-20 and 23 were prepared by grinding applying a hammer mill, type Bąk H 111/3, with 3.0 mm screen mesh size. The samples no. 24 to 41 constituted feed mixtures. Materials numbered from 42 to 52 are feed meals used in daily pellet production at CLPP in Motycz.

Table II-3. List of the materials used in the agglomeration research program

No.	Material	Confined compression ZD40 press	Confined compression Instron	Exrussion ZD40 press	Pelletmill CLM
1	2	3	4	5	6
1	Maize meal	+			
2	Rice	+			
3	Wheat, cv. Alba	+			
4	Wheat, cv. Jara	+			

Table II-3. Cont.

1	2	3	4	5	6
5	Wheat, cv. Almary	+			
6	Oat, cv. Dragon	+			
7	Oat, cv. Pegaz	+			
8	Barley, cv. Aramir	+			
9	Barley, cv. Ars	+	+	+*	
10	Barley, cv. Edgar	+	+	+*	
11	Barley, cv. Klimek	+	+	+*	
12	Barley, cv. Kos	+	+	+*	
13	Rye, cv. Amilo	+	+	+*	
14	Rye, cv. Dańkowskie Nowe	+	+	+*	
15	Rye, cv. Dańkowskie Złote	+	+	+*	
16	Rye, cv. Warko	+	+	+*	
17	Faba bean, cv. Nadwiślański	+	+	+*	
18	Lupine, cv. Emir	+	+	+*	
19	Vetch, cv. Szelejewska	+	+	+*	
20	Meat-bone flour	+			
21	Soybean meal	+			
22	Maize 75% with rice 25%	+			
23	Maize 50% with rice 50%	+			
24	Maize 25% with rice 75%	+			
25	Maize 75% with oat, Pegaz 25%	+			
26	Maize 50% with oat, Pegaz 50%	+			
27	Maize 25% with oat, Pegaz 75%	+			
28	Maize 75% with wheat, Alba 25%	+			
29	Maize 50% with wheat, Alba 50%	+			
30	Maize 25% with wheat, Alba 75%	+			
31	Maize 75% with soybean 25%	+			
32	Maize 50% with soybean 50%	+			
33	Maize 25% with soybean 75%	+			
34	Rice 75% with soybean 25%	+			
35	Rice 50% with soybean 50%	+			
36	Rice 25% with soybean 75%	+			
37	Maize 50%, rice 25% and soybean 25%	+			
38	Maize 25%, rice 50% and soybean 25%	+			
39	Maize 25%, rice 25% and soybean 50%	+			
40	Maize meal	+*	+	+*	+*
41	Barley meal	+*	+	+*	+*
42	Pea meal	+*	+	+*	+*
43	Soybean meal	+*	+	+*	+*
44	Wheat meal	+*	+	+*	+*
45	Rapeseed meal	+*	+	+*	+*
46	Lupine meal	+*	+	+*	+*
47	Wheat bran	+*		+*	+*
48	Dry plant matter (alfalfa)	+*		+*	+*
49	Meat-bone flour		+	+*	
50	Rape seeds, cv. Ceres				+*

+) performed at five moisture content levels; +*) performed at one moisture content level.

9.1.1. Methods for physical properties and chemical composition determination

Moisture content of the materials was determined and established according to the procedures described in section 3.1.1.

The following materials properties were determined: bulk density, ρ_n, tapped density, ρ_u, compressibility index, $S_z = \rho_u\ \rho_n^{-1}$, angle of repose, α_u, angle of slide α_z, particle mean diameter, $d_ś$, and coefficient of internal friction, μ_b. For the above parameters, excluding the two last, the methods presented in section 3.1 (chapter I) were used. Particle mean diameter, $d_ś$, was determined according to the equation 11, section 4.2.

A commonly used direct shearing method and the apparatus type AB-2a was used for the internal friction coefficient measurements. A material sample was placed in 60 mm square shear box assembly. This two-piece box is constructed so that the top and bottom half can slide relative to each other. Material was consolidated, applying the normal load (stress), which value was read from a dial vertical extensometer. During shear, the sample was horizontally displaced by a precision motor turning a screw. The constant strain rate was adjusted by a controller. The shearing force was measured by an extensometric system. Analogue signal from the extensometer was converted by a digital transducer and directed to the PC. Adjusted software allowed load-time or load-deformation characteristics to be recorded. All experiments were done for five following values of the normal load, i.e., 1, 1.5, 2, 2.5, and 3 kN. Average value of the internal friction coefficient was calculated from three repetitions.

Percentages of four following constituents of the feed materials and mixtures, i.e., ash (P_s), fibre (W_s), protein (B_o), and fat (T_s) was obtained from chemical analyses (Tab. III-48).

9.2. Determination of parameters of confined compression

The experiments were done according to research procedures elaborated in Department of Equipment Operation and Maintenance in Food Industry [29,30,38,45].

9.2.1. Equipment description

A measurement system with computer data recording of compression loads and piston displacements adapted to the hydraulic press, type ZD40 was presented in Figure II-1.

An original ring extensometric gauge (5) was designed to measure the compressive load. In order to that, a steel ring was glued with four resistance extensometers, two on the internal as well on the external surface of the ring, along the axis perpendicular to the loading force. This full bridge strain system was connected to an amplifier (7), from generated signal was directed to the PC computer (10), through a digital transducer (9).

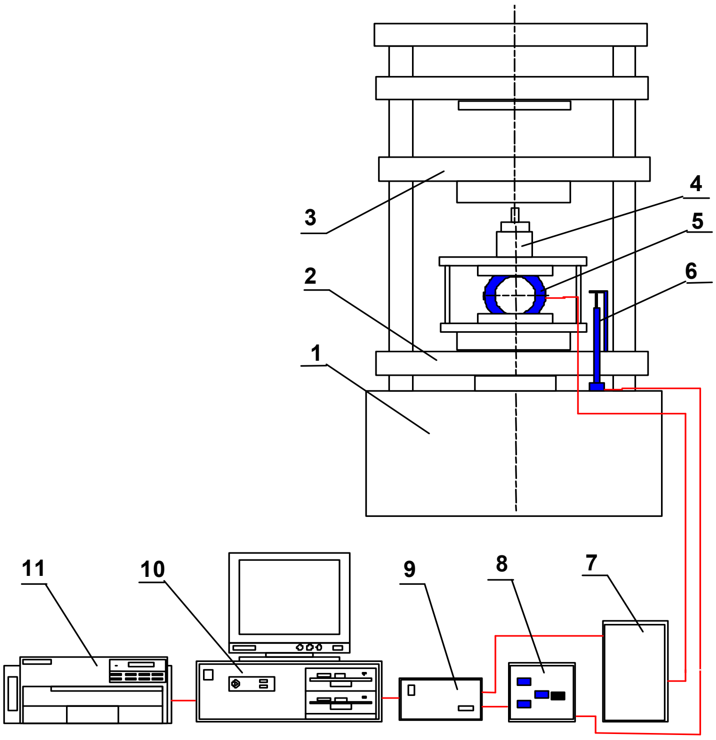

Fig. II-1. Experimental set-up for compression and extrusion testing: 1 – hydraulic press ZD40, 2 – moving bottom table, 3 – fixed upper table, 4 – compressing assembly, 5 – extensometric transducer, 6 – displacement transducer, 7 – amplifier, 8 – displacement amplifier MPL, 9 – analogue-digital transducer, 10 – PC computer, 11 – printer [43]

A movement of the loading piston was recorded with the help of a displacement transducer, type Psx (6), connected to a displacement amplifier MPL (8), and through a digital transducer (9) to the PC computer.

The loads and corresponded to them the piston displacements, recorded during one experiment, composed compression characteristics (curves), which were the subject of precise analyses. Specialized software allowed value of loads, density, energy inputs, etc. to be assessed for any point of the compression curve.

Another measuring system presented previously in Figure I-2 was designed to the Instron machine.

The compression chamber (Fig. II-2) of 25 mm diameter was used in the experiments.

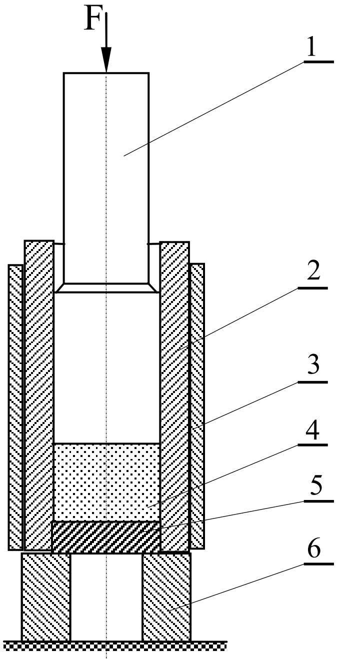

Fig. II-2. Scheme of the compression assembly: 1 – piston, 2 – cylinder, 3 – heating coat, 4 – compressed medium, 5 – bottom disk or ring (die), 6 – bottom stand

The main part of the system is a compression assembly (Fig. II-2). This assembly was set on the bottom table of the universal machine Instron 4302. Loads induced by the upper moving plate were received with the help of a digital transducer and recorded with the PC computer. The constant and adjusted capture speed helped to determine displacement of the piston [30]. The load-displacement curves were composed the two from.

In the experiments curried out on the Instron equipment, the compression assembly (Fig. II-2) of 15 mm diameter was used.

9.2.2. Determination of parameters of confined compression

The confined compression experiments were being done for material at the following five moisture levels, i.e., 10, 12, 14, 16, and 18% (±0.2%) according to the procedures described below.

The compression chamber (Fig. II-2) was filled with material sample, and fixed on the press table. Material was pressed with the compression rate equal to 0.3 mm s^{-1} for the ZD40 press, and 0.1 mm s^{-1} in the case of the Instron, until fixed load of 100 kN for the ZD press, and 9 kN for the Instron was achieved.

The formulated capsule (agglomerate) after had being removed outside the compression assembly was measured. Its height and diameter were determined.

A successive strength testing was undertaken for the agglomerates that had been obtained from the Instron experiments (just after compression). The agglomerates from ZD40 press were tightly closed and stocked over 24 hours. After that, their basic dimensions (height and diameter) were determined again, and they were subsequently submitted to the resistance testing.

The compression characteristics (curves) were registered for each individual test (Fig. II-3). A precise description of the compression characteristic was done in [27, 29, 30, 38].

On the basis, of the compression curves (Fig. II-3) the following process parameters were assigned and determined.

a) the compression load F_b, (also noted compression force) and corresponding to it the compression pressure P_b,
b) the compression energy L_b, (also noted as compression work) and corresponding to it the specific compression energy L_b', (work), Eq. 14,
c) the total compression energy $L_{c,}$ (also noted as total compression work) as the sum of the compression energy L_b, and the compaction energy L_s, ($L_c = L_b + L_s$) and corresponding specific total compression energy L_c', Eq. 16,
d) material densities ρ_b and ρ_c, at the points B and C points respectively.

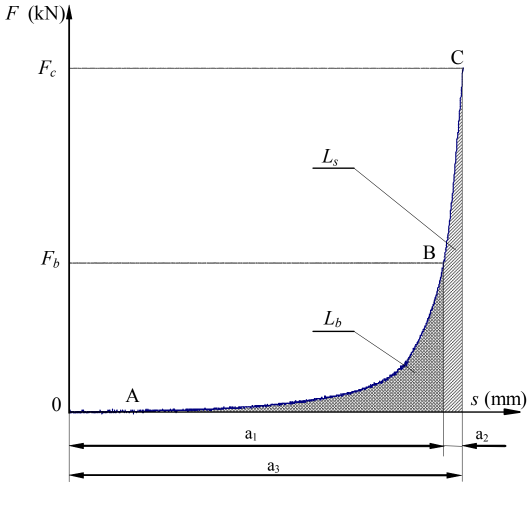

Fig. II-3. Compression characteristic: a_1 – main compression stage, a_2 – compaction stage, a_3 – compression

Three following coefficients of the material ability to agglomeration were determined.

a) the coefficient of material ability to compression k_1**,** (representing changes in material density under loading) according to the formulae:

$$k_1 = \frac{\rho_b / \rho_n}{P_b} \quad (\mathrm{MPa^{-1}}) \tag{12}$$

where ρ_b is the material density in the compression chamber corresponding to B point of the compression curve (g cm^{-3}), ρ_n is the initial material density (bulk density) (g cm^{-3}), and P_b is the compression pressure at B point, in MPa.

b) coefficient k_2, (a rate of the specific compression energy input L_b', to the corresponding increase in the material density) following the equation:

$$k_2 = \frac{L_b'}{\rho_b - \rho_n} \quad \left(\frac{\mathrm{J\,g^{-1}}}{\mathrm{g\,cm^{-3}}}\right) \tag{13}$$

$$L_b' = \frac{L_b}{m} \quad (\mathrm{J\,g^{-1}}) \tag{14}$$

where m is mass of the sample in grams.

c) coefficient k_3, (a rate of the specific total compression energy L_c', to the corresponding increase in the material density) according to the equation:

$$k_3 = \frac{L_c'}{\rho_c - \rho_n} \quad \left(\frac{\mathrm{J\,g^{-1}}}{\mathrm{g\,cm^{-3}}}\right) \tag{15}$$

where:

$$L_c' = \frac{L_c}{m} \quad (\mathrm{J\,g^{-1}}) \tag{16}$$

Necessary to the description, the material densities ρ_b and ρ_c, at the B and C points of the compression curve were calculated from the equations below:

$$\rho_b = \frac{m}{V_1} \qquad \rho_c = \frac{m}{V_2} \quad (\text{g cm}^{-3}) \qquad (17a, b)$$

where V_1 is the volume of the compressed material corresponding to the load at point B (pistons position), (cm^3), V_2 is the material volume corresponding to the load at point C, (cm^3), and m is the sample mass in grams.

Apart the above calculations, the density of agglomerates (capsules) just after removing from the compression chamber, as well as after 24 hours storage time, were determined (the former density, only for the Instron testing).

The densities of agglomerates after removing from the compression chamber, and after 24 hours of stocking were determined according to the equations 18 and 19 respectively:

$$\rho_k = \frac{m_k}{V_k} = \frac{4m_k}{\pi d_k^2 h_k} \quad (\text{g cm}^{-3}) \qquad (18)$$

where m_k is the agglomerate's weight (g), and V_k, d_k, h_k are the volume, in cm^3, diameter, in cm, and height, in cm, of the agglomerate just after being removed from the compression chamber, respectively.

$$\rho_{k1} = \frac{m_{k1}}{V_{k1}} = \frac{4m_{k1}}{\pi d_{k1}^2 h_{k1}} \quad (\text{g cm}^{-3}) \qquad (19)$$

where m_{k1} is the agglomerate's weight (g), and V_{k1}, d_{k1}, h_{k1} are the volume, in cm^3, diameter, in cm, and height, in cm, of the agglomerate after the 24 hour storing time, respectively.

Strength of agglomerates was evaluated by the uniaxial compression method on the Instron machine. The compression strength of agglomerate, i.e., the maximum load that an agglomerate of known diameter is able to withstand, was determined according to the equation:

$$\sigma_n = \frac{4F_n}{\pi\, d_a^{\,2}} \quad (\text{MPa}) \qquad (20)$$

where F_n is ultimate load, (in N), and d_a is the diameter of the agglomerate, (m).

The shape retention ability coefficient k_4, as a criterion expressing quality of the agglomerates was determined from the equation below:

$$k_4 = \frac{\sigma_n}{P_b} \qquad (21)$$

where σ_n is the compression strength of the agglomerate from the equation 20.

Average values for the above compression parameters and coefficients based on three repetitions for each material and experiment conditions.

9.3. Determination of parameters of extrusion and pelleting

Extrusion experiments followed procedures elaborated and described by Laskowski and Skonecki [27, 38], Laskowski *et al.* [23] applying a ZD40 hydraulic press. The granulation process experiments were done with the help of a CLM laboratory pelletmill.

9.3.1. Equipment description

Equipment for the extrusion testing was identical to that used for the compression experiments. The only difference was that, in the compression assembly (Fig. II-2), the bottom disk was replaced by a ring with the central hole of 5 mm diameter to allow the material extrusion from the compression zone.

The pelletmill was equipped with a system to the electrical power measurement (a three-phase wattmeter type MOD C52a connected to the main press motor). The pelletmill was driven by a three-phase motor of 10 KM of nominal power, and the rotor speed of 960 RPM. The pelleting assembly of the machine constituted of a ring matrix (200 mm of the internal diameter, with the thickness of 60 mm, and the width of 40 mm) with the 5 mm hole diameter, and the two pressing rolls of the diameter 90 mm and width 36 mm each.

9.3.2. Operating conditions and parameters of extrusion and pelleting

The extrusion experiments on ZD40 press followed similar procedures used for the compression research (section 9.2.2). An extrusion characteristic was recorded during each individual test (Fig. II-4).

The extrusion curve, until the point C is reached, consists of two distinct phases (stages). First, up to the point B called the main compression phase or proper compression phase a_1, and second beyond B point called the compaction phase a_2. At higher piston displacements than it corresponding to C point, this represents displacements up to the point E, material is being extruded from the compression zone. This stage may be split into the two following phases:

a) phase of material outflow accompanied by a decrease in the compression loads with the progressive piston displacement *s*, called the extrusion phase, a_4,
b) phase of material outflow accompanied by an increase in the compression loads named the final extrusion phase a_5, (beginning at D point).

The following nomenclature was used to characterise the two above specific points within the extrusion range. The initial point C was named as the outflow limit, and to the phases' splitting point D, the extrusion limit notation was designated.

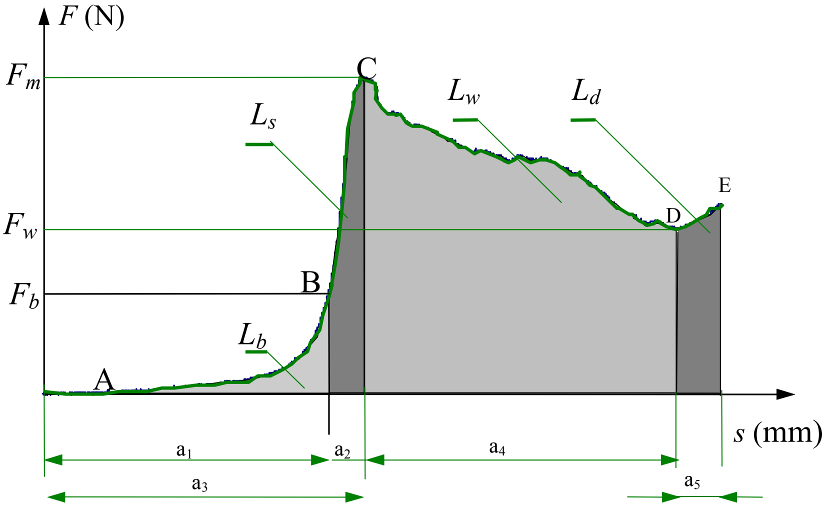

Fig. II-4. A characteristic recorded during one extrusion test (description in the text)

For the needs of the present work, in the subsequent analyses of the extrusion process, the parameters of the compression, previously described in section 9.2.2, were used, i.e., the compression pressure, and the specific compression and compaction energy expenditures.

Basing of the extrusion characteristics, the following parameters were determined:

a) values of the loads corresponding to the outflow limit F_m, and to the extrusion limit F_w,
b) values of the energy expenditures for the extrusion phase L_w, and for the final extrusion phase L_d.

In the analyses of the extrusion process, apart the above, we calculated:

a) the overall energy expenditure for the agglomeration L_k, according to the equation:

$$L_k = L_c + L_w \tag{22}$$

b) the overall energy expenditure for the extrusion L_z, from the equation:

$$L_z = L_k + L_d \tag{23}$$

In the analogous way to the compression experiments, the already known coefficients k_1, k_2, k_3 were determined, in order for the material ability to agglomeration assessment.

Material density changes based on the density values for the distinguished points of the extrusion curve, already denoted ρ_b and ρ_c at B and C points respectively. For the extruded product the capsule diameter d_g, was determined.

During the granulation experiments on CLM pelletmill, the following were measured:

a) material moisture content w_s, and moisture of agglomerate w_g,
b) temperature of agglomerate t_g, °C,
c) diameter of agglomerate d_g, mm,
d) mass of extruded agglomerates m_g, kg,
e) time of the granulation τ, in hours,
f) electrical energy expenditures E, kWh.

Afterwards, in the view to the process analysis the succeeded were calculated.

g) capacity of the press $Q_g = m_g \tau$, kg h^{-1},
h) mean electric output $P = E\ \tau$, kW,
i) specific energy consumption, $E_j = 1000E\ m_g^{-1}$, kWh t^{-1}.

The obtained agglomerates were successively employed to the strength testing and the following were determined:

a) failure load F_{ng}, N,
b) failure load related to the length of the agglomerate according to the equation:

$$W_{ng} = \frac{F_{ng}}{l} \quad (\mathrm{N\ mm^{-1}}) \tag{24}$$

where l is length of the tested agglomerate in mm.

c) pellet durability according to Pfost, P_{di}, %.

Strength characteristics of the agglomerates were determined on the Instron universal machine 4302. The loading force was acting perpendicularly to the main axis of the agglomerate of known length. The resulted failure load F_{ng}, was recorded. The pellet durability was determined according to the standard BN-71/9160-03 on a Pfost tester.

9.4. General conditions of agglomeration experiments

A general specification of the devices and feedstuffs used in the present work together with the moisture levels employed, are presented in Table II-4.

The granulation experiments were executed on a ring-die pelletmill CLM, using the die with 5 mm holes diameter (a specification of the mill was given in section 7.3.1). Nine feedstuffs (cereal meals), commonly used in industrial practice, were used in the research (Tab. II-3 no. 42-50, 52). The pelleting was made without steam conditioning.

Table II-4. Operating conditions of compression and extrusion studies

Material (no. according to Table II-3)	Moisture content w (%)	Sample mass m (g)	Piston diameter D (mm)	Piston speed (mm s^{-1})	Die temperature t (°C)	Max. compressive load F_c (kN)
Compression, ZD40 press						
1-41	10,12,14, 16,18	20	25	0.3	20	100
42-50	14	20	25	0.3	20	100
Compression, Instron universal machine						
9-20,42-48, 51	10,12,14, 16,18	3	15	0.1(6)	20	9
Extrusion, ZD40 press						
9-20, 42-51	14	20	25	0.3	80	Outflow limit F_m

10. INFLUENCE OF MATERIAL PROPERTIES ON AGGLOMERATION

10.1. Raw material properties analysis

The undertaken analysis includes only general notes on the physical properties of the materials used in the research. The results will be used in next stages in order for more profound description of the agglomeration process.

Average values of the physical properties at various moisture levels of the 51 feedstuffs are presented in chapter III, Table III-41 to III-47.

Bulk density of the materials (Tab. III-41) ranged from 0.174 to 0.796 g cm^{-3}. The lowest values were noticed for dry plant matter (alfalfa) from 0.174 to

0.188 g cm^{-3} within the moisture range studied, and the largest for faba bean cv. Nawiślański from 0.696 to 0.796 g cm^{-3}.

Tapped density values ranged from 0.232 to 0.917 g cm^{-3} (Tab. III-42). Within the range of moisture tested, tapped density of alfalfa was the lowest (0.232-0.48 g cm^{-3}) and density of faba bean was the highest (0.787-0.917 g cm^{-3}).

Mean values of the angle of repose as well as the angle of slide are presented in Tables III–43 and III-44. The values are between 34.6 and 50° for the former, and between 16.8 and 42.8° for the latter parameter. The highest angle of repose was observed for dry alfalfa (48.6-50.03°) and the lowest for rice (34.6-41.8°). The angle of slide was the lowest for barley meal (cv. Edgar (16.8-23.5°) and cv. Klimek (16.8-24.3°), and the highest for meat-bone flour (34.5-42.8°).

Table III-45 presents mean values of the coefficient of internal friction. Its values ranged from 0.383 to 1.04. The lowest were noticed for bone-meat flour (0.383-0.683), and the highest for the 25/75 rice and soybean mixture (0.907-1.04).

The compressibility index ranged between 1.032 and 1.346 (Tab. III-46). Wheat cultivar Jara had the lowest values (1.032-1.065), and dry green matter had the highest (1.281-1.346).

Particle mean diameter of the meals employed to the agglomeration (Tab. III-47) ranged from 0.58 to 1.28 mm. The smallest particles were characteristic for meat-bone flour (0.58-0.73 mm), and the largest for wheat meal (1.10-1.28 mm).

10.2. Results of the confined compression studies

The results of the confined compression experiments are presented in Tables III-49 to III-99 (chapter III). The tables include (according to the operating conditions listed in Tables II-3 and II-4) average values, standard deviations, standard errors, and 95% confidence intervals for experimental data, for selected parameters within the material moisture levels applied.

10.2.1. Influence of feedstuffs moisture on compression process parameters and the ability to compression

The analysis of the influence of feedstuffs moisture on the compression process based on changes, induced by it, in the following parameters:

a) material densities within the successive compression phases, ρ_b and ρ_c, and density of agglomerates, ρ_k and ρ_{k1};
b) compression process parameters, i.e., compression load P_b, and specific energy expenditures L_b', L_s', and L_c';
c) coefficients of the material ability to compression k_1, k_2, k_3;

d) strength characteristics of the agglomerate σ_n, as well as the shape retention ability coefficients k_4, in the view for the quality assessment of final products.

The analyses done, dealt with the feedstuffs compressed on the ZD40 press and the universal machine Instron separately. Relationships between a particular parameter and the material moisture were presented in the form of regression equations. Validity of the equations and their parameters were verified at the 0.05 significance level. The nonlinear estimation was applied.

The regression analyses results, applying to the whole material set, are presented in Table II-5 and Table II-7 for ZD40 press and Instron respectively. Their general forms have been validated for four leguminous seeds (faba bean, pea, lupine and vetch) (Tab. II-6 and II-8).

Material moisture content, what can be noticed when analyzing the results in Tables II-5 to II-8, influences significantly changes of material density, process parameters, the material ability to compression coefficients, and evidently, agglomerate quality criteria. The regression forms allow the decrease of the confined compression process parameters P_b, L_b, L_c to be associated with a rise of the material moisture. In the case of the compression work L_s, the influence of the moisture was not unambiguous.

Table II-5. Regression equations to predict compression process parameters as a function of material moisture (ZD40 press, all materials included)

Equation form	Correlation coefficient R	p-value
$\rho_b = -0.00015w^2 + 1.50$	–0.215	0.000
$\rho_c = -0.00007w^2 + 1.55$	–0.117	0.003
ρ_k – not significant	–	–
$\rho_{k1} = -0.00026w^2 + 1.17$	–0.198	0.000
$P_b = -0.204w^2 + 130.1$	–0.476	0.000
$L_b^{'} = -0.653w + 15.9$	–0.597	0.000
$L_s^{'} = 0.051w + 3.07$	0.124	0.002
$L_c^{'} = -0.618w + 19.2$	0.741	0.000
σ_n – not significant	–	–
$k_1 = 0.00016w^2 + 0.0073$	0.310	0.000
$k_2 = -0.777w + 18.5$	–0.615	0.000
$k_3 = -0.686w + 20.9$	–0.616	0.000
$k_4 = 0.0018w + 0.0006$	0.180	0.000

Table II-6. Regression equations to predict compression process parameters as a function of material moisture (ZD40 press, only leguminous seeds included)

Equation form	Correlation coefficient R	p-value
$\rho_b = -0.00012w^2 + 1.50$	–0.303	0.018
ρ_c – not significant	–	–
ρ_k – not significant	–	–
ρ_{k1} – not significant	–	–
$P_b = -8.36w + 213.6$	–0.780	0.000
$L_b' = -0.925w + 20.3$	–0.879	0.000
L_s' – not significant	–	–
$L_c' = -0.856w + 23.6$	–0.912	0.000
$\sigma_n = 0.362w - 2.56$	0.609	0.000
$k_1 = 0.00013w^2 + 0.00015$	0.559	0.000
$k_2 = -1.27w + 27.5$	–0.855	0.000
$k_3 = -1.19w + 30.5$	–0.858	0.000
$k_4 = 0.0059w - 0.054$	0.845	0.000

Table II-7. Regression equations to predict compression process parameters as a function of material moisture (Instron, all materials included)

Equation form	Correlation coefficient R	p-value
$\rho_b = 0.018w + 1.01$	0.662	0.000
$\rho_c = 0.019w + 1.07$	0.665	0.000
$\rho_k = 0.009w + 1.01$	0.299	0.000
$P_b = -0.553w + 39.4$	–0.453	0.000
$L_b' = -0.0025w^2 + 4.17$	–0.320	0.000
$L_s' = -0.0017w^2 + 2.35$	–0.292	0.000
$L_c' = -0.0042w^2 + 6.52$	–0.433	0.000
$\sigma_n = 0.274w - 2.39$	0.468	0.000
$k_1 = 0.0001w^2 + 0.046$	0.609	0.000
$k_2 = -0.012w^2 + 8.44$	–0.594	0.000
$k_3 = -0.016w^2 + 11.48$	–0.672	0.000
$k_4 = 0.01w - 0.097$	0.520	0.000

Table II-8. Regression equations to predict compression process parameters as a function of material moisture (Instron, only leguminous seeds included)

Equation form	Correlation coefficient R	p-value
$\rho_b = 0.0005w^2 + 1.18$	0.541	0.000
$\rho_c = 0.0005w^2 + 1.25$	0.496	0.000
$\rho_k = 0.018w + 0.89$	0.545	0.000
$P_b = -0.735w + 46.01$	–0.583	0.000
$L_b' = -0.0046w^2 + 5.17$	–0.542	0.000
$L_s' = -0.0012w^2 + 1.72$	–0.265	0.041
$L_c' = -0.0058w^2 + 6.86$	–0.545	0.000
$\sigma_n = 0.0172w^2 - 2.62$	0.762	0.000
$k_1 = 0.0001w^2 + 0.034$	0.558	0.000
$k_2 = -0.018w^2 + 11.25$	–0.668	0.000
$k_3 = -0.0206w^2 + 13.24$	–0.679	0.000
$k_4 = 0.0005w^2 - 0.084$	0.751	0.000

An increase in the feedstuffs moisture makes them more favoured to the compression. Higher moisture level induces an increase in the material ability to compression coefficient k_1, and decrease of the coefficients k_2 and k_3. Better agglomerate quality may be also expected. Agglomerates of higher strength σ_n, as well as of better ability to the shape retention (larger coefficient k_4) were obtained when had been compressed at higher moisture levels.

Changes of the material density as well as the agglomerate density showed a varied moisture dependency for the two types of presses used. The variability is probable to result from the relatively high differences in the maximum compressive load applied.

In a preliminary analysis, regression equations to describe the material moisture implications to the compression processing, were calculated for the group of leguminous seeds compressed on the ZD40 press. The results are listed in Tables II-9 to II-11. Some exemplary moisture generated changes of the compression parameters are presented in Figure II-5 to II-9. The data confirm the general trends observed in the previous regression analyses where all the materials had been being included.

The analyses correlating the agglomeration process parameters to the material moisture, presented above, allow, in some cases, the proportional interrelations to be observed. It concerns both the process parameters and the coefficients of the material ability to agglomeration. According to that, an assessment of the material ability to agglomeration for only one moisture level might be reasoned.

The literature review done on the above issue, and some experience from own experiments suggest the average moisture content about 14% to be the most adequate to determine the material ability to compression. For this moisture level, the employed in the research feedstuffs may be classified according to the mentioned criteria, what was done and presented in section 11.

Table II-9. Regression equations describing changes in the compression pressure P_b, and the specific energy expenditures L_b', and L_c' as a function of material moisture, w

Material	Equation form	Correlation coefficient R	p-value
Faba bean	$P_b = -7.88w + 213.5$	0.984	0.000
Pea	$P_b = -6.74w + 211.8$	0.954	0.000
Lupine	$P_b = -11.34w + 227.4$	0.991	0.000
Vetch	$P_b = -7.48w + 201.6$	0.985	0.000
Faba bean	$L_b' = -0.67w + 16.82$	0.980	0.000
	$L_c' = -0.68w + 20.86$	0.976	0.000
Pea	$L_b' = -1.01w + 22.62$	0.959	0.000
	$L_c' = -1.10w + 27.54$	0.939	0.000
Lupine	$L_b' = -1.23w + 22.81$	0.978	0.000
	$L_c' = -0.73\mathrm{w} + 22.06$	0.936	0.000
Vetch	$L_b' = -0.78w + 18.96$	0.988	0.000
	$L_c' = -0.90w + 25.01$	0.983	0.000

Table II-10. Regression equations describing relationships between the coefficients k_1, k_2 and k_3 and material moisture, w

Material	Equation form	Correlation coefficient R	p-value
Faba bean	$k_1 = 0.0003w^2 - 0.0055w + 0.04$	0.991	0.000
Pea	$k_1 = 0.000051w^2 + 0.0078w$	0.976	0.000
Lupine	$k_1 = 0.0011w^2 - 0.0231w + 0.14$	0.993	0.000
Vetch	$\mathrm{k}_1 = 0.0003w^2 - 0.0065w + 0.05$	0.985	0.000
Faba bean	$k_2 = -1.027w + 24.5$	0.987	0.000
Pea	$k_2 = 0.125w^2 - 5.02w + 55.8$	0.982	0.000
Lupine	$k_2 = 0.12w^2 - 4.64w + 47.4$	0.998	0.000
Vetch	$k_2 = -1.20w + 27.77$	0.991	0.000
Faba bean	$k_3 = -1.02w + 28.58$	0.982	0.000
Pea	$k_3 = 0.169w^2 - 6.33w + 68.8$	0.983	0.000
Lupine	$k_3 = 0.112w^2 - 4.01w + 44.2$	0.993	0.000
Vetch	$k_3 = -1.31w + 33.75$	0.989	0.000

Table II-11. Regression equations describing changes in the agglomerate strength σ_n, and the k_4 coefficient as a function of material moisture, *w*

Material	Equation form	Correlation coefficient *R*	p-value
Faba bean	$\sigma_n = -0.045w^2 + 1.62w - 10.8$	0.936	0.000
Pea	$\sigma_n = -0.038w^2 + 1.67w - 12.0$	0.931	0.000
Lupine	$\sigma_n = -0.013w^2 + 0.46w - 3.04$	0.910	0.000
Vetch	$\sigma_n = -0.050w^2 + 1.85w - 12.2$	0.932	0.000
Faba bean	$k_4 = 0.0055w - 0.049$	0.976	0.000
Pea	$k_4 = 0.0068w - 0.061$	0.945	0.000
Lupine	$k_4 = 0.0039w - 0.039$	0.964	0.000
Vetch	$k_4 = 0.0076w - 0.067$	0.977	0.000

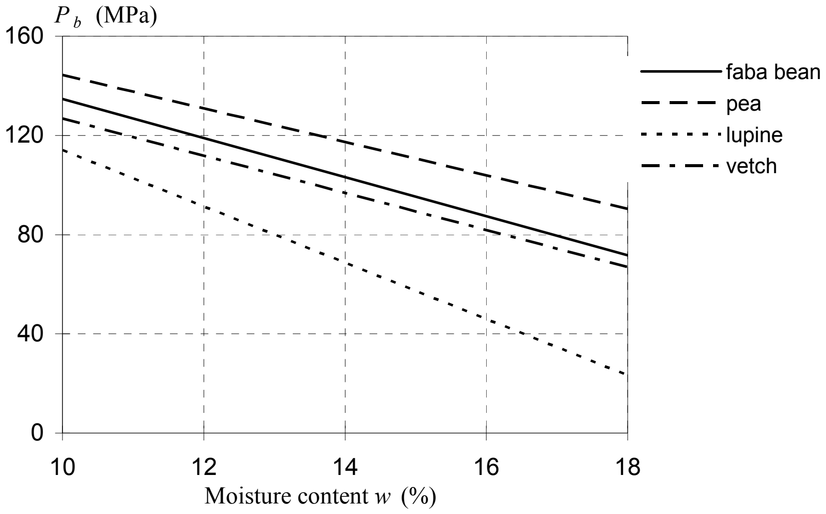

Fig. II-5. Relationships between the compression pressure P_b, and material moisture, *w*

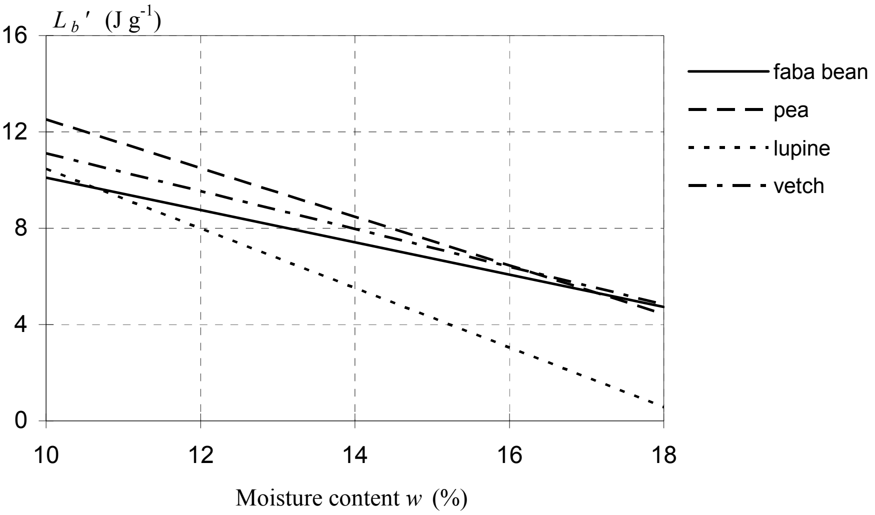

Fig. II-6. Relationships between the specific compression energy expenditure L_b', and material moisture, w

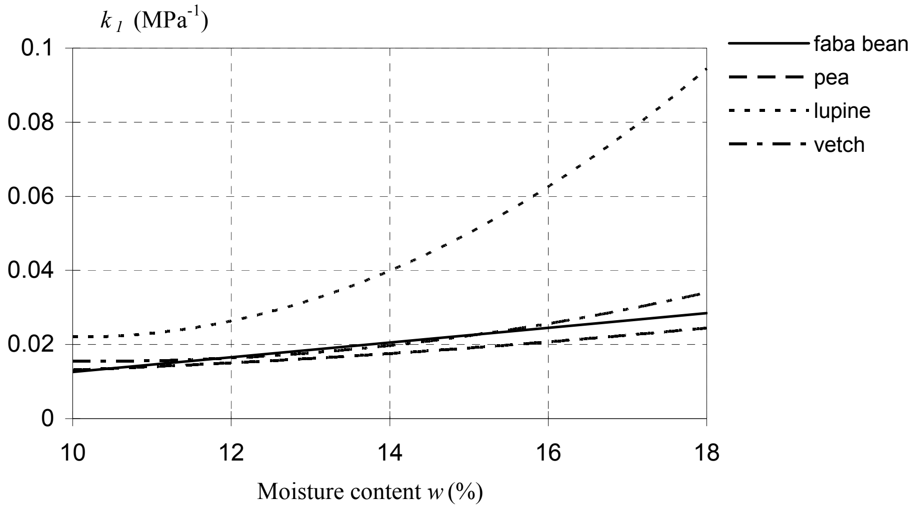

Fig. II-7. Relationships between coefficient k_1 and material moisture, w

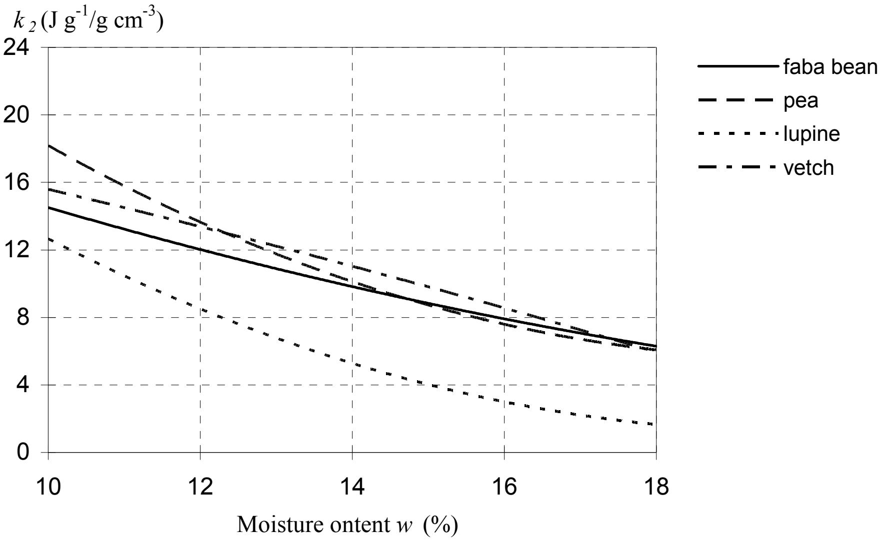

Fig. II-8. Relationships between coefficient k_2 and material moisture, w

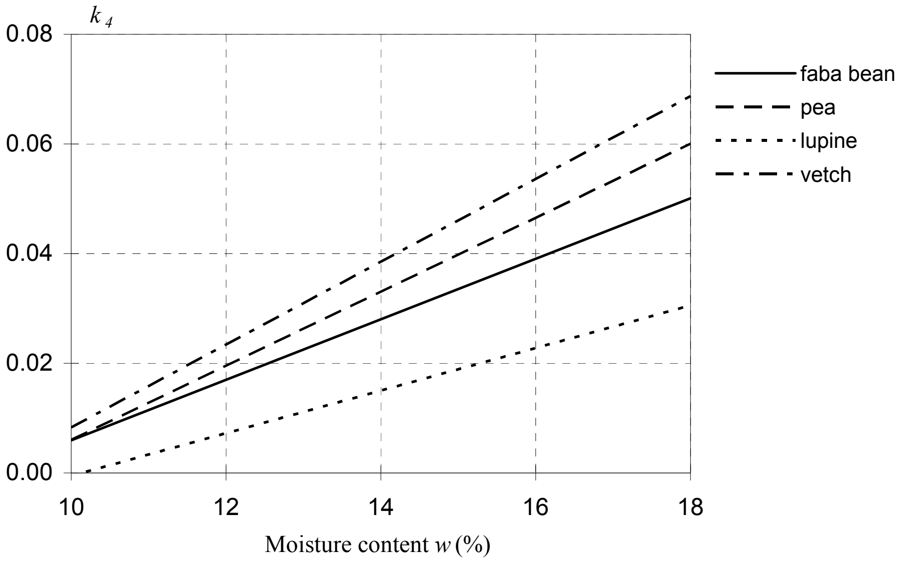

Fig. II-9. Relationships between coefficient k_4 and material moisture, w

10.2.2. Influence of feedstuff physical properties on compression process parameters and the ability to compression

Numerous experimental data focussed us on a rather synthetic analysis of the interfaces between the material properties and features of the compression process. An attempt was made to represent the observed interactions in form of analytical equations. The general functional formulae may be expressed as:

$$c = f\,(\rho_n,\ \rho_u,\ \alpha_u,\ \alpha_z,\ \mu_b,\ S_z,\ d_ś) \tag{25}$$

where c is a compression process criterion.

The independent variables in the model were the physical properties of feedstuffs described in section 9.1.1. The multiple linear regression method was used to the model development. The resulting equations and their parameters were statistically assessed at the 0.05 significance level. The insignificant variables were excluded from the models.

In the preliminary stage of the analyses, general relations for the materials compressed on the ZD40 press within the whole range of moisture used, were being attained (materials no. 1-40, Tab. II-3). The resulting equations and their parameters are listed in Table II-12.

Table II-12. Regression equations to predict compression parameters as a function of material moisture (ZD40 press, materials no. 1-41)

Parmeter	Regression coefficients for dependent variables								Corr.Coeff.	p-value
	Intercept	ρ_n	ρ_u	α_u	α_z	μ_b	S_z	$d_ś$	R	
ρ_b	1.48	0.250				–0.205			0.633	0.00
ρ_c	1.09		0.332	0.0045	0.0028	–0.187		0.113	0.705	0.00
ρ_k	0.65		0.692		0.0029	–0.237		0.215	0.804	0.00
ρ_{k1}	0.46		0.918			–0.286		0.278	0.793	0.00
L_b	628.7			–5.21	–6.48			–106.9	0.642	0.00
L_s	6.17				1.22			38.67	0.364	0.00
L_c	618.3			–6.29	–5.31				0.621	0.00
P_b	159.1		85.5		–3.28	–46.87			0.713	0.00
L_b'	31.4			–0.260	–0.324			–5.35	0.642	0.00
L_s'	0.299				0.061			1.94	0.364	0.00
L_c'	30.8			–0.314	–0.265				0.621	0.00
k_1	–0.137				0.0038			0.076	0.574	0.00
k_2	26.4		10.32	–0.271	–0.346			–5.32	0.711	0.00
k_3	25.6	13.63		–0.253	–0.262			–5.04	0.76	0.00
k_4	–0.623	1.15	–1.15				0.653		0.644	0.00
σ_n	–54.3	100.8	–98.8				55.46		0.448	0.00

The material physical characteristics employed in the analysis, influenced the course of agglomeration process less or more noticeably (Tab. II-12). Between them, some relevancy was reported for: angle of repose α_z, angle of side α_u, mean particle size $d_ś$, tapped density ρ_u, and coefficient of internal friction μ_b.

The analysis of the material relevancy to the distinguished phases of the compression process phases has led to some interesting observation. The densities of material ρ_b and ρ_c, as well as densities of agglomerate ρ_k and ρ_{K1} showed to be dependent on some material features including internal friction coefficient, tapped density and particle size. They were also related to the angle of repose and angle of slide and material bulk density ρ_n. Higher values of the internal friction coefficient lowered the material densities at B and C points. For the others of the material physical characteristics inverse consequences on the two densities were noticed.

Table II-13. Regression equations to predict compression parameters as a function of material moisture (ZD40 press, materials no. 9-20)

Parameter	Regression coefficients for dependent variables								Corr.Coeff.	p-value
	Intercept	ρ_n	ρ_u	α_u	α_z	μ_b	S_z	$d_ś$	R	
ρ_b	1.04	0.176		0.005	–0.005		0.204		0.742	0.00
ρ_c	1.61		0.058		–0.004				0.629	0.00
ρ_k	0.937	0.508							0.837	0.00
ρ_{k1}	0.790	0.619							0.802	0.00
L_b	435.1					–211.1		–145	0.720	0.00
L_s	2186	–2778	2432	–3.84			–1712		0.723	0.00
L_c	640.4			–5.33		–282.0			0.688	0.00
P_b	257.1					–122.3		–69.3	0.750	0.00
L_b'	21.75					–10.55		–7.25	0.720	0.00
L_s'	109.3	–138.9	121.6	–0.192			–85.61		0.723	0.00
L_c'	32.02			–0.266		–14.10			0.688	0.00
k_1	0.054						–0.088	0.072	0.710	0.00
k_2	7.49	20.59				–17.04			0.758	0.00
k_3	50.8			–0.495		–8.76		–12.2	0.789	0.00
k_4	–0.027					0.069			0.499	0.00
σ_n	no significant coefficients									

Table II-14. Regression equations to predict compression parameters as a function of physical properties of feedstuffs (Instron, materials no. 9-20 from Table II-3)

Para-	Regression coefficients for dependent variables								Corr.Coeff.	p-value
meter	Intercept	ρ_n	ρ_u	α_u	α_z	μ_b	S_z	$d_ś$	R	
ρ_b	1.35		–0.538			0.437			0.684	0.00
ρ_c	1.46		–0.547			0.389			0.646	0.00
ρ_k	no significant coefficients									
L_b	no significant coefficients									
L_s	9.89			–6.53					0.541	0.001
L_c	no significant coefficients									
P_b	no significant coefficients									
L_b'	no significant coefficients									
L_s'	3.29			–2.17					0.541	0.001
L_c'	no significant coefficients									
k_1	0.018	–0.113	0.003			0.055			0.938	0.00
k_2	7.19	7.32						–6.63	0.789	0.00
k_3	1.72	15.44		–6.85					0.774	0.00
k_4	0.201	–0.202							0.527	0.001
σ_n	6.36	–6.37							0.521	0.001

Table II-15. Regression equations to predict compression parameters as a function of physical properties of feedstuffs (ZD40 press, materials no.42-48 from Table II-3)

Para-	Regression coefficients for dependent variables								Corr.Coeff.	p-value
meter	Intercept	ρ_n	ρ_u	α_u	α_z	μ_b	S_z	$d_ś$	R	
ρ_b	no significant coefficients									
ρ_c	1.50	–0.865	0.760						0.841	0.00
ρ_k	no significant coefficients									
ρ_{k1}	no significant coefficients									
L_b	no significant coefficients									
L_s	no significant coefficients									
L_c	113.1	–155.8	130.1	6.07	–7.98	44.2		47.1	0.999	0.03
P_b	no significant coefficients									
k_1	0.065	–0.077		–0.0008	0.0013				0.999	0.00
k_2	no significant coefficients									
k_3	8.73	9.85		0.206	–0.401				0.985	0.001
k_4	–0.062	–0.133			0.005				0.955	0.002
σ_n	–4.22	–13.55			0.475				0.927	0.007

Table II-16. Regression equations to predict compression parameters as a function of physical properties of feedstuffs (Instron, materials no. 42-48 from Table II-3)

Parameter	Regression coefficients for dependent variables								Corr.Coeff.	p-value
	Intercept	ρ_n	ρ_u	α_u	α_z	μ_b	S_z	$d_ś$	R	
ρ_b	0.648	4.47	–3.75		0.0021	0.227		0.420	0.999	0.01
ρ_c	0.778	3.62	–3.27		0.0055	0.264		0.434	0.989	0.24
L_b	27.7	23.22	–34.49					–5.93	0.968	0.02
L_s	11.33	–60.1	39.18		0.139				0.932	0.07
L_c	39.56	–42.50	10.46	0.112	0.018			–8.76	0.999	0.01
P_b	35.29		–6.70	0.423	–0.460	3.58		–8.89	0.999	0.03
k_1	0.062	0.163	–0.218		0.0006	0.016		0.039	0.989	0.24
k_2	14.68	–26.40	24.27			–4.08		–7.89	0.960	0.14
k_3	19.76	–59.9	53.45			–6.00		–10.07	0.990	0.03

Interesting outcomes were being obtained for the compression parameters, and coefficients of the material ability to compression, as well as for the agglomerate quality criteria. All the confined compression parameters P_b, L_b, L_s, and L_c and the coefficients k_1, k_2, k_3 are influenced by the angle of slide of a material compressed. Additionally, for a particular criterion influence of some between the others may be observed. The coefficients of the above equations allow an increase of the angle of slide, and angle of repose resulting in lower values of the mentioned compression parameters to be remarked. The others show some variation in influencing the agglomeration process.

The regression equations for the shape retention ability coefficient k_4, and for the strength of agglomerate σ_n, show them to be dependent on the bulk and tapped densities of the feedstuffs.

It is worth a note, the models based on 435 individual experimental points, with the correlation coefficients ranged from 0.364 to 0.804, and at high significance levels ($p<0.001$). This emphasizes both the “goodness of fit”and importance of a particular material property to the agglomeration process description.

Similar to the experiments on the ZD40 press, the comparative research and analyses of the relevancy of material physical characteristics to the compression process parameters, with the help of Instron machine, were done. Two cases were respected, depending on the kind of material and moisture employed.

a) feedstuffs no. 9-20 from Table II-3 (all moisture levels included in the analysis),
b) feedstuffs no. 42-48 from the same Table II-3 (at 14% moisture content).

Resulting equations for the former analysis are presented in Table II-13 (ZD40 press) and Table II-14 for Instron, and in Tables II-15 (ZD40 press) and II-16 (Instron) for the latter.

For the first group, the developed relations showed the material density changes and the material ability to compression to be dependent, for a majority of cases, on the listed below material characteristics:

a) internal friction coefficient, bulk and tapped material densities, angle of repose (angle of slide for the density changes), particle mean size – when ZD40 was applied,
b) tapped density of material and internal friction coefficient – when Instron was applied.

For the second group, relying on the resulting equations (Tab. II-15 and II-16), a variable material interface to the agglomeration parameters, for the two devices applied, may be drawn out.

The above analysis on the influence of material physical properties on the compression process parameters allows it to be concluded, that they demonstrate a different and complex influence on the process parameters, material suitability to agglomeration and quality of agglomerates obtained. The extent of the influence is showed to be dependent on both feedstuff and device in question.

10.3. Results of extrusion and pelleting studies

Extrusion experiments were done with the help of ZD40 press within the operating conditions presented in Table II-4 (section 9.4) employing the feedstuffs listed in Table II-3 (section 9.1). A laboratory pelletmill CLM (section 9.4) and the materials listed in Table II-3 were used in the granulation studies. Experiments were done at one material moisture content level, namely at about 14% for the extrusion (materials no. 9-20), and at the levels of moisture specified in Table II-18, for the pelleting (materials no. 42-52).

Results of the extrusion and pelleting experiments are presented in Table II-17a, b and Table II-18a, b respectively. The parameters listed in the tables were described in section 2.3.2. For the extrusion testing, the analysis of the influence of material properties on the respected parameters is presented in section 10.3.1, and in section 10.3.2 for the pelleting.

10.3.1. Influence of material physical properties on extrusion parameters and the ability to compression

The influence of material properties on the extrusion process parameters and the material ability to compression was analyzed separately for two sets of materials. The first set included materials numbered from 9 to 20, and the second from 42 to

51 according to Table II-3. In the analysis, the following parameters listed in Table II-17a and b were being included, i.e., density, loads, energy inputs for the compression and extrusion phases, compression pressure, coefficients of the material ability to compression and, at last, diameter of agglomerates.

Table II-17a. Mean values of extrusion parameters (ZD40 press)

Parameter		ρ_b	ρ_c	F_b	F_m	F_w	L_b	L_s	L_c	L_w	L_k	L_z
No.	Material	(g cm^{-3})	(g cm^{-3})	(kN)	(kN)	(kN)	(J)	(J)	(J)	(J)	(J)	(J)
1	Barley, cv. Ars	1.49	1.61	42.56	122.1	65.01	127	181	308	1413	1721	1.49
2	Barley, cv. Edgar	1.48	1.60	39.44	99.57	50.08	95	148	243	1144	1387	1.48
3	Barley, cv. Klimek	1.48	1.58	38.53	90.76	48.73	94	125	219	1277	1496	1.48
4	Barley, cv. Kos	1.48	1.56	43.72	90.61	46.41	99	101	200	1246	1446	1.48
5	Rye, cv. Amilo	1.52	1.62	39.72	98.47	47.97	91	108	199	1266	1465	1.52
6	Rye, cv. D. Nowe	1.50	1.59	43.05	106.5	45.93	97	128	225	1159	1384	1.50
7	Rye, cv. D. Złote	1.50	1.61	38.67	67.05	28.61	70	81	151	690	841	1.50
8	Rye, cv. Warko	1.49	1.59	36.53	101.4	48.27	90	120	210	1036	1246	1.49
9	Faba bean, cv. Nadwiślański	1.45	1.54	38.13	79.16	53.75	86	106	192	1260	1451	1.45
10	Pea, cv. Fidelia	1.49	1.59	32.85	65.73	37.76	76	90	166	976	1141	1.49
11	Lupine, cv. Emir	1.44	1.55	18.85	34.23	28.25	37	59	96	581	677	1.44
12	Vetch, cv. Szelejewska	1.46	1.62	34.63	91.75	46.44	86	182	268	1273	1541	1.46
13	Maize	1.48	1.61	43.27	128.3	96.89	140	200	340	1756	2097	1.48
14	Barley	1.51	1.64	48.48	131.1	67.32	141	197	338	1420	1758	1.51
15	Pea	1.47	1.56	32.93	64.12	34.16	48	90	139	842	981	1.47
16	Soybean meal	1.45	1.55	22.29	69.87	54.13	48	89	137	1308	1445	1.45
17	Wheat	1.49	1.59	37.01	97.37	52.13	104	124	228	1351	1579	1.49
18	Rapeseed meal	1.42	1.49	20.69	39.96	30.68	52	41	93	819	913	1.42
19	Lupine	1.42	1.47	13.02	26.31	18.85	27	21	49	470	519	1.42
20	Wheat bran	1.49	1.61	42.56	122.1	65.01	127	181	308	1413	1721	1.49
21	Dry plant matter (alfalfa)	1.48	1.60	39.44	99.57	50.08	95	148	243	1144	1387	1.48
22	Meat-bone flour	1.48	1.58	38.53	90.76	48.73	94	125	219	1277	1496	1.48

ρ_b – material density at point B, ρ_c – material density at point C, F_b – compression load, F_m – load at the outflow limit, F_w – load at the extrusion limit, L_b – compression energy, L_s – compaction energy (between points B and C), L_c – total compression energy, L_w – energy expenditures for extrusion phase, L_k – overall energy expenditure for agglomeration, L_z – overall energy expenditure for extrusion.

Table II-17b. Mean values of extrusion parameters (ZD40 press) cont.

No.	Parameter Material	P_b (MPa)	L_b' (J g^{-1})	L_s' (J g^{-1})	L_c' (J g^{-1})	k_1 (MPa^{-1})	k_2 (J g^{-1}/g cm^{-3})	k_3 (J g^{-1}/g cm^{-3})	d_g (mm)
1	Barley, cv. Ars	86.74	6.33	9.05	15.38	0.034	6.40	13.80	8.00
2	Barley, cv. Edgar	80.38	4.75	7.42	12.17	0.035	4.94	11.31	7.77
3	Barley, cv. Klimek	78.53	4.68	6.27	10.95	0.035	4.95	10.45	7.20
4	Barley, cv. Kos	89.10	4.95	5.05	10.00	0.030	5.31	9.87	7.87
5	Rye, cv. Amilo	80.95	4.57	5.40	9.97	0.029	5.18	10.26	6.93
6	Rye, cv. D. Nowe	87.74	4.87	6.40	11.27	0.026	5.74	11.95	7.37
7	Rye, cv. D. Złote	78.80	3.48	4.05	7.53	0.029	4.06	7.86	7.23
8	Rye, cv. Warko	74.45	4.50	5.98	10.48	0.033	5.04	10.59	7.00
9	Faba bean, cv. Nadwiślański	77.71	4.28	5.30	9.58	0.024	6.26	12.36	6.90
10	Pea, cv. Fidelia	66.96	3.80	4.48	8.28	0.029	5.21	10.02	6.60
11	Lupine, cv. Emir	38.42	1.83	2.97	4.80	0.065	2.11	4.88	6.67
12	Vetch, cv. Szelejewska	70.57	4.28	9.10	13.38	0.028	5.81	15.09	6.67
13	Maize	88.18	7.00	10.02	17.02	0.026	8.34	17.59	6.67
14	Barley	98.80	7.05	9.83	16.88	0.027	7.39	15.61	7.50
15	Pea	67.12	2.42	4.52	6.93	0.031	3.12	7.96	6.47
16	Soybean meal	45.43	2.40	4.45	6.85	0.048	3.02	7.62	6.27
17	Wheat	75.43	5.18	6.20	11.38	0.031	6.03	11.83	6.67
18	Rapeseed meal	42.17	2.60	2.07	4.67	0.064	2.90	4.84	6.60
19	Lupine	26.53	1.37	1.07	2.43	0.090	1.66	2.74	6.73
20	Wheat bran	48.50	2.67	2.48	5.15	0.100	2.26	4.13	7.53
21	Dry plant matter (alfalfa)	65.00	4.98	4.78	9.77	0.091	3.90	7.13	6.13
22	Meat-bone flour	91.36	5.95	17.58	23.53	0.027	6.32	20.31	6.23

P_b – compression pressure at point B, L_b' – specific compression energy, L_s' – specific compaction energy (between points B and C), L_c' – specific total compression energy, k_1 – coefficient of the material ability to compression (rate of material density changes to the pressure applied at point B), k_2 – coefficient (rate of the specific compression energy inputs to the corresponding increase in the material density), k_3 – coefficient (rate of the specific total compression energy to the corresponding increase in the material density) d_g – diameter of agglomerate.

Table II-18a. Results of pelleting experiments (CLM pelletmill)

No.	Material	Material moisture		Temperature of pellets T_g (°C)	Pelletmill capacity Q_g (kg h^{-1})	Power output P (kW)
		W_s (%)	W_g (%)			
1	Wheat	15.1	13.2	57.5	195.4	8.67
2	Wheat bran	14.2	13.7	58.0	154.6	6.35
3	Barley	12.6	11.4	66.0	148.8	7.63
4	Maize	11.8	11.3	56.5	181.8	9.61
5	Pea	15.4	13.2	58.0	147.3	7.23
6	Lupine	14.2	13.5	46.0	240.6	7.73
7	Rape seeds	9.1	8.9	35.0	510.0	5.90
8	Rapeseed meal	14.0	13.4	55.5	196.0	8.00
9	Soybean meal	13.1	12.9	59.5	138.6	6.67
10	Dry plant matter	14.4	9.5	89.5	67.50	7.30

Table II-18b. Results of pelleting experiments (CLM pelletmill) cont.

No.	Material	Specific energy consumption		Pellet strength (Instron 4302)		Pellet durability (Pfost's tester) P_{di} (%)	Pellet diameter d_g (mm)
		E_j (kWh t^{-1})	E_j (J g^{-1})	Failure load F_{ng} (N)	Stength of agglomerate W_{ng} (N mm^{-1})		
1	Wheat	44.4	159.7	158.4	3.67	77.9	5.23
2	Wheat bran	41.1	147.8	181.0	4.23	90.0	5.35
3	Barley	51.2	184.4	183.4	4.35	80.7	5.22
4	Maize	52.9	190.3	156.6	3.83	59.3	5.20
5	Pea	49.0	176.5	484.9	11.03	96.0	5.15
6	Lupine	32.1	115.6	364.9	8.23	96.3	5.24
7	Rape seeds	11.7	41.94	—	—	—	—
8	Rapeseed meal	40.8	147.0	190.7	4.69	79.5	5.36
9	Soybean meal	48.1	173.0	237.8	5.49	88.4	5.28
10	Dry plant matter	108.2	389.3	1202	30.19	98.0	5.18

Relationships between the parameters of extrusion and material physical properties were presented in the form of analytical equations. A general formulae similar to that in the compression process analyses, is expressed by the equation 14, where parameter „*c*" denotes a particular criterion of the extrusion process. The variables dependent were the physical properties of the materials processed.

The multiple linear regression method was used to develop the most representative model of the process.

The development of models for the extrusion testing resulted in the significant relationships to the material properties only for some parameters.For the first group of materials, (no. 9-20), the following regression equations might be presented:

$$\rho_c = 2.76 - 0.014\ \alpha_u - 0.017\ \alpha_z - 0.32\ \mu_b \tag{26}$$

where the correlation coefficient R was equal to 0.884, and significance level $p = 0.005$, and

$$d_g = 10.41 - 4.93\ \mu_b \tag{27}$$

with the correlation coefficient $R = -0.735$, and $p = 0.006$.

Table II-19. Regression equations to predict extrusion process parameters as a function of physical properties of feedstuff, (ZD40 press, materials no. 42-51 from Table II-3)

Extrusion	Regression parameter (material physical property)								Corr. Coeff.	p-value
parameter	Intercept	ρ_n	ρ_u	α_u	α_z	μ_b	S_z	$d_ś$	R	
ρ_b				no significant coefficients						
ρ_c				no significant coefficients						
F_m				no significant coefficients						
F_w	−148317	−448988	473547	6391	−9176	156988			0.994	0.03
F_b				no significant coefficients						
L_b	−219.2	−921.6	830.7	7.59	0.77	16.11		15.84	0.999	0.05
L_s				no significant coefficients						
L_c				no significant coefficients						
L_w				no significant coefficients						
L_k				no significant coefficients						
L_z				no significant coefficients						
P_b				no significant coefficients						
k_1	−0.034	−0.160			0.0068				0.945	0.003
k_2	−11.47	−52.68	50.23	0.364	−0.665	9.13		8.68	0.999	0.001
k_3				no significant coefficients						
d_g	6.92	−3.72						2.19	0.927	0.001

For the second group, (materials no. 42-51), regression relations are listed in Table II-19. Some significance was confirmed to the extrusion limit load F_w, compression energy expenditures L_b, coefficients of material ability to compression k_1 and k_2, and agglomerate diameter d_g. The mentioned above process parameters (excluding the compressibility index) are significantly, though in a various ways, influenced by the material properties. An increase of the bulk material density ρ_n, lowers values of the extrusion process parameters. Whereas, when the significance was observed, an increase in some of the material properties like angle of repose, internal friction coefficient, and particle size, caused a rise in the extrusion process parameters.

Generally, we can confirm the necessity of the continuous studies on the interfaces between material properties and parameters of the agglomeration process.

10.3.2. Results of pelleting studies

Vast number of experimental data has resulted from the pelleting experiments. Average values of the parameters, which describe properties of pellets as well as the granulation process itself, are listed in Tables II-18a and II-18b (section 10.3.1).

The results proved the temperature increase (in the range from 35 to 89.5°C for the studies made here) as the result of the friction effects during the material flow through the die. This leads directly to some variability in the throughput of the pelletmill. For the above temperature range, the pelletmill capacity was at the level of 510 kg h^{-1} for rapeseed, and 67.5 kg h^{-1} for dry green matter (alfalfa). These observations were also reflected by the specific energy consumption to pelleting the two above feedstuffs, which ranged from 41.4 to 389.3 J g^{-1} respectively.

From the industrial practice perspective, one of the most important feed quality criteria is its durability. The pellet durability P_{di}, according to Pfost and agglomerate strength W_{ng}, are commonly used to quantify this property.

Within the set of material employed in the experiment program, dry green matter showed the highest values of the both indices (P_{di} = 98%, W_{ng} = 30.19 N mm^{-1}). Whereas, the lowest pellet durability and strength were obtained for corn meal (59.3% and 3.83 N mm^{-1} respectively).

The analysis of the material suitability to granulation showed, that used for this assessment criteria acquired variable values dependently on the kind of material processed. The development of the regression equations relating material physical properties to the pellet characteristic was done applying the already known formulae 14 (section 10.2.2). In the case, parameter „*c*" denotes a particular criterion of the granulation process.

The multiple linear regression analysis of the experimental data, in which all materials processed were being included, has led to only one significant relationship, i.e., for the granule diameter. This may be expressed in the form of the following equation with the correlation coefficient R = 0.981, and at the significance level equal to 0.003.

$$d_g = 6.12 + 2.07\,\rho_n - 2.19\,\rho_k - 0.012\,\alpha_u \tag{28}$$

Similar analysis has been additionally performed for the same materials and the extrusion experiments data (section 10.3.1). Few more, significant relations have being derived from it (Tab. II-19).

Generally, the results of the undertaken studies confirmed a statement, that the right selection of feed materials and mixtures to the pelleting must include their natural granulation ability.

11. MATERIAL ABILITY TO AGGLOMERATION AND AGGLOMERATE SHAPE RETENTION ABILITY

The analysis presented above has proved suitability of the coefficients of material ability to compression k_1, k_2, k_3 in view of the material ability to granulation assessment. According to this statement, we are allowed to classify used in the research materials regarding to their granulation ability. The analysis of moisture influence on the compression process parameters (section 10.2.1) had proved that 14% of water level is the most adequate for the right assessment of the material ability to compression. Thus, relying on the average values of the coefficients k_1, k_2, k_3 at the moisture content level of 14%, materials have being classified within a granulation ability criterion (Tab. II-20).

Values of the coefficient k_1 were sorted in the increasing order, and inversely in decreasing one the coefficients k_2 and k_3 (higher compression ability). As may be observed from Table II-20, it also includes the material ranking according to the agglomerate shape retention ability coefficient, k_4. This allows the material ability to agglomeration be compared to this important agglomerate quality factor.

Relying on the data presented in the respected table, the worst ability to agglomeration may be appointed for rice and dry green matter. The best is characteristic for meat-bone flour, soybean meal, and maize with rice and soybean mixture at the amount of 75 percent of the latter.

Table II-20. Ranked feedstuffs by values of coefficients k_1, k_2, k_3, k_4 (ZD40 press, moisture 14%)

Rank no.	Material no.	k_1	Material no.	k_2	Material no.	k_3	Material no.	k_4
1	2	0.016	50	14.89	2	19.17	45	0.001
2	18	0.018	2	14.02	50	17.40	47	0.001
3	17	0.018	26	12.05	26	15.19	42	0.002
4	26	0.019	25	10.86	20	15.09	2	0.004
5	44	0.019	20	10.77	17	14.38	26	0.004
6	20	0.020	9	10.50	25	14.29	25	0.006
7	14	0.020	43	10.43	43	13.13	46	0.007
8	42	0.020	17	10.22	18	13.01	4	0.007
9	5	0.021	42	9.81	24	12.95	14	0.010
10	25	0.021	18	9.53	41	12.89	13	0.010
11	45	0.021	40	9.51	9	12.84	19	0.011
12	43	0.021	24	9.45	42	12.69	24	0.011
13	4	0.022	4	9.16	40	12.65	15	0.013
14	13	0.022	39	9.16	39	12.53	36	0.013
15	15	0.022	14	9.10	5	12.22	5	0.014
16	9	0.022	5	9.03	14	12.14	16	0.014
17	12	0.022	1	8.82	36	12.05	43	0.016
18	46	0.023	12	8.75	45	11.94	12	0.018
19	16	0.023	44	8.74	1	11.94	44	0.019
20	24	0.023	45	8.46	44	11.89	1	0.020
21	10	0.024	30	8.30	46	11.76	10	0.020
22	11	0.024	46	8.27	12	11.29	32	0.021
23	40	0.025	11	8.19	4	11.25	31	0.022
24	1	0.026	32	8.11	47	11.21	30	0.023
25	8	0.027	8	8.10	11	11.05	38	0.024
26	39	0.027	31	8.09	30	10.92	11	0.024
27	47	0.028	36	8.03	15	10.91	3	0.025
28	48	0.028	10	8.02	8	10.73	17	0.025
29	30	0.029	15	7.93	13	10.61	33	0.025
30	36	0.029	16	7.72	16	10.58	40	0.026
31	32	0.030	13	7.57	10	10.49	8	0.027
32	31	0.030	3	7.43	48	10.42	9	0.028
33	27	0.031	47	7.25	31	10.41	37	0.029
34	3	0.032	41	7.10	19	10.40	39	0.032
35	28	0.035	27	6.55	38	10.16	18	0.033
36	33	0.036	49	5.96	27	9.96	27	0.033
37	19	0.037	33	5.93	32	9.93	34	0.035
38	41	0.041	6	5.71	33	9.70	20	0.036
39	6	0.044	21	5.67	34	9.69	48	0.039
40	50	0.045	48	5.50	37	9.35	41	0.043
41	29	0.045	28	5.50	6	9.34	22	0.045
42	49	0.047	19	5.19	28	9.21	35	0.048
43	37	0.059	29	4.89	49	8.76	49	0.061
44	7	0.062	7	3.90	3	8.74	28	0.067
45	34	0.072	37	3.47	29	8.37	6	0.068
46	21	0.075	34	3.14	23	7.91	29	0.099
47	38	0.115	35	1.41	7	7.74	7	0.164
48	35	0.133	38	1.29	35	7.49	21	
49	22	0.168	22	1.02	21	6.93	23	
50	23	0.233	23	0.69	22	5.83	50	

En essence, the performed studies on the material ability to agglomeration have resulted in establishing few quantifying indices for the right material ability to agglomeration assessment. They are sufficiently sensitive and may be applied when classifying material by its granulation ability as well. The research will be continued within different and more complex conditions resulting from the thermal treatment of feedstuffs.

12. CONCLUSIONS

Research on the magnitude of the interfaces between material physical properties and parameters of agglomeration, as well as the ability to compression of feedstuffs followed the evaluated experimental program and described procedures. Feedstuffs physical properties of high relevance to compression, extrusion and pelleting processes were being established. It has been proved that the right assessment of the technological properties of a material is not likely to respect today's requirements without applying the above.

Criteria to describe the course of agglomeration processes were established. The parameters appointed for the compression studies (corresponding to B and C points) might be successfully used for the material ability to granulation assessment.

Coefficients of the material ability to compression were elaborated. They may also quantify the material ability to granulation. The rank of the feedstuffs used in the research, according to the elaborated coefficients was reported. The undertaken studies and subsequent interpretations allowed the established criteria of the material ability to granulation with a reference to the material compression ability, as more objective than existing up to now other proposals, to be promoted. The described classifying procedure of feedstuffs may be adapted to industrial practice.

The studies done allow some conclusions to be presented:

1. Parameters of compression, extrusion and granulation, the material ability to agglomeration, and quality of final products depend significantly on the kind of material, its moisture and physical properties. The range of the influence on a particular criterion shows some variability.
2. The ability to granulation of biological materials might be assessed by studies on their density changes and parameters of confined compression. A quantifying assessment of this material feature may base on the coefficients k_1, k_2 and k_3. The higher k_1 coefficient and at the same time the lower k_2 and k_3 coefficients, the higher material ability to the density increase.
3. The studies on the influence of material moisture on compression showed, that a particular process criterion was, in many cases, proportionally dependent on it (it concerns both the process parameters and the coefficients of the material ability to compression). The feedstuff moisture content of 14%

has bean postulated as the most favoured when an assessment of the agglomeration ability is needed. Between the materials used, the lowest ability to granulation was observed for rice, alfalfa, and the highest for the meat-bone flour, soybean, and the mixture of maize with rice and soy.

4. An increase in material moisture causes:
   a) changes in its physical properties, in density of materials in the compression chamber, as well in density of agglomerates,
   b) a decrease in compression pressure and specific compression energies,
   c) some increase in the material ability to granulation (increase of k_1, and decrease of k_2 and k_3 coefficients), strength of agglomerate (σ_n), and the shape retention ability coefficient (k_4).
5. The analysis of a variety of material physical properties on features of compression and extrusion showed a various and complex impact of the former on the process parameters, material ability to agglomeration, and quality of final products.

13. REFERENCES

1. **Brudka B.:** Significance of fodder mixtures granulation, and some technological parameters influencing pellet quality and the capacity of pelleting mills (in Polish). Biul. Inf. Przem. Pasz., 3, 25-45, 1970.
2. **Chasseray P.:** Les industries de premieres transformations des cereals. Technique et Documentation Ed, Lavosier, 105-139, 1991.
3. **Czaban J., Kamiński Z.:** Energy consumption of pressure of fodder mixtures in the closed chamber (in Polish). Proceedings of the IV Międz. Konf. Nauk.-Techn. „MOTROL'2003" „Motorization and Energetics in Agriculture", AR Lublin, Lublin-Kijów, 5, 55-62, 2003.
4. **David L., Lefumeux J.:** Pratique de la compression et technigues nouvelles. David ed., La Iarrie, 1972.
5. **De Blank H., Hendrix E., Litjens M., van Maaren H.:** On-Line Control and Optimisation of the Pelleting Process of Animal Feed. J. Sci. Food Agric., 74 (1), 13-19, 1997.
6. **Drzymała Z.:** Industrial briquetting: Fundamentals and methods (in Polish). PWN, Warszawa, 1988.
7. **Friedrich W., Robohm K. F.:** Pressfähigkeit von Komponenten und Mischungen. Teil I. Wirkung von Getreide - Messtechnik und Auswertung. Teil II. Wirkung von Olmuhlennachprodukten. Teil III. Wirkung von Komponenten mit vorherrschenden Inhaltsstoffen. Teil IV. Wirkung unterschiedlicher Inhaltsstoffe in Mischungen und Verdichtungswiderstand. Kraftfutter, 64/65, (4/9/11/3), 1981/1982.
8. **Grochowicz J.:** Properties of raw feed materials and their technological significance (in Polish). Pasze Przemysłowe, 4, 12-15, 1994.
9. **Grochowicz J.:** Granulation and formation of feedstuffs (in Polish). Pasze Przemysłowe, 5, 11-13, 1995.
10. **Grochowicz J.:** Production techniques of agglomerated feedstuffs (in Polish). Przegląd Zbożowo- Młynarski, 10, 13-16, 1995.
11. **Grochowicz J.:** Technology for feedstuffs production (in Polish). PWRiL, Warszawa, 1996.
12. **Grochowicz J.** (under redaction): Advanced techniques of industrial feedstuffs production (in Polish). PAGROS, Lublin, 1998.
13. **Grochowicz J.:** Pelletmills – design, modifications, application. Pasze Przemysłowe, 2, 17-28, 1998.
14. **Grochowicz J., Zawiślak K., Walczyński S., Podgórska H.:** Effect of thermal processes on the possibility of introducing liquid additives and the stability of biologically active components. Biul. Nauk. Przem. Pasz., 1/2, 63-75, 1998.

15. **Haines - Nutt R.:** Elastic recovery and surface area changes in compacted powder systems. Powder Technology, 9, 287-290, 1974.
16. **Hejft R.:** Pressure agglomeration of fodder and the principles of constructing granulating-briquetting machines (in Polish). Rozprawy Naukowe, 11, Wyd. Politechniki Białostockiej, 1991.
17. **Hejft R.:** Pressure agglomeration of plant materials (in Polish**)**. Politechnika Białostocka, Wyd. i Zakład Poligrafii Instytutu Technologii Eksploatacji, Radom, 2002.
18. **Kłassien P. V., Griszajew L. G.:** Principles of the granulation technique (in Polish). WNT, Warszawa, 1989.
19. **Korol W.:** Influence of thermal treatment on the nutritious components of feeds – fundamental alimentary components (part I) (in Polish). Pasze Przemysłowe, 4, 21-24, 1998.
20. **Kumar M.:** Compaction behavior of ground corn. J. of Food Sci, 38, 877-878, 1973.
21. **Laskowski J.:** Study on feed pelleting process (in Polish). Wyd. Akad. Roln., Seria Wyd. Rozprawy Naukowe 113, Lublin, 1989.
22. **Laskowski J. Janiak G.:** Procedure of determination strength factors of grain for processing. (in Polish). Biul. Nauk. Przem. Pasz., 1, 45-58, 1996.
23. **Laskowski J., de Monredon F., Skonecki S., Melcion J.-P.:** Testing procedure of pelletability of ingredients and compound feeds. Int. Agrophysics, 8, 643-648, 1994.
24. **Laskowski J., F. Le Deschault de Monredon, Soumah A.T.:** Multidimensional analysis of the pelletability of feeds and feed mixtures. Int. Agrophysics, 11(3), 229-233, 1997.
25. **Laskowski J., Melcion J.-P.:** Utilisation de graines entieres de colza. Adaptation du materiel existant: le broyage. Rev. Alim. Anim., 389, 35-40, 1985.
26. **Laskowski J., Melcion J.-P., Skonecki S.:** Effects of the Fat Content on Plant Material Density During Agglomeration. Technical Sciences, 6, 39-47, 2003.
27. **Laskowski J., Skonecki S.:** Studies on the granulation mechanism of ground feed materials. Proceedings of „Machinery in Grinding of Agricultural and Food Materials”. ATR Bydgoszcz, 22-28, 1992.
28. **Laskowski J., Skonecki S.:** Agglomeration ability of chosen cereal materials. Proceedings of the III ICCE’ 93 International Conference on Crumblers Engineering. ATR Bydgoszcz, Wyd. TNOiK w Bydgoszczy, 132-136, 1993.
29. **Laskowski J., Skonecki S.:** The method of determination the biological materials pressure agglomeration (in Polish). Proceedings of III Polish and II International Scientific Conference „Theory and Technology Development in Agriculture Technical Modernization” ATR Olsztyn, 29-33, 1994.
30. **Laskowski J., Skonecki S.:** Computer aiding in studies on the process of pelleting of biological materials (in Polish). Zesz. Probl. Post. Nauk Roln., 423, 151-161, 1995.
31. **Laskowski J., Skonecki S.:** Analysis of the predisposition to compression of raw fodder materials. Proceedings of the 4th International Conference „Problems on Agricultural and Forest Engineering”, SGGW Warszawa, WTRiL, Warszawa, 200-205, 1997.
32. **Laskowski J., Skonecki S.:** Study on the application of crushing parameters to the assessment of ability to compression of biological materials (in Polish). Preceedings of the I Zjazd Polskiego Towarzystwa Agrofizycznego, Instytut Agrofizyki PAN, Lublin, 75-77, 1997.
33. **Laskowski J., Skonecki S.:** Influence of moisture on the physical properties and parameters of the compression process of legumes’ seeds. Int. Agrophysics, 11, 245-256, 1997.
34. **Laskowski J., Skonecki S.:** Comparative evaluation of the processes of agro-biological materials. Inżynieria Rolnicza, Warszawa, 2 (3), 45-54, 1998.
35. **Laskowski J., Skonecki S.:** Energy consumption during pelleting process of feed mixtures (in Polish). Proceedings of the II Międz. Konf. Nauk.-Tech. MOTROL’99 „Motorization and Energetics in Agriculture”, A.R. Lublin, Part II, 124-131, 1999.
36. **Laskowski J., Skonecki S.:** Influence of moisture on the physical properties and parameters of the compression process of cereals’ grains. Int. Agrophysics, 13, 477-486, 1999.
37. **Laskowski J., Skonecki S.:** Effect of material temperature on densification parameters of leguminous seeds. Inżynieria Rolnicza, 5 (16), 133-146, 2000.
38. **Laskowski J., Skonecki S.:** Studies on compaction processes of the feedstuffs-methodological aspect. Inżynieria Rolnicza, 2, 187-193, 2001.

39. **Laskowski J., Skonecki S.:** Influence of material’s temperature on compression parameters of ground barley grains. Int. Agrophysics, 15 (3), 173-179, 2001.
40. **Laskowski J., Skonecki S.:** Effect of material temperature on compacting parameters f ground rye grain (in Polish). Inżynieria Rolnicza, 4 (37), 177-182, 2002.
41. **Laskowski J., Skonecki S.:** Energy consumption during agglomeration process of biological materials (in Polish). Proceedings of the IV Międz. Konf. Nauk. – Techn. „MOTROL’2003” „Motorization and Energetics in Agriculture”, AR Lublin, Lublin-Kijów, Narodowy Uniwesytet Rolniczy, Kijów, 6, 291-299, 2003.
42. **Laskowski J., Skonecki S.:** Influence of moisture of maize, oat and wheat on the extrusion parameters (in Polish). Acta Agrophysica, 82, 107-117, 2003.
43. **Laskowski J., Skonecki S., Gowin J.:** Measuring system for testing machines of type ZD with computer registration and analysis of compression process parameters (in Polish). Zesz. Probl. Post. Nauk Roln., 424, 279-284, 1995.
44. **Laskowski J., Skonecki S., Melcion J.-P.:** The ability to compression of ground plant materials (in Polish). Proceedings of the VI Konf. Nauk.- Tech. „Machinery Design and Maintenance in Food Industry. Politechnika Gdańska, SIiTMP, Warszawa, 1, 87-92, 1993.
45. **Laskowski J., Skonecki S., Melcion J.-P.:** Study on the assessment of biological materials ability to pelleting (in Polish). Zesz. Probl. Post. Nauk Roln., 444, 133-140, 1996.
46. **Locussol L.:** Contribution a l’etude des presses a extrusion utilisees dans l’alimentation animale. Bull. Anciens Eleves Ecole Frcse de Meunerie, 206, 71-75, 1965.
47. **Mac Mahon M. J., Payne J. V.:** Guide pour la fabrication de granules. Holmen Chemicals Ltd., 1981
48. **Melcion J.-P.:** Nouvelle technique d’etude de l’agglomeration des aliments des animaux. Prix Protector Inter, 34, 1974.
49. **Melcion J.-P.:** Le role de l’eau dans les operations unitaires (manutention, broyage, melange, agglomeration). Aliscope, Elevaga et Alim. Animale 9/10, 15-17, 1988.
50. **Melcion J.-P., Ilari J.-L.:** Technologie des pulvérulents dans les IAA. Lavoisier Tec & Doc, Paris, 2003.
51. **Payne I.-D.:** Improving quality of pellet feeds. Milling Feed and Fertilizer, 5, 34-41, 1978.
52. **Reinders M., Van Bestelaere G.:** Die Suche nach optimalen Bedingungen fur das Verpressen von Minschfutterpellet. Die Muhle + Mischfuttertechnik, 9/10, 1971.
53. **Skonecki S., Sudół A., Laskowski J.:** Influence of grain mechanical properties on the compression parameters of wheat (in Polish). Acta Agrophysica, 2 (1), 179-189, 2003.
54. **Tabil Jr. L., Sokhansanj S.:** Process Conditions Affecting the Physical Quality of Alfalfa Pellets. Applied Engineering in Agriculture, 12 (3), 345-350, 1996.
55. **Thomas M., van der Poel A. F. B.:** Physical quality of pelleted animal feed. 1.Criteria for pellet quality. Anim. Feed Sci. Technol., 61, 89-112, 1996.
56. **Thomas M., van Vliet T., van der Poel A. F. B.:** Physical quality of pelleted animal feed. 3.Contribution of feedstuff components. Anim. Feed Sci. Technol., 70, 59-78, 1998.
57. **Thomas M., van Zuilichem D. J., van der Poel A. F. B.:** Physical quality of pelleted animal feed. 2. Contribution of processes and its conditions. Anim. Feed Sci. Technol., 64, 173-192, 1997.
58. **Tregret L.:** Caracterisation de l’aptitude a lagglomeration de diverses matieres premieres en vue de l’optimisation du pressage des aliments des animaux. These de fin d’etudes. ENITIAA, Nantes, 1978.
59. **Tylżanowski J.:** Production technology of pelleted feedstuffs (in Polish). Studium Przemysłu Paszowego, WCT NOT, Warszawa, 7, 1975.
60. **Walczyński S., Zawiślak K.:** Investigation of pellets quality obtained in granulation process without the steam treatment (in Polish). Biul. Nauk. Przem. Pasz., 1/4, 95-101, 2000.
61. **Wellin F.:** Pelleting equipment and operations. Feed Manufacturing Technology, AFMA, Inc., Arlington, 1976.
62. **Zawiślak K.:** Factors influencing pellet quality (in Polish). Pasze Przemysłowe, 2-3, 15-16, 1996.

Chapter III

CATALOGUE OF MATERIAL PROPERTIES AND PARAMETERS OF GRINDING AND AGGLOMERATION

Table III-1. Mean values of resistance parameters of wheat cultivars at different moisture content levels

Cultivar	Moisture (%)	h_1 (mm)	$tg\alpha$ (N mm^{-1})	F_1 (N)	F_2 (N)	L_1 (mJ)	L_2 (mJ)	L_{j1} (mJ g^{-1})	L_{j2} (mJ g^{-1})
1	2	3	4	5	6	7	8	9	10
Alkora	11	0.334	326	71.1	777	14.3	364	363	9240
	14	0.376	285	59	765	14	364	324	8424
	15.5	0.471	282	65.9	912	19.2	418	469	10211
	17	0.577	176	58.5	763	18.8	357	455	8640
	18.5	0.817	136	62	867	31	405	658	8596
Delta	11	0.352	324	57.6	591	12.2	282	300	6934
	14	0.441	253	53.1	645	16.1	315	386	7552
	15.5	0.512	230	58.3	649	20.7	327	470	7425
	17	0.600	154	48.3	699	18.6	357	454	8714
	18.5	0.911	116	58.6	875	30.9	470	659	10024
Gółka	11	0.382	263	62.3	686	14.4	311	332	7170
	14	0.558	257	67.5	611	24.8	308	524	6508
	15.5	0.568	222	65.3	582	23.5	296	539	6789
	17	0.838	149	67.3	737	32.4	420	711	9217
	18.5	0.982	105	62.2	689	34.9	364	792	8260
Henika	11	0.402	366	102.7	645	22.3	332	544	8099
	14	0.544	316	90.7	745	30.6	370	666	8053
	15.5	0.643	293	100	703	38.4	361	908	8536
	17	0.694	208	88.7	862	36.9	423	794	9102
	18.5	0.946	139	86.4	779	43.9	427	957	9308
Jara	11	0.304	314	62	665	9.6	338	242	8520
	14	0.328	273	58.1	677	10.6	310	276	8072
	15.5	0.426	270	53.5	604	13.4	267	365	7273
	17	0.581	169	58.8	843	21.3	366	522	8970
	18.5	0.684	146	50.9	853	22.8	379	530	8810
Jota	11	0.342	307	86.4	748	14.7	373	346	8779
	14	0.457	292	76.2	667	21.4	324	513	7767
	15.5	0.514	260	73	638	21.3	313	520	7641
	17	0.716	202	74.3	667	32.6	321	761	7493
	18.5	0.971	120	73.1	711	41.6	353	945	8019

Table III-1. Cont.

1	2	3	4	5	6	7	8	9	10
Kadett	11	0.296	284	59.4	639	9.1	302	227	7533
	14	0.363	255	56.9	684	11.6	302	325	8461
	15.5	0.481	217	51.2	772	16.7	332	412	8191
	17	0.651	146	53.9	772	20.9	352	530	8926
	18.5	0.837	107	52.1	726	26.4	342	619	8019
Livilla	11	0.330	310	65.5	614	13.3	302	314	7130
	14	0.448	279	74.4	802	20.3	368	456	8266
	15.5	0.534	231	66.8	630	26	327	586	7370
	17	0.596	249	65.2	765	25.2	376	584	8714
	18.5	0.962	122	66.8	775	36.8	415	801	9033
Omega	11	0.340	290	64	624	13.6	330	352	8541
	14	0.310	331	55.5	772	10.6	370	243	8482
	15.5	0.393	283	51.7	879	13.8	395	340	9732
	17	0.619	167	53.3	881	23.4	391	510	8522
	18.5	0.752	109	49.8	937	23.3	432	541	10031
Ostka	11	0.423	305	67.5	482	17.9	260	415	6028
	14	0.511	235	68	640	20.8	311	496	7416
	15.5	0.625	257	67.6	732	27.6	353	636	8134
	17	0.785	156	67.5	724	32.4	369	683	7779
	18.5	1.034	112	66.4	787	37.4	419	874	9792
Panda	11	0.351	323	73	504	14.4	253	352	6184
	14	0.354	317	68.7	606	14.6	296	360	7299
	15.5	0.461	259	68.9	689	21.2	326	504	7750
	17	0.669	181	67.2	655	27	362	603	8085
	18.5	0.757	163	69.8	833	30.8	468	692	10515
Sawa	11	0.407	328	71.8	542	17.6	255	405	5868
	14	0.452	304	63.5	660	18.6	310	390	6500
	15.5	0.540	302	62.9	652	21.3	296	533	7407
	17	0.730	207	62.3	687	27.8	355	618	7892
	18.5	0.859	162	62.6	777	32.5	412	752	9533
Sigma	11	0.337	380	82.8	538	15.1	301	355	7076
	14	0.362	348	72.8	803	14.8	391	320	8454
	15.5	0.515	286	68.4	711	21.9	335	516	7893
	17	0.596	217	62.7	741	22.9	355	493	7643
	18.5	0.733	154	56.4	752	26.4	364	593	8176

Table III-2. Mean values of resistance parameters of wheat cultivars for different kernel fraction size

Cultivar	Fraction size	h_1 (mm)	$tg\alpha$ (N mm^{-1})	F_1 (N)	F_2 (N)	L_1 (mJ)	L_2 (mJ)	L_{j1} (mJ g^{-1})	L_{j2} (mJ g^{-1})
1	2	3	4	5	6	7	8	9	10
Alkora	<2.25-2.7)	0.515	192	54.2	505	15.8	196	557	6910
	<2.7-2.9)	0.466	234	56.4	672	15.7	290	435	8035
	<2.9-3.1)	0.522	248	59.7	850	17.7	385	406	8831
	<3.1-3.3)	0.503	252	62.9	989	18.4	477	370	9592
	<3.3-4.0>	0.653	241	83.1	1056	32.4	553	571	9746
Delta	<2.25-2.7)	0.561	181	48.5	411	16.1	177	596	6552
	<2.7-2.9)	0.529	203	54.5	548	17.1	266	461	7171
	<2.9-3.1)	0.574	196	57.4	651	20.7	336	479	7775
	<3.1-3.3)	0.538	229	52.7	759	18.6	399	369	7916
	<3.3-4.0>	0.592	242	58.8	905	23.1	474	404	8290
Gółka	<2.25-2.7)	0.556	162	49.9	404	15.9	172	565	6112
	<2.7-2.9)	0.591	183	55.5	530	19.8	239	545	6579
	<2.9-3.1)	0.674	200	67.4	642	25.9	312	611	7360
	<3.1-3.3)	0.758	205	71.6	708	30.1	378	631	7924
	<3.3-4.0>	0.721	224	73.7	847	32.8	474	574	8295
Henika	<2.25-2.7)	0.581	249	82.6	483	26.1	218	849	7091
	<2.7-2.9)	0.642	271	91.9	639	3.5	309	866	76455
	<2.9-3.1)	0.591	302	95.9	788	31.5	385	683	8348
	<3.1-3.3)	0.662	255	95.4	867	35.8	462	681	8788
	<3.3-4.0>	0.748	243	101.3	971	43.6	539	749	9259
Jara	<2.25-2.7)	0.436	196	48.5	453	12	179	444	6623
	<2.7-2.9)	0.454	204	52.4	625	13.6	258	399	7569
	<2.9-3.1)	0.441	233	54.7	718	13.6	314	348	8035
	<3.1-3.3)	0.490	265	60.6	794	17.5	375	388	8314
	<3.3-4.0>	0.513	250	63.9	981	20.3	485	386	9222
Jota	<2.25-2.7)	0.528	215	73.2	447	21	199	708	6709
	<2.7-2.9)	0.566	218	70.7	568	21.4	255	617	7352
	<2.9-3.1)	0.560	233	72.7	673	23.9	310	588	7627
	<3.1-3.3)	0.627	250	79.3	771	28	387	591	8168
	<3.3-4.0>	0.693	244	82.1	850	33.3	449	611	8238
Kadett	<2.25-2.7)	0.530	189	53	421	16.5	175	597	6332
	<2.7-2.9)	0.484	201	51.4	571	14.6	248	427	7253
	<2.9-3.1)	0.499	220	54.7	712	15.7	313	389	7755
	<3.1-3.3)	0.582	198	58.5	865	19.7	400	421	8548
	<3.3-4.0>	0.604	177	55.1	955	20.2	460	373	8494

Table III-2. Cont.

1	2	3	4	5	6	7	8	9	10
Livilla	<2.25-2.7)	0.507	245	60.4	446	19	199	636	6661
	<2.7-2.9)	0.546	239	68.3	550	22.5	259	617	7102
	<2.9-3.1)	0.582	223	68.2	665	22.6	322	537	7651
	<3.1-3.3)	0.719	212	74.6	785	32.4	403	662	8234
	<3.3-4.0>	0.603	246	68.4	917	26	475	451	8239
Omega	<2.25-2.7)	0.468	191	46.1	481	12.7	190	481	7196
	<2.7-2.9)	0.422	230	50.1	602	13.1	269	392	8049
	<2.9-3.1)	0.418	232	46.3	789	12.6	341	325	8796
	<3.1-3.3)	0.517	240	57.7	878	18.1	408	387	8724
	<3.3-4.0>	0.552	251	64.1	1039	23	525	428	9770
Ostka	<2.25-2.7)	0.660	179	56	410	21.6	180	764	6367
	<2.7-2.9)	0.686	193	63.2	494	25.6	230	735	6604
	<2.9-3.1)	0.608	214	65.8	596	22.8	278	564	6877
	<3.1-3.3)	0.686	226	70.8	699	28.3	361	582	7424
	<3.3-4.0>	0.697	233	73.8	894	32.8	485	536	7926
Panda	<2.25-2.7)	0.525	218	69.2	444	19.7	220	655	7315
	<2.7-2.9)	0.498	244	68.9	574	19.9	293	536	7892
	<2.9-3.1)	0.478	267	70.9	661	19.6	342	441	7695
	<3.1-3.3)	0.525	259	69.8	733	21.8	390	435	7782
	<3.3-4.0>	0.627	231	68.8	880	29	476	495	8125
Sawa	<2.25-2.7)	0.597	222	60.7	408	21.2	187	710	6263
	<2.7-2.9)	0.558	269	64.5	481	21.5	234	569	6193
	<2.9-3.1)	0.576	261	64.3	618	22	291	512	6772
	<3.1-3.3)	0.600	282	69.7	717	25.5	359	517	7279
	<3.3-4.0>	0.622	272	64.8	918	26.1	464	442	7858
Sigma	<2.25-2.7)	0.470	219	54.2	416	14.2	177	519	6469
	<2.7-2.9)	0.452	272	58	568	14.8	256	420	7265
	<2.9-3.1)	0.467	277	64.5	682	16.6	323	393	7647
	<3.1-3.3)	0.510	306	72.9	799	21	295	427	5998
	<3.3-4.0>	0.602	283	81.7	912	28.9	484	511	8558

Table III-3. Mean bulk densities of selected materials, (kg m^{-3}), at different moisture content levels

No.	Material	Moisture content (%)				
		10	12	14	16	18
1	Barey cv. Ars	689	680	671	660	642
2	Barey cv. Edgar	711	704	693	677	662
3	Barey cv. Klimek	664	651	642	631	620
4	Barey cv. Kos	659	649	640	631	618
5	Rye cv. Amilo	784	781	773	763	751
6	Rye cv. Dańkowskie Złote	786	778	772	758	742
7	Rye cv. Dańkowskie Nowe	760	752	742	731	725
8	Rye cv. Warko	740	734	729	712	700
9	Faba bean cv. Nadwiślański	815	807	800	790	781
10	Pea cv. Fidelia	789	779	762	748	731
11	Lupine cv. Emir	770	761	752	739	720
12	Vetch cv. Szelejewska	827	819	810	799	782
13	Maize cv. Kosmo	840	831	822	805	790
14	Maize cv. Koka	818	810	795	776	753
15	Maize cv. KLG2210	832	828	812	786	762
16	Soybean	708	689	684	679	666

Table III-4. Mean tapped densities of selected materials, (kg m^{-3}), at different moisture content levels

No.	Material	Moisture content (%)				
		10	12	14	16	18
1	Barey cv. Ars	742	732	721	710	692
2	Barey cv. Edgar	756	750	737	713	705
3	Barey cv. Klimek	722	709	697	686	675
4	Barey cv. Kos	707	696	689	678	662
5	Rye cv. Amilo	834	830	822	813	798
6	Rye cv. Dańkowskie Złote	826	818	812	798	781
7	Rye cv. Dańkowskie Nowe	813	803	793	782	774
8	Rye cv. Warko	778	772	768	749	778
9	Faba bean cv. Nadwiślański	906	889	886	870	852
10	Pea cv. Fidelia	860	848	828	815	771
11	Lupine cv. Emir	845	834	826	810	789
12	Vetch cv. Szelejewska	920	910	903	887	860
13	Maize cv. Kosmo	857	856	840	821	823
14	Maize cv. Koka	874	865	849	828	816
15	Maize cv. KLG2210	879	878	867	839	822
16	Soybean	767	750	751	747	731

Table III-5. Mean 1000 kernels weight, (g), of selected materials, at different moisture content levels

No.	Material	Moisture content (%)				
		10	12	14	16	18
1	Barey cv. Ars	43.40	44.52	45.69	46.85	47.95
2	Barey cv. Edgar	41.32	42.40	43.54	44.65	45.89
3	Barey cv. Klimek	39.20	40.52	41.65	42.70	43.98
4	Barey cv. Kos	45.01	46.15	47.30	48.40	49.52
5	Rye cv. Amilo	31.17	32.21	33.12	33.97	34.56
6	Rye cv. Dańkowskie Złote	32.18	33.20	34.39	35.40	36.20
7	Rye cv. Dańkowskie Nowe	31.70	32.62	33.81	34.52	35.21
8	Rye cv. Warko	27.10	27.70	28.60	29.50	30.40
9	Faba bean cv. Nadwiślański	530.2	542.3	553.1	565.2	577.2
10	Pea cv. Fidelia	144.1	148.3	152.1	156.6	160.1
11	Lupine cv. Emir	153.4	157.9	162.1	166.2	171.0
12	Vetch cv. Szelejewska	56.20	57.70	59.10	60.50	62.10
13	Maize cv. Kosmo	338.3	343.7	349.7	353.5	365.6
14	Maize cv. Koka	325.7	333.5	341.5	354.5	361.9
15	Maize cv. KLG2210	248.5	256.6	265.1	272.0	280.9
16	Soybean	106.5	112.9	121.4	122.1	122.6

Table III-6. Mean angle of slide, (deg), of selected materials at different moisture content levels

No.	Material	Moisture content (%)				
		10	12	14	16	18
1	Barey cv. Ars	19.5	20.0	21.0	21.5	23.0
2	Barey cv. Edgar	20.0	20.5	21.5	22.5	24.5
3	Barey cv. Klimek	21.0	22.0	22.5	23.5	25.0
4	Barey cv. Kos	20.0	20.5	21.5	23.0	24.0
5	Rye cv. Amilo	21.0	21.5	22.5	23.0	24.5
6	Rye cv. Dańkowskie Złote	20.0	20.0	21.5	22.5	24.0
7	Rye cv. Dańkowskie Nowe	19.5	20.0	20.0	22.0	23.5
8	Rye cv. Warko	19.5	20.0	20.0	21.5	23.5
9	Faba bean cv. Nadwiślański	10.0	11.5	13.0	14.0	15.0
10	Pea cv. Fidelia	11.0	12.5	13.0	15.5	17.0
11	Lupine cv. Emir	11.5	13.0	14.0	16.5	18.0
12	Vetch cv. Szelejewska	12.0	13.5	14.5	17.0	19.0
13	Maize cv. Kosmo	13.3	13.6	14.1	16.1	18.2
14	Maize cv. Koka	15.1	15.5	16.9	21.2	26.3
15	Maize cv. KLG2210	13.6	14.0	15.7	18.6	21.7
16	Soybean	10.8	11.6	12.6	13.8	16.1

Table III-7. Mean angle of repose, (deg), of selected materials at different moisture content levels

No.	Material	Moisture content (%)				
		10	12	14	16	18
1	Barey cv. Ars	30.0	32.6	33.5	36.3	39.2
2	Barey cv. Edgar	31.5	33.4	35.3	37.1	40.2
3	Barey cv. Klimek	31.5	33.0	35.0	38.2	41.3
4	Barey cv. Kos	29.0	32.1	34.4	36.5	38.9
5	Rye cv. Amilo	27.5	29.3	33.0	35.4	37.3
6	Rye cv. Dańkowskie Złote	23.5	24.0	26.8	30.2	34.5
7	Rye cv. Dańkowskie Nowe	25.4	27.6	31.0	33.2	36.9
8	Rye cv. Warko	24.0	26.9	28.0	30.6	33.5
9	Faba bean cv. Nadwiślański	21.3	22.2	25.4	27.6	29.5
10	Pea cv. Fidelia	22.1	24.6	28.6	32.4	33.2
11	Lupine cv. Emir	23.0	23.5	29.8	32.6	34.7
12	Vetch cv. Szelejewska	29.5	31.9	34.2	36.4	38.5
13	Maize cv. Kosmo	17.7	26.1	29.7	34.9	37.2
14	Maize cv. Koka	27.9	33.0	34.1	38.1	39.0
15	Maize cv. KLG2210	31.5	32.5	35.1	37.7	39.8
16	Soybean	26.1	26.4	31.0	34.5	34.5

Table III-8. Mean kernel (seed) weight, *m* ($g \cdot 10^{-3}$), of selected materials

No.	Material	Mean	Std. Dev.	Std. Err.	95% confidence interval
1	Barey cv. Ars	56.16	7.97	0.50	55.16-57.14
2	Barey cv. Edgar	58.12	7.69	0.48	57.16-59.08
3	Barey cv. Klimek	55.90	6.24	0.39	55.12-56.67
4	Barey cv. Kos	53.32	6.23	0.39	52.54-54.09
5	Rye cv. Amilo	37.85	4.74	0.30	37.26-38.44
6	Rye cv. Dańkowskie Złote	43.32	5.16	0.32	42.67-43.96
7	Rye cv. Dańkowskie Nowe	41.72	6.43	0.40	40.91-42.51
8	Rye cv. Warko	42.12	6.07	0.38	41.35-42.87
9	Faba bean cv. Nadwiślański	568.7	55.47	3.50	561.8-575.6
10	Pea cv. Fidelia	154.1	22.38	1.41	151.3-156.9
11	Lupine cv. Emir	169.5	35.83	2.26	165.0-173.9
12	Vetch cv. Szelejewska	56.62	6.44	0.40	55.81-57.41

Table III-9. Mean kernel (seed) thickness, *h* (mm), of selected materials

No.	Material	Mean	Std. Dev.	Std. Err.	95% confidence interval
1	Barey cv. Ars	3.01	0.16	0.010	2.99-3.03
2	Barey cv. Edgar	2.95	0.15	0.010	2.93-2.96
3	Barey cv. Klimek	2.92	0.18	0.011	2.90-2.94
4	Barey cv. Kos	2.98	0.14	0.009	2.96-3.00
5	Rye cv. Amilo	2.65	0.18	0.011	2.62-2.67
6	Rye cv. Dańkowskie Złote	2.75	0.17	0.011	2.73-2.77
7	Rye cv. Dańkowskie Nowe	2.78	0.18	0.011	2.75-2.79
8	Rye cv. Warko	2.73	0.18	0.011	2.71-2.75
9	Faba bean cv. Nadwiślański	7.10	0.21	0.013	7.07-7.12
10	Pea cv. Fidelia	4.88	0.23	0.015	4.85-4.90
11	Lupine cv. Emir	4.82	0.17	0.011	4.79-4.83
12	Vetch cv. Szelejewska	3.38	0.19	0.012	3.35-3.39

Table III-10. Mean kernel (seed) weigh, *b* (mm), of selected materials

No.	Material	Mean	Std. Dev.	Std. Err.	95% confidence interval
1	Barey cv. Ars	3.93	0.19	0.012	3.90-3.95
2	Barey cv. Edgar	3.81	0.21	0.013	3.78-3.83
3	Barey cv. Klimek	3.66	0.21	0.013	3.63-3.68
4	Barey cv. Kos	3.81	0.40	0.025	3.75-3.85
5	Rye cv. Amilo	2.74	0.19	0.012	2.71-2.76
6	Rye cv. Dańkowskie Złote	2.81	0.17	0.010	2.78-2.83
7	Rye cv. Dańkowskie Nowe	2.83	0.18	0.012	2.80-2.85
8	Rye cv. Warko	2.83	0.19	0.012	2.80-2.85
9	Faba bean cv. Nadwiślański	8.60	0.21	0.013	8.57-8.62
10	Pea cv. Fidelia	6.82	0.23	0.015	6.79-6.85
11	Lupine cv. Emir	5.92	0.17	0.011	5.89-5.93
12	Vetch cv. Szelejewska	4.18	0.19	0.012	4.15-4.19

Table III-11. Mean kernel (seed) length, *c* (mm), of selected materials

No.	Material	Mean	Std. Dev.	Std. Err.	95% confidence interval
1	Barey cv. Ars	9.43	0.82	0.052	9.32-9.52
2	Barey cv. Edgar	9.36	0.67	0.042	9.27-9.44
3	Barey cv. Klimek	10.42	1.04	0.066	10.28-10.54
4	Barey cv. Kos	10.37	1.24	0.079	10.21-10.52
5	Rye cv. Amilo	7.48	0.52	0.033	7.41-7.54
6	Rye cv. Dańkowskie Złote	8.06	0.55	0.035	7.99-8.13
7	Rye cv. Dańkowskie Nowe	7.88	0.63	0.040	7.80-7.96
8	Rye cv. Warko	8.08	0.66	0.042	8.00-8.16
9	Faba bean cv. Nadwiślański	10.67	0.21	0.013	10.64-10.69
10	Pea cv. Fidelia	6.88	0.23	0.015	6.84-6.90
11	Lupine cv. Emir	6.87	0.17	0.011	6.84-6.88
12	Vetch cv. Szelejewska	4.37	0.19	0.012	4.34-4.38

Table III-12. Mean deformation at rupture, Δh_1 (mm), of selected materials

No.	Material	Mean	Std. Dev.	Std. Err.	95% confidence interval
1	Barey cv. Ars	0.64	0.15	0.009	0.62-0.66
2	Barey cv. Edgar	0.70	0.20	0.013	0.68-0.73
3	Barey cv. Klimek	0.72	0.17	0.011	0.69-0.74
4	Barey cv. Kos	0.74	0.23	0.014	0.72-0.77
5	Rye cv. Amilo	0.47	0.17	0.01	0.45-0.49
6	Rye cv. Dańkowskie Złote	0.43	0.16	0.01	0.41-0.45
7	Rye cv. Dańkowskie Nowe	0.44	0.19	0.012	0.41-0.46
8	Rye cv. Warko	0.45	0.15	0.009	0.44-0.47
9	Faba bean cv. Nadwiślański	0.96	0.24	0.015	0.93-0.99
10	Pea cv. Fidelia	0.68	0.23	0.015	0.65-0.71
11	Lupine cv. Emir	1.05	0.36	0.023	1.01-1.10
12	Vetch cv. Szelejewska	0.55	0.17	0.011	0.53-0.57

Table III-13. Mean apparent stiffness values, $tg\alpha$ (N mm^{-1}), of selected materials

No.	Material	Mean	Std. Dev.	Std. Err.	95% confidence interval
1	Barey cv. Ars	220	89.1	5.6	209-231
2	Barey cv. Edgar	192	101.8	6.4	180-205
3	Barey cv. Klimek	227	76.8	4.9	218-237
4	Barey cv. Kos	194	54.8	3.5	187-200
5	Rye cv. Amilo	226	101.8	6.4	214-239
6	Rye cv. Dańkowskie Złote	244	90.4	5.7	233-256
7	Rye cv. Dańkowskie Nowe	267	124.5	7.9	252-283
8	Rye cv. Warko	238	121.1	7.7	223-253
9	Faba bean cv. Nadwiślański	390	136.3	8.6	373-407
10	Pea cv. Fidelia	411	200.4	12.7	386-436
11	Lupine cv. Emir	346	194.1	12.3	321-370
12	Vetch cv. Szelejewska	358	194.7	12.3	333-382

Table III-14. Mean loads at kernel rupture, F_I (N), of selected materials

No.	Material	Mean	Std. Dev.	Std. Err.	95% confidence interval
1	Barey cv. Ars	158	26.15	1.65	154-161
2	Barey cv. Edgar	166	26.22	1.66	163-170
3	Barey cv. Klimek	167	26.81	1.70	163-170
4	Barey cv. Kos	134	32.85	2.08	130-138
5	Rye cv. Amilo	96	29.87	1.89	92-99
6	Rye cv. Dańkowskie Złote	93	29.88	1.89	89-97
7	Rye cv. Dańkowskie Nowe	93	28.84	1.82	89-97
8	Rye cv. Warko	86	27.37	1.73	82-89
9	Faba bean cv. Nadwiślański	530	168.1	10.64	509-551
10	Pea cv. Fidelia	239	97.53	6.17	227-251
11	Lupine cv. Emir	276	72.84	4.61	267-286
12	Vetch cv. Szelejewska	142	56.79	3.59	135-149

Table III-15. Mean loads at the kernel collapse threshold, F_2 (N), of selected materials

No.	Material	Mean	Std. Dev.	Std. Err.	95% confidence interval
1	Barey cv. Ars	550	210.7	13.33	524-576
2	Barey cv. Edgar	554	171.6	10.85	532-575
3	Barey cv. Klimek	680	166.2	10.51	659-700
4	Barey cv. Kos	476	132.6	8.39	460-493
5	Rye cv. Amilo	267	105.1	6.65	253-280
6	Rye cv. Dańkowskie Złote	401	124.5	7.88	385-416
7	Rye cv. Dańkowskie Nowe	305	104.0	6.58	292-318
8	Rye cv. Warko	318	103.1	6.53	306-331
9	Faba bean cv. Nadwiślański	4444	1039	65.75	4314-4573
10	Pea cv. Fidelia	1262	398.3	25.20	1212-1311
11	Lupine cv. Emir	1580	326.7	20.66	1539-1621
12	Vetch cv. Szelejewska	455	163.0	10.31	435-476

Table III-16. Mean strain energy up to kernel rupture, L_1 (mJ), of selected materials

No.	Material	Mean	Std. Dev.	Std. Err.	95% confidence interval
1	Barey cv. Ars	40.96	14	0.9	39.2-42.7
2	Barey cv. Edgar	43.73	14.21	0.9	42.0-45.5
3	Barey cv. Klimek	47.06	14.57	0.9	45.2-48.9
4	Barey cv. Kos	43.86	24.45	1.5	40.8-46.9
5	Rye cv. Amilo	23.18	14.35	0.9	21.4-25.0
6	Rye cv. Dańkowskie Złote	19.94	16.15	1.0	17.9-22.0
7	Rye cv. Dańkowskie Nowe	22.24	17.66	1.1	20.0-24.4
8	Rye cv. Warko	21.01	13.37	0.8	19.3-22.7
9	Faba bean cv. Nadwiślański	220.1	95.69	6.1	208-232
10	Pea cv. Fidelia	68.29	29.62	1.9	64.6-72.0
11	Lupine cv. Emir	134.6	45.62	2.9	128-140
12	Vetch cv. Szelejewska	33.93	11.38	0.7	32.5-35.3

Table III-17. Mean crushing energy up to the kernel collapse threshold, L_2 (mJ), of selected materials

No.	Material	Mean	Std. Dev.	Std. Err.	95% confidence interval
1	Barey cv. Ars	429	155	9.81	410-448
2	Barey cv. Edgar	411	130	8.27	394-427
3	Barey cv. Klimek	488	122	7.77	473-504
4	Barey cv. Kos	362	90.01	5.69	350-373
5	Rye cv. Amilo	161	64.38	4.07	153-169
6	Rye cv. Dańkowskie Złote	199	73.50	4.65	190-208
7	Rye cv. Dańkowskie Nowe	169	65.18	4.12	161-177
8	Rye cv. Warko	174	55.28	3.50	167-181
9	Faba bean cv. Nadwiślański	5634	1797	113	5410-5858
10	Pea cv. Fidelia	1241	602	38.1	1166-1317
11	Lupine cv. Emir	1907	459	29.05	1850-1965
12	Vetch cv. Szelejewska	359	129	8.21	343-375

Table III-18. Mean specific strain energy up to kernel rupture, L_{j1} (J g^{-1}), of selected materials

No.	Material	Mean	Std. Dev.	Std. Err.	95% confidence interval
1	Barey cv. Ars	0.73	0.23	0.015	0.70-0.76
2	Barey cv. Edgar	0.77	0.30	0.019	0.73-0.80
3	Barey cv. Klimek	0.85	0.29	0.018	0.82-0.89
4	Barey cv. Kos	0.82	0.46	0.029	0.76-0.88
5	Rye cv. Amilo	0.62	0.42	0.026	0.57-0.68
6	Rye cv. Dańkowskie Złote	0.46	0.36	0.023	0.41-0.50
7	Rye cv. Dańkowskie Nowe	0.54	0.43	0.027	0.49-0.59
8	Rye cv. Warko	0.51	0.35	0.022	0.47-0.55
9	Faba bean cv. Nadwiślański	0.39	0.17	0.011	0.37-0.41
10	Pea cv. Fidelia	0.45	0.19	0.012	0.42-0.47
11	Lupine cv. Emir	0.80	0.24	0.015	0.77-0.83
12	Vetch cv. Szelejewska	0.60	0.20	0.012	0.58-0.63

Table III-19. Mean specific crushing energy up to the kernel collapse threshold, L_{j2} (J g^{-1}), of selected materials

No.	Material	Mean	Std. Dev.	Std. Err.	95% confidence interval
1	Barey cv. Ars	7.53	2.15	0.136	7.27-7.80
2	Barey cv. Edgar	7.00	1.76	0.111	6.78-7.22
3	Barey cv. Klimek	8.66	1.56	0.098	8.47-8.86
4	Barey cv. Kos	6.72	1.19	0.075	6.58-6.87
5	Rye cv. Amilo	4.26	1.61	0.102	4.06-4.46
6	Rye cv. Dańkowskie Złote	4.57	1.54	0.098	4.38-4.76
7	Rye cv. Dańkowskie Nowe	4.00	1.21	0.077	3.85-4.15
8	Rye cv. Warko	4.13	1.17	0.074	3.99-4.28
9	Faba bean cv. Nadwiślański	9.83	2.65	0.168	9.50-10.16
10	Pea cv. Fidelia	7.92	3.42	0.217	7.50-8.35
11	Lupine cv. Emir	11.35	2.50	0.158	11.04-11.66
12	Vetch cv. Szelejewska	6.31	2.06	0.130	6.06-6.57

Table III-20. Mean values of the compression parameters at different moisture levels, barley cv. Ars

No.	Parameter	Unit	Moisture content (%)				
			10	12	14	16	18
1	m	(g·10^{-3})	53.41	53.27	56.12	56.65	61.32
2	h	(mm)	2.96	2.96	3.01	3.03	3.10
3	b	(mm)	3.85	3.89	3.93	3.94	4.05
4	c	(mm)	9.28	9.33	9.54	9.39	9.59
5	Δh_1	(mm)	0.53	0.59	0.62	0.68	0.79
6	$tg\alpha$	(N mm^{-1})	211	245	257	240	147
7	F_1	(N)	165	161	170	153	140
8	F_2	(N)	352	360	598	783	657
9	L_1	(mJ)	30.86	37.97	43.04	46.36	46.57
10	L_2	(mJ)	282	322	464	585	491
11	L_{j1}	(J g^{-1})	0.58	0.72	0.77	0.82	0.76
12	L_{j2}	(J g^{-1})	5.26	6.01	8.24	10.23	7.95

Table III-21. Mean values of the compression parameters at different moisture levels, barley cv. Edgar

No.	Parameter	Unit	Moisture content (%)				
			10	12	14	16	18
1	*m*	(g·10^{-3})	57.72	55.75	58.20	57.49	61.45
2	*h*	(mm)	2.95	2.95	2.91	2.92	3.01
3	*b*	(mm)	3.83	3.77	3.79	3.79	3.89
4	*c*	(mm)	9.32	9.27	9.55	9.29	9.36
5	Δh_1	(mm)	0.49	0.61	0.70	0.77	0.94
6̃	$tg\alpha$	(N mm^{-1})	208	235	256	157	108
7	F_1	(N)	181	170	184	156	141
8	F_2	(N)	372	506	548	761	580
9	L_1	(mJ)	31.85	40.09	55.27	47.43	44.03
10	L_2	(mJ)	293	372	430	534	424
11	L_{j1}	(J g^{-1})	0.56	0.72	0.99	0.83	0.73
12	L_{j2}	(J g^{-1})	5.06	6.59	7.29	9.21	6.85

Table III-22. Mean values of the compression parameters at different moisture levels, barley cv. Klimek

No.	Parameter	Unit	Moisture content (%)				
			10	12	14	16	18
1	*m*	(g·10^{-3})	54.31	54.69	54.49	58.16	57.84
2	*h*	(mm)	2.88	2.91	2.87	2.99	2.97
3	*b*	(mm)	3.59	3.66	3.56	3.74	3.74
4	*c*	(mm)	10.08	10.84	10.16	10.18	10.83
5	Δh_1	(mm)	0.60	0.57	0.65	0.88	0.88
6̃	$tg\alpha$	(N mm^{-1})	234	253	279	186	188
7	F_1	(N)	176	169	186	152	150
8	F_2	(N)	649	526	657	666	900
9	L_1	(mJ)	45.51	39.51	55.4	49.01	45.9
10	L_2	(mJ)	448	392	486	487	629
11	L_{j1}	(J g^{-1})	0.84	0.72	1.04	0.86	0.80
12	L_{j2}	(J g^{-1})	8.19	7.13	8.85	8.33	10.81

Table III-23. Mean values of the compression parameters at different moisture levels, barley cv. Kos

No.	Parameter	Unit	Moisture content (%)				
			10	12	14	16	18
1	m	(g·10^{-3})	52.29	50.34	55.22	53.72	55.01
2	h	(mm)	2.96	2.98	2.99	2.97	3.00
3	b	(mm)	3.70	3.74	3.94	3.79	3.86
4	c	(mm)	10.15	10.11	10.91	10.91	9.76
5	Δh_1	(mm)	0.56	0.57	0.79	0.88	0.93
6̃	$tg\alpha$	(N mm^{-1})	226	196	221	186	142
7	F_1	(N)	132	123	154	139	124
8	F_2	(N)	499	359	417	493	613
9	L_1	(mJ)	27.8	27.17	57.97	54.76	51.59
10	L_2	(mJ)	354	288	357	379	430
11	L_{j1}	(J g^{-1})	0.53	0.54	1.07	1.03	0.94
12	L_{j2}	(J g^{-1})	6.75	5.67	6.40	7.00	7.80

Table III-24. Mean values of the compression parameters at different moisture levels, rye cv. Amilo

No.	Parameter	Unit	Moisture content (%)				
			10	12	14	16	18
1	m	(g·10^{-3})	37.62	36.36	38.82	39.28	37.19
2	h	(mm)	2.64	2.58	2.66	2.69	2.66
3	b	(mm)	2.72	2.65	2.77	2.78	2.78
4	c	(mm)	7.52	7.44	7.49	7.57	7.40
5	Δh_1	(mm)	0.35	0.46	0.43	0.58	0.53
6̃	$tg\alpha$	(N mm^{-1})	295	284	222	192	141
7	F_1	(N)	107	106	102	86	77
8	F_2	(N)	226	276	182	266	382
9	L_1	(mJ)	18.61	29.34	21.16	24.35	22.47
10	L_2	(mJ)	123	151	126	180	226
11	L_{j1}	(J g^{-1})	0.49	0.83	0.55	0.64	0.61
12	L_{j2}	(J g^{-1})	3.23	4.17	3.23	4.61	6.04

Table III-25. Mean values of the compression parameters at different moisture levels, rye cv. Dańkowskie Złote

No.	Parameter	Unit	Moisture content (%)				
			10	12	14	16	18
1	m	$(g\cdot10^{-3})$	43.25	42.04	42.33	44.36	44.62
2	h	(mm)	2.74	2.72	2.79	2.81	2.71
3	b	(mm)	2.77	2.80	2.82	2.88	2.78
4	c	(mm)	8.16	8.03	7.98	8.10	8.04
5	Δh_1	(mm)	0.39	0.37	0.43	0.49	0.48
6	$tg\alpha$	$(N\ mm^{-1})$	313	288	230	196	198
7	F_1	(N)	104	95	97	78	91
8	F_2	(N)	452	314	340	386	511
9	L_1	(mJ)	20.41	14.84	22.4	20.17	21.88
10	L_2	(mJ)	211	133	177	203	272
11	L_{j1}	$(J\ g^{-1})$	0.47	0.35	0.53	0.45	0.49
12	L_{j2}	$(J\ g^{-1})$	4.87	3.16	4.18	4.54	6.10

Table III-26. Mean values of the compression parameters at different moisture levels, rye cv. Dańkowskie Nowe

No.	Parameter	Unit	Moisture content (%)				
			10	12	14	16	18
1	m	$(g\cdot10^{-3})$	39.36	39.80	43.07	43.14	43.21
2	h	(mm)	2.74	2.72	2.82	2.77	2.82
3	b	(mm)	2.79	2.81	2.88	2.82	2.85
4	c	(mm)	7.77	7.77	7.83	7.97	8.08
5	Δh_1	(mm)	0.30	0.37	0.44	0.50	0.59
6	$tg\alpha$	$(N\ mm^{-1})$	327	311	256	222	222
7	F_1	(N)	103	99	89	93	80
8	F_2	(N)	335	279	327	278	306
9	L_1	(mJ)	13.29	21.5	20.45	29.62	26.35
10	L_2	(mJ)	142	153	190	171	188
11	L_{j1}	$(J\ g^{-1})$	0.34	0.55	0.48	0.70	0.62
12	L_{j2}	$(J\ g^{-1})$	3.53	3.84	4.34	3.96	4.31

Table III-27. Mean values of the compression parameters at different moisture levels, rye cv. Warko

No.	Parameter	Unit	Moisture content (%)				
			10	12	14	16	18
1	m	(g·10^{-3})	40.38	41.69	40.82	43.24	44.44
2	h	(mm)	2.69	2.73	2.68	2.81	2.76
3	b	(mm)	2.81	2.82	2.76	2.87	2.88
4	c	(mm)	8.09	7.94	8.08	8.00	8.31
5	Δh_1	(mm)	0.41	0.42	0.46	0.49	0.48
6	$tg\alpha$	(N mm^{-1})	287	296	220	206	181
7	F_1	(N)	95	101	86	71	77
8	F_2	(N)	381	265	329	359	259
9	L_1	(mJ)	19.8	23.22	22.46	18.07	21.5
10	L_2	(mJ)	172	149	170	211	167
11	L_{j1}	(J g^{-1})	0.50	0.57	0.56	0.42	0.50
12	L_{j2}	(J g^{-1})	4.26	3.57	4.14	4.88	3.80

Table III-28. Mean values of the compression parameters at different moisture levels, faba bean cv. Nadwiślański

No.	Parameter	Unit	Moisture content (%)				
			10	12	14	16	18
1	m	(g·10^{-3})	560	554	562	578	590
2	h	(mm)	7.05	6.92	7.17	7.16	7.22
3	b	(mm)	8.55	8.42	8.67	8.66	8.72
4	c	(mm)	10.61	10.48	10.73	10.72	10.79
5	Δh_1	(mm)	0.80	0.86	0.86	0.98	1.29
6	$tg\alpha$	(N mm^{-1})	513	516	373	330	221
7	F_1	(N)	627	641	653	407	322
8	F_2	(N)	3939	3475	4907	5060	4837
9	L_1	(mJ)	214	245	252	186	204
10	L_2	(mJ)	4290	3974	5176	7424	7303
11	L_{j1}	(J g^{-1})	0.38	0.45	0.45	0.32	0.35
12	L_{j2}	(J g^{-1})	7.63	7.17	9.19	12.78	12.36

Table III-29. Mean values of the compression parameters at different moisture levels, pea cv. Fidelia

No.	Parameter	Unit	Moisture content (%)				
			10	12	14	16	18
1	m	(g·10^{-3})	145	153	142	167	164
2	h	(mm)	4.67	4.69	4.90	5.04	5.09
3	b	(mm)	6.61	6.64	6.85	6.99	7.04
4	c	(mm)	6.67	6.69	6.90	7.04	7.09
5	Δh_1	(mm)	0.53	0.57	0.52	0.80	0.98
6	$tg\alpha$	(N mm^{-1})	501	615	486	282	172
7	F_1	(N)	290	295	263	206	142
8	F_2	(N)	866	958	1259	1716	1510
9	L_1	(mJ)	63	69	56	79	74
10	L_2	(mJ)	709	780	916	1986	1816
11	L_{j1}	(J g^{-1})	0.44	0.45	0.40	0.48	0.46
12	L_{j2}	(J g^{-1})	4.90	5.09	6.47	11.88	11.27

Table III-30. Mean values of the compression parameters at different moisture levels, lupine cv. Emir

No.	Parameter	Unit	Moisture content (%)				
			10	12	14	16	18
1	m	(g·10^{-3})	163	169	165	174	178
2	h	(mm)	4.84	4.74	4.71	4.82	4.96
3	b	(mm)	5.94	5.84	5.81	5.92	6.06
4	c	(mm)	6.89	6.79	6.76	6.87	7.01
5	Δh_1	(mm)	0.73	0.87	0.86	1.18	1.62
6	$tg\alpha$	(N mm^{-1})	654	360	336	249	131
7	F_1	(N)	330	328	271	249	204
8	F_2	(N)	1883	1512	1338	1727	1440
9	L_1	(mJ)	113	133	112	149	166
10	L_2	(mJ)	1775	1772	1954	2384	1652
11	L_{j1}	(J g^{-1})	0.69	0.78	0.68	0.89	0.94
12	L_{j2}	(J g^{-1})	10.86	10.43	11.80	14.29	9.36

Table III-31. Mean values of the compression parameters at different moisture levels, vetch cv. Szelejewska

No.	Parameter	Unit	Moisture content (%)				
			10	12	14	16	18
1	m	$(g\cdot 10^{-3})$	52.04	54.51	57.53	59.06	59.93
2	h	(mm)	3.59	3.36	3.31	3.31	3.31
3	b	(mm)	4.39	4.16	4.11	4.11	4.11
4	c	(mm)	4.58	4.35	4.30	4.30	4.30
5	Δh_1	(mm)	0.41	0.42	0.52	0.65	0.77
6	$tg\alpha$	$(N\ mm^{-1})$	557	545	317	240	132
7	F_1	(N)	185	200	122	111	91
8	F_2	(N)	667	420	378	417	395
9	L_1	(mJ)	28.73	31.45	30.58	39.26	39.63
10	L_2	(mJ)	367	248	316	457	405
11	L_{j1}	$(J\ g^{-1})$	0.55	0.58	0.54	0.67	0.67
12	L_{j2}	$(J\ g^{-1})$	7.06	4.54	5.50	7.72	6.73

Table III-32. Specific grinding energy, E (kJ kg^{-1}), of selected materials, screen size 1 mm

No.	Material	Mean	Std. Dev.	Std. Err.	95% confidence interval
1	Barey cv. Ars	179	28.7	3.30	173-186
2	Barey cv. Edgar	188	23.0	2.70	182-193
3	Barey cv. Klimek	216	30.5	3.50	209-223
4	Barey cv. Kos	169	31.1	3.60	162-176
5	Rye cv. Amilo	134	21.2	2.40	129-139
6	Rye cv. Dańkowskie Złote	122	12.1	1.40	119-124
7	Rye cv. Dańkowskie Nowe	118	10.1	1.20	115-120
8	Rye cv. Warko	123	22.1	2.60	118-128
9	Faba bean cv. Nadwiślański	138	52.6	6.10	126-150
10	Pea cv. Fidelia	112	38.6	4.50	103-121
11	Lupine cv. Emir	384	112.2	13.00	359-410
12	Vetch cv. Szelejewska	96	33.0	3.80	89-104
13	Maize cv. Kosmo	218	56.1	6.50	205-231
14	Maize cv. Koka	232	64.5	7.50	217-247
15	Maize cv. KLG2210	227	63.2	7.30	213-242
16	Soybean	255	111.2	12.90	230-281

Table III-33. Specific grinding energy, *E* (kJ kg^{-1}), of selected materials, screen size 1.5 mm

No.	Material	Mean	Std. Dev.	Std. Err.	95% confidence interval
1	Barey cv. Ars	135	20.4	2.30	131-140
2	Barey cv. Edgar	142	11.8	1.40	139-144
3	Barey cv. Klimek	158	17.8	2.10	154-162
4	Barey cv. Kos	126	22.2	2.60	121-131
5	Rye cv. Amilo	102	18.0	2.10	98-106
6	Rye cv. Dańkowskie Złote	91	11.7	1.40	88-93
7	Rye cv. Dańkowskie Nowe	88	13.9	1.60	85-91
8	Rye cv. Warko	90	18.6	2.20	86-95
9	Faba bean cv. Nadwiślański	113	48.3	5.60	102-124
10	Pea cv. Fidelia	77	30.3	3.50	70-84
11	Lupine cv. Emir	266	88.6	10.20	246-287
12	Vetch cv. Szelejewska	61	18.5	2.10	57-65
13	Maize cv. Kosmo	129	33.4	3.90	121-137
14	Maize cv. Koka	129	39.7	4.60	120-139
15	Maize cv. KLG2210	130	40.0	4.60	121-140
16	Soybean	280	114.2	13.20	254-306

Table III-34. Specific grinding energy, *E* (kJ kg^{-1}), of selected materials, screen size 2 mm

No.	Material	Mean	Std. Dev.	Std. Err.	95% confidence interval
1	Barey cv. Ars	106	13.8	1.60	102-109
2	Barey cv. Edgar	112	7.7	0.90	110-114
3	Barey cv. Klimek	123	16.8	1.90	120-127
4	Barey cv. Kos	97	14.8	1.70	93-100
5	Rye cv. Amilo	78	14.6	1.70	74-81
6	Rye cv. Dańkowskie Złote	69	10.9	1.30	66-72
7	Rye cv. Dańkowskie Nowe	67	11.3	1.30	64-69
8	Rye cv. Warko	66	16.2	1.90	63-70
9	Faba bean cv. Nadwiślański	87	46.0	5.30	77-98
10	Pea cv. Fidelia	61	35.9	4.10	53-70
11	Lupine cv. Emir	212	96.3	11.10	190-234
12	Vetch cv. Szelejewska	45	20.3	2.30	41-50
13	Maize cv. Kosmo	90	27.4	3.20	84-97
14	Maize cv. Koka	88	29.2	3.40	81-94
15	Maize cv. KLG2210	90	30.6	3.50	83-97
16	Soybean	175	92.6	10.70	154-197

Table III-35. Mean specific grinding energy, *E* (kJ kg^{-1}), of selected materials at different moisture levels, screen size 1 mm

No.	Material	Moisture content (%)				
		10	12	14	16	18
1	Barey cv. Ars	146	162	168	199	220
2	Barey cv. Edgar	165	171	180	198	225
3	Barey cv. Klimek	179	192	226	223	259
4	Barey cv. Kos	128	147	176	179	215
5	Rye cv. Amilo	109	115	137	142	167
6	Rye cv. Dańkowskie Złote	104	117	114	124	130
7	Rye cv. Dańkowskie Nowe	107	117	116	126	141
8	Rye cv. Warko	99	108	114	132	160
9	Faba bean cv. Nadwiślański	93	97	112	158	229
10	Pea cv. Fidelia	78	80	102	120	181
11	Lupine cv. Emir	255	268	394	475	530
12	Vetch cv. Szelejewska	61	72	87	110	151
13	Maize cv. Kosmo	137	188	218	254	295
14	Maize cv. Koka	144	184	234	286	313
15	Maize cv. KLG2210	134	175	264	280	283
16	Soybean	132	188	220	328	407

Table III-36. Mean specific grinding energy, *E* (kJ kg^{-1}), of selected materials at different moisture levels, screen size 1.5 mm

No.	Material	Moisture content (%)				
		10	12	14	16	18
1	Barey cv. Ars	108	123	132	149	164
2	Barey cv. Edgar	125	136	140	152	155
3	Barey cv. Klimek	133	148	161	167	182
4	Barey cv. Kos	101	110	126	135	160
5	Rye cv. Amilo	81	82	108	113	126
6	Rye cv. Dańkowskie Złote	73	82	82	92	112
7	Rye cv. Dańkowskie Nowe	76	86	86	95	110
8	Rye cv. Warko	70	81	81	96	123
9	Faba bean cv. Nadwiślański	75	79	84	129	198
10	Pea cv. Fidelia	51	54	68	80	133
11	Lupine cv. Emir	162	175	279	339	378
12	Vetch cv. Szelejewska	41	48	55	70	92
13	Maize cv. Kosmo	78	108	139	158	163
14	Maize cv. Koka	75	107	133	153	180
15	Maize cv. KLG2210	72	96	159	165	160
16	Soybean	132	215	264	369	420

Table III-37. Mean specific grinding energy, E (kJ kg^{-1}), of selected materials at different moisture levels, screen size 2 mm

No.	Material	Moisture content (%)				
		10	12	14	16	18
1	Barey cv. Ars	86	97	105	117	123
2	Barey cv. Edgar	102	107	112	119	119
3	Barey cv. Klimek	100	114	127	133	144
4	Barey cv. Kos	76	87	98	105	117
5	Rye cv. Amilo	62	60	82	88	96
6	Rye cv. Dańkowskie Złote	54	62	60	72	85
7	Rye cv. Dańkowskie Nowe	57	65	62	73	87
8	Rye cv. Warko	48	60	60	69	96
9	Faba bean cv. Nadwiślański	52	57	57	100	171
10	Pea cv. Fidelia	35	35	48	60	130
11	Lupine cv. Emir	111	118	190	296	347
12	Vetch cv. Szelejewska	28	31	35	50	82
13	Maize cv. Kosmo	49	74	94	120	114
14	Maize cv. Koka	48	67	89	112	123
15	Maize cv. KLG2210	44	64	113	112	115
16	Soybean	63	112	153	249	299

Table III-38. Mean particle diameter, $d_ś$ (mm), of ground materials at different moisture levels, screen size 1.0 mm

No.	Material	Moisture content (%)				
		10	12	14	16	18
1	Barey cv. Ars	0.358	0.360	0.360	0.369	0.354
2	Barey cv. Edgar	0.372	0.370	0.373	0.379	0.382
3	Barey cv. Klimek	0.392	0.385	0.378	0.395	0.394
4	Barey cv. Kos	0.390	0.381	0.368	0.383	0.378
5	Rye cv. Amilo	0.377	0.370	0.358	0.355	0.341
6	Rye cv. Dańkowskie Złote	0.342	0.349	0.345	0.351	0.347
7	Rye cv. Dańkowskie Nowe	0.349	0.356	0.359	0.353	0.351
8	Rye cv. Warko	0.356	0.361	0.369	0.366	0.346
9	Faba bean cv. Nadwiślański	0.319	0.318	0.336	0.306	0.263
10	Pea cv. Fidelia	0.339	0.341	0.339	0.350	0.287
11	Lupine cv. Emir	0.421	0.429	0.378	0.352	0.352
12	Vetch cv. Szelejewska	0.339	0.342	0.354	0.368	0.352
13	Maize cv. Kosmo	0.453	0.479	0.468	0.470	0.485
14	Maize cv. Koka	0.453	0.479	0.468	0.470	0.485
15	Maize cv. KLG2210	0.458	0.490	0.484	0.485	0.501
16	Soybean	0.510	0.477	0.414	0.472	0.622

Table III-39. Mean particle diameter, $d_{\acute{s}}$ (mm), of ground materials at different moisture levels, screen size 1.5 mm

No.	Material	Moisture content (%)				
		10	12	14	16	18
1	Barey cv. Ars	0.427	0.436	0.442	0.447	0.455
2	Barey cv. Edgar	0.449	0.448	0.450	0.455	0.467
3	Barey cv. Klimek	0.445	0.464	0.463	0.470	0.471
4	Barey cv. Kos	0.452	0.451	0.447	0.450	0.459
5	Rye cv. Amilo	0.458	0.454	0.439	0.438	0.452
6	Rye cv. Dańkowskie Złote	0.431	0.434	0.435	0.429	0.417
7	Rye cv. Dańkowskie Nowe	0.413	0.434	0.443	0.437	0.419
8	Rye cv. Warko	0.451	0.441	0.459	0.448	0.425
9	Faba bean cv. Nadwiślański	0.411	0.403	0.421	0.389	0.345
10	Pea cv. Fidelia	0.420	0.426	0.428	0.445	0.392
11	Lupine cv. Emir	0.494	0.488	0.464	0.448	0.435
12	Vetch cv. Szelejewska	0.440	0.441	0.451	0.462	0.463
13	Maize cv. Kosmo	0.530	0.553	0.560	0.559	0.565
14	Maize cv. Koka	0.530	0.553	0.560	0.559	0.565
15	Maize cv. KLG2210	0.532	0.568	0.571	0.563	0.567
16	Soybean	0.529	0.540	0.474	0.482	0.617

Table III-40. Mean particle diameter, $d_{\acute{s}}$ (mm), of ground materials at different moisture levels, screen size 2 mm

No.	Material	Moisture content (%)				
		10	12	14	16	18
1	Barey cv. Ars	0.532	0.534	0.545	0.551	0.552
2	Barey cv. Edgar	0.522	0.553	0.551	0.566	0.575
3	Barey cv. Klimek	0.567	0.575	0.569	0.580	0.570
4	Barey cv. Kos	0.551	0.546	0.548	0.547	0.553
5	Rye cv. Amilo	0.557	0.563	0.543	0.524	0.522
6	Rye cv. Dańkowskie Złote	0.546	0.543	0.552	0.542	0.524
7	Rye cv. Dańkowskie Nowe	0.561	0.543	0.554	0.543	0.523
8	Rye cv. Warko	0.566	0.560	0.577	0.568	0.535
9	Faba bean cv. Nadwiślański	0.492	0.489	0.511	0.475	0.408
10	Pea cv. Fidelia	0.514	0.529	0.535	0.544	0.461
11	Lupine cv. Emir	0.620	0.615	0.613	0.584	0.575
12	Vetch cv. Szelejewska	0.519	0.523	0.538	0.560	0.545
13	Maize cv. Kosmo	0.612	0.632	0.655	0.660	0.662
14	Maize cv. Koka	0.612	0.632	0.655	0.660	0.662
15	Maize cv. KLG2210	0.617	0.653	0.675	0.683	0.682
16	Soybean	0.616	0.586	0.536	0.509	0.705

Table II-41. Mean bulk densities, ρ_n (g cm^{-3}), of selected ground feedstuffs

Material	Moisture content (%)				
	10	12	14	16	18
Maize meal	0.583	0.603	0.603	0.600	0.585
Rice	0.766	0.778	0.785	0.786	0.754
Wheat, cv. Alba	0.539	0.518	0.510	0.524	0.532
Wheat, cv. Jara	0.691	0.689	0.672	0.665	0.643
Wheat, cv. Almary	0.638	0.682	0.664	0.651	0.629
Oat, cv. Dragon	0.342	0.361	0.359	0.351	0.346
Oat, cv. Pegaz	0.329	0.349	0.336	0.334	0.330
Barley, cv. Aramir	0.559	0.548	0.540	0.527	0.510
Barley, cv. Ars	0.512	0.508	0.499	0.517	0.505
Barley, cv. Edgar	0.533	0.543	0.522	0.520	0.516
Barley, cv. Klimek	0.526	0.540	0.536	0.509	0.509
Barley, cv. Kos	0.565	0.576	0.552	0.539	0.536
Rye cv. Amilo	0.637	0.637	0.643	0.627	0.601
Rye cv. Dańkowskie Nowe	0.678	0.677	0.662	0.642	0.647
Rye cv. Dańkowskie Złote	0.666	0.681	0.646	0.640	0.637
Rye cv. Warko	0.622	0.603	0.601	0.580	0.565
Faba bean cv. Nadwiślański	0.796	0.786	0.767	0.727	0.696
Pea, cv. Fidelia	0.750	0.772	0.765	0.697	0.673
Lupine, cv. Emir	0.585	0.581	0.572	0.560	0.530
Vetch, cv. Szelejewska	0.762	0.782	0.728	0.715	0.659
Dry plant matter (alfalfa)	0.188	0.187	0.184	0.176	0.174
Meat-bone flour	0.600	0.662	0.624	0.597	0.582
Soybean meal	0.551	0.566	0.587	0.581	0.574
Maize 75% with rice 25%	0.625	0.635	0.633	0.631	0.606
Maize 50% with rice 50%	0.668	0.676	0.675	0.676	0.649
Maize 25% with rice 75%	0.724	0.733	0.728	0.725	0.706
Maize 75% with oat, Pegaz 25%	0.528	0.540	0.532	0.530	0.527
Maize 50% with oat, Pegaz 50%	0.496	0.510	0.506	0.501	0.494
Maize 25% with oat, Pegaz 75%	0.407	0.420	0.418	0.412	0.402
Maize 75% with wheat, Alba 25%	0.564	0.576	0.568	0.551	0.542
Maize 50% with wheat, Alba 50%	0.560	0.562	0.558	0.552	0.540
Maize 25% with wheat, Alba 75%	0.554	0.552	0.548	0.540	0.538
Maize 75% with soybean 25%	0.579	0.608	0.595	0.594	0.577
Maize 50% with soybean 50%	0.563	0.589	0.584	0.583	0.572
Maize 25% with soybean 75%	0.545	0.583	0.582	0.580	0.568
Rice 75% with soybean 25%	0.686	0.703	0.697	0.684	0.641
Rice 50% with soybean 50%	0.626	0.653	0.658	0.638	0.610
Rice 25% with soybean 75%	0.581	0.614	0.613	0.606	0.585
Maize 50%, rice 25% and soybean 25%	0.616	0.627	0.627	0.614	0.603
Maize 25%, rice 50% and soybean 25%	0.647	0.663	0.654	0.652	0.637
Maize 25%, rice 25% and soybean 50%	0.591	0.610	0.610	0.608	0.590
Maize	0.629	0.637	0.625	0.612	0.598
Barley	0.551	0.559	0.548	0.531	0.522
Pea	0.748	0.754	0.728	0.695	0.671
Soybean meal	0.661	0.668	0.652	0.639	0.621
Wheat	0.659	0.663	0.642	0.631	0.619
Rapeseed meal	0.541	0.548	0.527	0.512	0.501
Lupine	0.617	0.612	0.599	0.591	0.582
Wheat bran	0.315	0.309	0.304	0.301	0.299
Dry plant matter (alfalfa)	0.262	0.259	0.258	0.253	0.251
Meat-bone flour	0.612	0.687	0.635	0.602	0.586

Table III-42. Mean tapped densities, ρ_u (g cm^{-3}), of selected ground feedstuffs

Material	Moisture content (%)				
	10	12	14	16	18
Maize meal	0.729	0.728	0.719	0.713	0.686
Rice	0.877	0.872	0.863	0.850	0.848
Wheat, cv. Alba	0.625	0.618	0.610	0.612	0.600
Wheat, cv. Jara	0.720	0.717	0.708	0.686	0.685
Wheat, cv. Almary	0.704	0.718	0.712	0.689	0.658
Oat, cv. Dragon	0.397	0.405	0.427	0.411	0.396
Oat, cv. Pegaz	0.430	0.405	0.407	0.404	0.395
Barley, cv. Aramir	0.620	0.616	0.603	0.602	0.598
Barley, cv. Ars	0.564	0.568	0.570	0.601	0.567
Barley, cv. Edgar	0.619	0.615	0.590	0.588	0.579
Barley, cv. Klimek	0.593	0.601	0.585	0.571	0.567
Barley, cv. Kos	0.636	0.607	0.603	0.603	0.607
Rye cv. Amilo	0.736	0.765	0.759	0.716	0.697
Rye cv. Dańkowskie Nowe	0.734	0.724	0.731	0.743	0.750
Rye cv. Dańkowskie Złote	0.768	0.773	0.751	0.791	0.698
Rye cv. Warko	0.681	0.685	0.707	0.664	0.656
Faba bean cv. Nadwiślański	0.905	0.917	0.880	0.827	0.787
Pea, cv. Fidelia	0.876	0.862	0.818	0.792	0.734
Lupine, cv. Emir	0.677	0.671	0.617	0.601	0.562
Vetch, cv. Szelejewska	0.836	0.839	0.757	0.732	0.718
Dry plant matter (alfalfa)	0.248	0.240	0.240	0.232	0.234
Meat-bone flour	0.735	0.771	0.770	0.773	0.740
Soybean meal	0.636	0.653	0.644	0.638	0.625
Maize 75% with rice 25%	0.750	0.736	0.726	0.718	0.688
Maize 50% with rice 50%	0.795	0.794	0.785	0.778	0.656
Maize 25% with rice 75%	0.845	0.840	0.832	0.825	0.809
Maize 75% with oat, Pegaz 25%	0.665	0.678	0.670	0.668	0.655
Maize 50% with oat, Pegaz 50%	0.566	0.560	0.554	0.552	0.550
Maize 25% with oat, Pegaz 75%	0.498	0.490	0.488	0.487	0.480
Maize 75% with wheat, Alba 25%	0.702	0.700	0.695	0.692	0.683
Maize 50% with wheat, Alba 50%	0.688	0.680	0.677	0.661	0.652
Maize 25% with wheat, Alba 75%	0.645	0.642	0.638	0.632	0.624
Maize 75% with soybean 25%	0.694	0.720	0.694	0.681	0.659
Maize 50% with soybean 50%	0.677	0.685	0.664	0.661	0.642
Maize 25% with soybean 75%	0.658	0.673	0.657	0.649	0.633
Rice 75% with soybean 25%	0.818	0.811	0.788	0.745	0.715
Rice 50% with soybean 50%	0.753	0.739	0.728	0.704	0.665
Rice 25% with soybean 75%	0.697	0.691	0.679	0.667	0.651
Maize 50%, rice 25% and soybean 25%	0.739	0.735	0.706	0.702	0.677
Maize 25%, rice 50% and soybean 25%	0.776	0.772	0.732	0.724	0.696
Maize 25%, rice 25% and soybean 50%	0.714	0.708	0.685	0.671	0.659
Maize	0.798	0.796	0.785	0.779	0.701
Barley	0.681	0.676	0.664	0.652	0.644
Pea	0.889	0.871	0.852	0.848	0.803
Soybean meal	0.798	0.783	0.763	0.759	0.741
Wheat	0.795	0.798	0.785	0.770	0.751
Rapeseed meal	0.635	0.639	0.620	0.601	0.587
Lupine	0.761	0.738	0.712	0.691	0.625
Wheat bran	0.398	0.392	0.386	0.381	0.377
Dry plant matter (alfalfa)	0.328	0.325	0.319	0.312	0.309
Meat-bone flour	0.751	0.835	0.781	0.738	0.718

Table III-43. Mean angle of repose, α_u (deg), of selected ground feedstuffs

Material	Moisture content (%)				
	10	12	14	16	18
Maize meal	40.13	41.23	41.50	41.63	40.37
Rice	36.03	36.30	37.07	36.47	35.63
Wheat, cv. Alba	37.80	38.10	38.90	40.20	41.80
Wheat, cv. Jara	39.67	40.17	42.10	44.00	44.30
Wheat, cv. Almary	39.27	39.87	40.20	40.93	41.80
Oat, cv. Dragon	38.23	40.03	43.77	46.30	47.63
Oat, cv. Pegaz	36.13	41.60	43.93	47.57	46.00
Barley, cv. Aramir	36.80	37.50	38.60	39.80	41.00
Barley, cv. Ars	44.33	45.17	45.63	44.17	42.83
Barley, cv. Edgar	44.17	44.33	44.50	45.00	45.63
Barley, cv. Klimek	47.77	46.87	46.67	47.17	47.43
Barley, cv. Kos	45.30	47.00	46.23	45.17	45.07
Rye cv. Amilo	39.20	40.93	41.10	40.77	39.80
Rye cv. Dańkowskie Nowe	39.40	40.20	41.30	42.47	42.27
Rye cv. Dańkowskie Złote	39.60	40.93	41.40	41.77	41.97
Rye cv. Warko	42.67	42.63	43.47	43.67	42.80
Faba bean cv. Nadwiślański	38.67	39.20	43.67	40.33	40.13
Pea, cv. Fidelia	39.07	39.13	41.13	40.33	40.30
Lupine, cv. Emir	36.80	43.23	42.37	41.27	39.27
Vetch, cv. Szelejewska	36.23	38.03	36.83	38.03	38.53
Dry plant matter (alfalfa)	48.67	48.97	49.40	50.03	49.80
Meat-bone flour	41.60	42.67	42.97	43.43	44.40
Soybean meal	40.36	40.36	40.53	41.23	42.13
Maize 75% with rice 25%	38.70	38.70	39.57	39.57	39.80
Maize 50% with rice 50%	37.50	38.43	38.40	37.87	37.67
Maize 25% with rice 75%	36.37	36.63	36.97	37.40	37.50
Maize 75% with oat, Pegaz 25%	39.50	41.40	41.70	42.50	42.00
Maize 50% with oat, Pegaz 50%	38.20	41.20	42.00	43.80	44.20
Maize 25% with oat, Pegaz 75%	37.40	41.00	42.50	45.40	45.00
Maize 75% with wheat, Alba 25%	39.20	40.03	41.80	41.40	40.60
Maize 50% with wheat, Alba 50%	38.60	39.30	39.70	40.80	41.10
Maize 25% with wheat, Alba 75%	38.70	39.00	39.40	40.30	41.50
Maize 75% with soybean 25%	41.98	42.14	42.23	39.23	37.83
Maize 50% with soybean 50%	40.91	41.61	41.98	39.40	38.07
Maize 25% with soybean 75%	40.91	40.91	40.91	40.14	37.83
Rice 75% with soybean 25%	37.47	37.65	38.24	36.62	34.99
Rice 50% with soybean 50%	38.65	38.83	39.00	37.83	35.81
Rice 25% with soybean 75%	40.53	40.56	40.58	38.42	36.62
Maize 50%, rice 25% and soybean 25%	39.23	39.23	39.40	38.24	36.43
Maize 25%, rice 50% and soybean 25%	38.83	39.00	39.23	38.07	36.25
Maize 25%, rice 25% and soybean 50%	40.53	40.53	40.54	38.65	35.37
Maize	40.32	40.51	40.89	41.10	40.91
Barley	44.13	45.61	46.03	45.91	45.13
Pea	42.17	43.05	44.56	44.26	43.92
Soybean meal	39.17	40.22	40.85	40.09	39.13
Wheat	36.26	37.43	38.36	39.84	40.96
Rapeseed meal	39.16	40.25	41.58	42.36	42.62
Lupine	41.12	44.92	45.36	43.15	42.32
Wheat bran	42.39	43.05	43.63	43.25	43.03
Dry plant matter (alfalfa)	47.27	48.14	48.65	49.69	49.03
Meat-bone flour	40.82	42.93	43.63	44.16	45.82

Table III-44. Mean angle of slide, a_z (deg), of selected ground feedstuffs

Material	Moisture content (%)				
	10	12	14	16	18
Maize meal	27.33	27.83	28.33	31.83	35.00
Rice	27.17	29.50	29.83	30.67	32.00
Wheat, cv. Alba	26.20	28.50	30.00	32.20	33.00
Wheat, cv. Jara	30.33	30.67	33.67	35.00	36.67
Wheat, cv. Almary	29.17	30.83	31.83	33.50	35.83
Oat, cv. Dragon	26.83	33.83	33.00	29.67	26.33
Oat, cv. Pegaz	25.50	32.83	32.33	28.17	25.33
Barley, cv. Aramir	24.30	26.90	30.30	31.40	32.90
Barley, cv. Ars	17.17	18.50	18.50	21.00	23.83
Barley, cv. Edgar	16.83	18.67	21.83	21.83	23.50
Barley, cv. Klimek	16.83	17.50	20.50	21.50	24.33
Barley, cv. Kos	17.00	17.67	20.67	23.00	23.83
Rye cv. Amilo	18.00	18.83	20.67	21.67	24.50
Rye cv. Dańkowskie Nowe	20.50	20.33	21.83	22.00	23.67
Rye cv. Dańkowskie Złote	18.33	19.67	21.67	22.00	22.83
Rye cv. Warko	18.00	19.00	21.00	22.17	24.33
Faba bean cv. Nadwiślański	23.00	22.67	21.67	21.33	21.67
Pea, cv. Fidelia	23.67	22.67	22.33	21.67	22.67
Lupine, cv. Emir	22.00	20.67	21.33	22.67	23.67
Vetch, cv. Szelejewska	25.33	25.00	22.33	21.33	22.33
Dry plant matter (alfalfa)	34.50	35.50	35.33	35.67	40.17
Meat-bone flour	34.50	35.83	39.17	41.00	42.83
Soybean meal	29.00	29.33	31.83	32.55	33.15
Maize 75% with rice 25%	32.00	33.33	33.33	34.33	34.50
Maize 50% with rice 50%	29.67	31.83	32.17	34.67	36.00
Maize 25% with rice 75%	29.83	31.00	31.00	32.33	35.00
Maize 75% with oat, Pegaz 25%	30.33	27.90	28.80	31.00	34.20
Maize 50% with oat, Pegaz 50%	26.50	27.83	28.83	31.17	33.33
Maize 25% with oat, Pegaz 75%	25.83	28.00	28.83	30.50	31.83
Maize 75% with wheat, Alba 25%	27.17	27.83	28.83	32.00	34.00
Maize 50% with wheat, Alba 50%	26.67	28.33	29.17	32.17	33.50
Maize 25% with wheat, Alba 75%	26.50	28.33	29.83	32.17	33.33
Maize 75% with soybean 25%	30.00	30.17	31.67	35.67	36.00
Maize 50% with soybean 50%	30.00	30.83	31.17	33.67	35.33
Maize 25% with soybean 75%	30.33	31.83	34.83	37.67	38.17
Rice 75% with soybean 25%	29.83	30.17	30.50	31.50	34.67
Rice 50% with soybean 50%	30.00	32.33	33.17	34.17	36.67
Rice 25% with soybean 75%	30.50	32.00	33.33	36.83	36.83
Maize 50%, rice 25% and soybean 25%	30.17	30.33	32.33	34.50	34.83
Maize 25%, rice 50% and soybean 25%	29.33	29.33	31.83	33.67	35.67
Maize 25%, rice 25% and soybean 50%	29.50	31.33	31.83	35.17	36.67
Maize	27.24	27.50	28.14	29.54	33.14
Barley	25.35	26.50	29.27	31.33	32.57
Pea	28.13	29.02	30.03	31.50	31.26
Soybean meal	26.27	27.91	29.00	29.63	30.13
Wheat	26.13	27.10	28.13	28.50	30.22
Rapeseed meal	25.32	26.53	27.00	28.13	30.22
Lupine	32.12	33.52	34.00	34.94	34.72
Wheat bran	28.37	29.45	30.00	30.59	31.52
Dry plant matter (alfalfa)	31.20	33.86	34.51	34.94	35.84
Meat-bone flour	32.12	34.38	38.52	40.16	41.21

Table III-45. Mean coefficients of internal friction μ_b of selected ground feedstuffs

Material	Moisture content (%)				
	10	12	14	16	18
Maize meal	0.920	0.947	0.997	1.000	0.980
Rice	0.887	0.893	0.910	0.900	0.890
Wheat, cv. Alba	0.577	0.623	0.663	0.677	0.700
Wheat, cv. Jara	0.737	0.780	0.800	0.867	0.863
Wheat, cv. Almary	0.660	0.763	0.793	0.823	0.857
Oat, cv. Dragon	0.597	0.607	0.623	0.610	0.597
Oat, cv. Pegaz	0.533	0.567	0.590	0.600	0.590
Barley, cv. Aramir	0.553	0.577	0.603	0.613	0.637
Barley, cv. Ars	0.467	0.557	0.603	0.607	0.630
Barley, cv. Edgar	0.510	0.523	0.530	0.603	0.657
Barley, cv. Klimek	0.513	0.537	0.617	0.637	0.650
Barley, cv. Kos	0.487	0.523	0.570	0.703	0.713
Rye cv. Amilo	0.553	0.627	0.653	0.683	0.767
Rye cv. Dańkowskie Nowe	0.633	0.657	0.670	0.720	0.800
Rye cv. Dańkowskie Złote	0.550	0.627	0.697	0.710	0.860
Rye cv. Warko	0.537	0.567	0.623	0.717	0.720
Faba bean cv. Nadwiślański	0.640	0.620	0.700	0.740	0.970
Pea, cv. Fidelia	0.690	0.720	0.640	0.900	0.880
Lupine, cv. Emir	0.680	0.730	0.750	0.810	0.780
Vetch, cv. Szelejewska	0.430	0.650	0.780	0.770	0.680
Dry plant matter (alfalfa)	0.620	0.647	0.673	0.677	0.783
Meat-bone flour	0.383	0.517	0.603	0.670	0.683
Soybean meal	0.953	0.967	0.960	0.971	0.923
Maize 75% with rice 25%	0.907	0.950	1.000	0.980	0.957
Maize 50% with rice 50%	0.867	0.940	0.950	0.950	0.943
Maize 25% with rice 75%	0.883	0.933	0.940	0.957	0.970
Maize 75% with oat, Pegaz 25%	0.600	0.620	0.687	0.670	0.660
Maize 50% with oat, Pegaz 50%	0.590	0.593	0.633	0.610	0.597
Maize 25% with oat, Pegaz 75%	0.570	0.580	0.597	0.603	0.590
Maize 75% with wheat, Alba 25%	0.603	0.637	0.673	0.683	0.647
Maize 50% with wheat, Alba 50%	0.593	0.637	0.667	0.660	0.627
Maize 25% with wheat, Alba 75%	0.580	0.633	0.663	0.650	0.600
Maize 75% with soybean 25%	0.900	0.913	0.950	0.947	0.910
Maize 50% with soybean 50%	0.923	0.970	0.987	0.957	0.907
Maize 25% with soybean 75%	0.930	0.940	0.977	0.983	0.937
Rice 75% with soybean 25%	0.840	0.843	0.950	0.970	0.847
Rice 50% with soybean 50%	0.967	0.973	0.970	0.970	0.747
Rice 25% with soybean 75%	1.040	0.993	0.980	0.937	0.907
Maize 50%, rice 25% and soybean 25%	0.903	0.910	0.960	0.967	0.937
Maize 25%, rice 50% and soybean 25%	0.877	0.930	0.967	0.967	0.960
Maize 25%, rice 25% and soybean 50%	0.937	0.927	0.953	0.960	0.787
Maize	0.926	0.957	0.985	0.997	0.992
Barley	0.598	0.615	0.621	0.628	0.652
Pea	0.598	0.620	0.621	0.629	0.610
Soybean meal	0.738	0.802	0.876	0.825	0.810
Wheat	0.675	0.703	0.756	0.789	0.721
Rapeseed meal	0.518	0.612	0.692	0.716	0.638
Lupine	0.696	0.750	0.786	0.837	0.810
Wheat bran	0.745	0.818	0.850	0.874	0.892
Dry plant matter (alfalfa)	0.610	0.635	0.650	0.667	0.679
Meat-bone flour	0.456	0.598	0.617	0.692	0.708

Table III-46. Mean material compressibility index, S_z of selected ground feedstuffs

Material	Moisture content (%)				
	10	12	14	16	18
Maize meal	1.250	1.208	1.192	1.188	1.171
Rice	1.144	1.121	1.099	1.082	1.124
Wheat, cv. Alba	1.160	1.193	1.196	1.168	1.128
Wheat, cv. Jara	1.043	1.041	1.054	1.032	1.065
Wheat, cv. Almary	1.104	1.052	1.072	1.058	1.046
Oat, cv. Dragon	1.161	1.123	1.189	1.172	1.146
Oat, cv. Pegaz	1.310	1.160	1.211	1.209	1.196
Barley, cv. Aramir	1.109	1.124	1.117	1.142	1.173
Barley, cv. Ars	1.102	1.119	1.143	1.164	1.124
Barley, cv. Edgar	1.161	1.132	1.130	1.132	1.123
Barley, cv. Klimek	1.128	1.113	1.090	1.122	1.115
Barley, cv. Kos	1.126	1.054	1.092	1.117	1.132
Rye cv. Amilo	1.155	1.201	1.180	1.143	1.159
Rye cv. Dańkowskie Nowe	1.083	1.070	1.104	1.157	1.159
Rye cv. Dańkowskie Złote	1.153	1.135	1.162	1.235	1.095
Rye cv. Warko	1.095	1.137	1.177	1.144	1.160
Faba bean cv. Nadwiślański	1.136	1.167	1.148	1.138	1.132
Pea, cv. Fidelia	1.168	1.117	1.070	1.136	1.091
Lupine, cv. Emir	1.157	1.155	1.080	1.073	1.061
Vetch, cv. Szelejewska	1.097	1.073	1.039	1.024	1.089
Dry plant matter (alfalfa)	1.315	1.281	1.300	1.316	1.346
Meat-bone flour	1.227	1.164	1.233	1.298	1.272
Soybean meal	1.154	1.153	1.098	1.094	1.183
Maize 75% with rice 25%	1.200	1.159	1.146	1.136	1.135
Maize 50% with rice 50%	1.191	1.175	1.163	1.151	1.011
Maize 25% with rice 75%	1.167	1.146	1.143	1.138	1.145
Maize 75% with oat, Pegaz 25%	1.258	1.256	1.260	1.260	1.243
Maize 50% with oat, Pegaz 50%	1.141	1.098	1.095	1.102	1.113
Maize 25% with oat, Pegaz 75%	1.224	1.167	1.168	1.182	1.194
Maize 75% with wheat, Alba 25%	1.245	1.215	1.224	1.256	1.261
Maize 50% with wheat, Alba 50%	1.229	1.210	1.213	1.198	1.208
Maize 25% with wheat, Alba 75%	1.165	1.163	1.164	1.171	1.160
Maize 75% with soybean 25%	1.198	1.184	1.165	1.145	1.143
Maize 50% with soybean 50%	1.202	1.162	1.137	1.135	1.122
Maize 25% with soybean 75%	1.206	1.154	1.129	1.119	1.114
Rice 75% with soybean 25%	1.130	1.153	1.130	1.090	1.115
Rice 50% with soybean 50%	1.202	1.132	1.108	1.103	1.092
Rice 25% with soybean 75%	1.200	1.126	1.109	1.101	1.113
Maize 50%, rice 25% and soybean 25%	1.200	1.172	1.126	1.143	1.123
Maize 25%, rice 50% and soybean 25%	1.200	1.164	1.119	1.111	1.092
Maize 25%, rice 25% and soybean 50%	1.208	1.160	1.124	1.102	1.116
Maize	1.269	1.250	1.256	1.273	1.172
Barley	1.236	1.209	1.212	1.228	1.234
Pea	1.189	1.155	1.170	1.220	1.197
Soybean meal	1.207	1.172	1.170	1.188	1.193
Wheat	1.206	1.204	1.223	1.220	1.213
Rapeseed meal	1.174	1.166	1.176	1.174	1.172
Lupine	1.233	1.206	1.189	1.169	1.074
Wheat bran	1.263	1.269	1.270	1.266	1.261
Dry plant matter (alfalfa)	1.252	1.255	1.236	1.233	1.231
Meat-bone flour	1.227	1.215	1.230	1.226	1.225

Table III-47. Mean particle size, $d_{ś}$ (mm) of selected ground feedstuffs

Material	Moisture content (%)				
	10	12	14	16	18
Maize meal	0.810	0.817	0.827	0.837	0.840
Rice	0.703	0.707	0.713	0.727	0.743
Wheat, cv. Alba	0.745	0.780	0.790	0.810	0.827
Wheat, cv. Jara	1.102	1.150	1.198	1.264	1.285
Wheat, cv. Almary	1.063	1.132	1.192	1.222	1.263
Oat, cv. Dragon	1.045	1.141	1.136	1.181	1.222
Oat, cv. Pegaz	0.810	0.897	0.930	0.937	0.910
Barley, cv. Aramir	0.972	0.979	0.985	0.995	0.994
Barley, cv. Ars	1.005	0.949	0.944	1.058	1.058
Barley, cv. Edgar	0.948	0.926	0.955	1.001	1.027
Barley, cv. Klimek	0.940	0.949	0.992	1.039	1.043
Barley, cv. Kos	0.819	0.809	0.855	0.895	0.959
Rye cv. Amilo	0.925	0.937	0.937	1.008	1.055
Rye cv. Dańkowskie Nowe	1.007	0.976	1.025	1.038	1.079
Rye cv. Dańkowskie Złote	0.963	0.949	0.973	1.035	1.130
Rye cv. Warko	0.910	0.920	0.925	0.979	1.077
Faba bean cv. Nadwiślański	0.730	0.800	0.780	0.940	1.050
Pea, cv. Fidelia	0.930	0.750	0.810	0.920	1.050
Lupine, cv. Emir	0.992	0.989	1.058	1.114	1.282
Vetch, cv. Szelejewska	0.710	0.706	0.935	0.871	0.996
Dry plant matter (alfalfa)	0.733	0.797	0.817	0.827	0.833
Meat-bone flour	0.883	0.960	0.980	0.993	0.993
Soybean meal	0.900	0.923	0.963	0.972	0.985
Maize 75% with rice 25%	0.780	0.823	0.843	0.843	0.857
Maize 50% with rice 50%	0.790	0.793	0.803	0.803	0.813
Maize 25% with rice 75%	0.760	0.773	0.780	0.790	0.803
Maize 75% with oat, Pegaz 25%	0.810	0.820	0.841	0.848	0.845
Maize 50% with oat, Pegaz 50%	0.815	0.842	0.885	0.893	0.892
Maize 25% with oat, Pegaz 75%	0.812	0.870	0.912	0.917	0.900
Maize 75% with wheat, Alba 25%	0.800	0.802	0.810	0.821	0.837
Maize 50% with wheat, Alba 50%	0.782	0.589	0.800	0.817	0.830
Maize 25% with wheat, Alba 75%	0.765	0.789	0.798	0.810	0.827
Maize 75% with soybean 25%	0.800	0.820	0.830	0.843	0.853
Maize 50% with soybean 50%	0.853	0.900	0.910	0.930	0.963
Maize 25% with soybean 75%	0.887	0.923	0.937	0.950	1.000
Rice 75% with soybean 25%	0.770	0.770	0.810	0.810	0.843
Rice 50% with soybean 50%	0.840	0.863	0.893	0.893	0.923
Rice 25% with soybean 75%	0.870	0.903	0.930	0.960	1.003
Maize 50%, rice 25% and soybean 25%	0.810	0.827	0.860	0.860	0.893
Maize 25%, rice 50% and soybean 25%	0.793	0.830	0.827	0.837	0.863
Maize 25%, rice 25% and soybean 50%	0.827	0.870	0.880	0.907	0.960
Maize	0.936	0.940	0.948	0.955	0.963
Barley	1.016	1.120	1.126	1.130	1.132
Pea	0.868	0.872	0.886	0.890	0.913
Soybean meal	0.810	0.816	0.820	0.828	0.829
Wheat	1.044	1.054	1.062	1.070	1.073
Rapeseed meal	0.849	0.852	0.860	0.867	0.869
Lupine	0.791	0.810	0.900	0.921	0.936
Wheat bran	0.689	0.725	0.760	0.784	0.798
Dry plant matter (alfalfa)	0.604	0.629	0.680	0.725	0.812
Meat-bone flour	0.581	0.662	0.715	0.728	0.730

Table III-48. Percentage of chemical components in selected ground feedstuffs

Material	Ash, P_s	Fibre, W_s	Protein, B_o	Fat, T_s
Maize meal	1.02	2.06	9.73	3.87
Rice	0.96	0.69	6.24	1.72
Wheat, cv. Alba	1.38	2.02	8.94	1.89
Wheat, cv. Jara	1.35	1.98	10.39	1.95
Wheat, cv. Almary	1.36	2.24	10.01	1.42
Oat, cv. Dragon	2.64	9.80	10.70	4.53
Oat, cv. Pegaz	2.26	4.46	11.74	3.44
Barley, cv. Aramir	1.45	4.47	9.80	1.89
Barley, cv. Ars	2.65	4.40	9.70	1.97
Barley, cv. Edgar	2.20	3.96	10.60	1.70
Barley, cv. Klimek	2.09	4.23	10.13	1.59
Barley, cv. Kos	2.13	3.33	8.58	1.99
Rye cv. Amilo	1.65	1.74	7.24	1.53
Rye cv. Dańkowskie Nowe	1.43	1.89	8.41	1.37
Rye cv. Dańkowskie Złote	1.54	1.47	7.61	1.23
Rye cv. Warko	1.81	1.73	8.16	1.52
Faba bean cv. Nadwiślański	3.07	8.71	23.13	1.20
Pea, cv. Fidelia	2.78	5.02	22.58	0.66
Lupine, cv. Emir	2.86	11.10	29.63	5.14
Vetch, cv. Szelejewska	2.96	4.45	26.45	0.75
Dry plant matter (alfalfa)	6.53	18.49	11.78	2.66
Meat-bone flour	32.06		27.86	12.00
Soybean meal	5.16	5.16	34.40	17.20
Maize 75% with rice 25%	1.01	1.72	8.85	3.25
Maize 50% with rice 50%	0.99	1.38	7.98	2.80
Maize 25% with rice 75%	0.98	1.03	7.10	2.25
Maize 75% with oat, Pegaz 25%	1.33	2.67	10.23	3.77
Maize 50% with oat, Pegaz 50%	1.64	3.27	10.73	3.66
Maize 25% with oat, Pegaz 75%	1.95	3.86	11.24	3.55
Maize 75% with wheat, Alba 25%	1.08	2.05	9.89	3.38
Maize 50% with wheat, Alba 50%	1.24	2.02	10.06	2.88
Maize 25% with wheat, Alba 75%	1.35	2.00	10.23	2.39
Maize 75% with soybean 25%	2.06	2.84	15.89	7.20
Maize 50% with soybean 50%	3.09	3.61	22.06	10.54
Maize 25% with soybean 75%	4.13	4.39	28.23	16.30
Rice 75% with soybean 25%	2.01	1.81	13.28	5.59
Rice 50% with soybean 50%	3.06	2.92	20.31	9.46
Rice 25% with soybean 75%	4.09	4.04	27.36	13.33
Maize 50%, rice 25% and soybean 25%	2.04	2.49	15.02	6.67
Maize 25%, rice 50% and soybean 25%	2.03	2.15	14.15	6.12
Maize 25%, rice 25% and soybean 50%	3.08	3.78	21.19	9.99
Maize	1.02	1.98	8.91	4.05
Barley	2.02	4.17	9.40	1.73
Pea	2.47	5.12	22.54	0.98
Soybean meal	5.08	5.06	43.71	1.51
Wheat	1.37	2.19	9.95	1.79
Rapeseed meal	6.39	13.03	35.22	0.70
Lupine	2.86	11.05	29.21	4.53
Wheat bran	4.25	5.53	12.85	3.23
Dry plant matter (alfalfa)	6.57	18.60	11.85	2.68
Meat-bone flour	29.75		26.77	8.90

Table III-49. Mean material densities at B point, ρ_b (g cm^{-3}), at different moisture levels; ZD40 press, F_c = 100 kN

Material	Moisture content (%)				
	10	12	14	16	18
Maize meal	1.490	1.493	1.493	1.463	1.453
Rice	1.510	1.510	1.500	1.490	1.490
Wheat, cv. Alba	1.527	1.530	1.510	1.500	1.480
Wheat, cv. Jara	1.540	1.537	1.530	1.527	1.507
Wheat, cv. Almary	1.515	1.536	1.521	1.516	1.493
Oat, cv. Dragon	1.465	1.480	1.456	1.461	1.447
Oat, cv. Pegaz	1.450	1.440	1.430	1.430	1.420
Barley, cv. Aramir	1.510	1.510	1.500	1.490	1.483
Barley, cv. Ars	1.516	1.518	1.511	1.499	1.505
Barley, cv. Edgar	1.516	1.509	1.498	1.497	1.481
Barley, cv. Klimek	1.530	1.539	1.514	1.508	1.500
Barley, cv. Kos	1.519	1.523	1.511	1.495	1.495
Rye cv. Amilo	1.512	1.552	1.508	1.501	1.479
Rye cv. Dańkowskie Nowe	1.496	1.523	1.509	1.504	1.477
Rye cv. Dańkowskie Złote	1.498	1.514	1.535	1.533	1.502
Rye cv. Warko	1.514	1.526	1.506	1.502	1.484
Faba bean cv. Nadwiślański	1.513	1.497	1.497	1.491	1.478
Pea, cv. Fidelia	1.478	1.518	1.521	1.515	1.512
Lupine, cv. Emir	1.480	1.469	1.458	1.427	1.395
Vetch, cv. Szelejewska	1.481	1.476	1.467	1.467	1.464
Dry plant matter (alfalfa)	1.520	1.533	1.533	1.543	1.507
Meat-bone flour	1.657	1.640	1.537	1.527	1.520
Soybean meal	1.343	1.267	1.243		
Maize 75% with rice 25%	1.500	1.497	1.490	1.483	1.453
Maize 50% with rice 50%	1.520	1.500	1.470	1.480	1.453
Maize 25% with rice 75%	1.500	1.500	1.500	1.497	1.480
Maize 75% with oat, Pegaz 25%	1.490	1.487	1.473	1.460	1.453
Maize 50% with oat, Pegaz 50%	1.480	1.483	1.473	1.460	1.437
Maize 25% with oat, Pegaz 75%	1.483	1.483	1.473	1.453	1.440
Maize 75% with wheat, Alba 25%	1.520	1.510	1.503	1.490	1.480
Maize 50% with wheat, Alba 50%	1.517	1.513	1.506	1.497	1.477
Maize 25% with wheat, Alba 75%	1.530	1.513	1.513	1.483	1.473
Maize 75% with soybean 25%	1.453	1.447	1.453	1.450	1.453
Maize 50% with soybean 50%	1.410	1.433	1.383	1.383	1.337
Maize 25% with soybean 75%	1.393	1.353	1.340	1.273	1.283
Rice 75% with soybean 25%	1.457	1.463	1.467	1.443	1.417
Rice 50% with soybean 50%	1.433	1.417	1.417	1.417	1.387
Rice 25% with soybean 75%	1.400	1.383	1.370	1.373	1.370
Maize 50%, rice 25% and soybean 25%	1.507	1.487	1.493	1.483	1.483
Maize 25%, rice 50% and soybean 25%	1.550	1.530	1.500	1.497	1.487
Maize 25%, rice 25% and soybean 50%	1.463	1.453	1.440	1.440	1.417

Table III-50. Mean material densities at C point, ρ_c (g cm^{-3}), at different moisture levels; ZD40 press, F_c = 100 kN

Material	Moisture content (%)				
	10	12	14	16	18
Maize meal	1.523	1.527	1.540	1.520	1.510
Rice	1.530	1.530	1.530	1.530	1.520
Wheat, cv. Alba	1.570	1.560	1.550	1.540	1.530
Wheat, cv. Jara	1.570	1.570	1.570	1.570	1.570
Wheat, cv. Almary	1.572	1.586	1.575	1.573	1.559
Oat, cv. Dragon	1.534	1.552	1.525	1.549	1.539
Oat, cv. Pegaz	1.510	1.500	1.490	1.490	1.480
Barley, cv. Aramir	1.540	1.530	1.530	1.520	1.520
Barley, cv. Ars	1.560	1.558	1.552	1.540	1.546
Barley, cv. Edgar	1.562	1.554	1.540	1.544	1.531
Barley, cv. Klimek	1.581	1.589	1.563	1.555	1.552
Barley, cv. Kos	1.570	1.570	1.554	1.540	1.543
Rye cv. Amilo	1.564	1.600	1.555	1.551	1.534
Rye cv. Dańkowskie Nowe	1.551	1.572	1.558	1.551	1.532
Rye cv. Dańkowskie Złote	1.566	1.565	1.585	1.585	1.561
Rye cv. Warko	1.577	1.574	1.553	1.551	1.540
Faba bean cv. Nadwiślański	1.570	1.554	1.557	1.552	1.543
Pea, cv. Fidelia	1.538	1.566	1.574	1.569	1.572
Lupine, cv. Emir	1.529	1.529	1.546	1.538	1.532
Vetch, cv. Szelejewska	1.550	1.548	1.534	1.531	1.537
Dry plant matter (alfalfa)	1.600	1.597	1.600	1.623	1.580
Meat-bone flour	1.833	1.803	1.760	1.700	1.690
Soybean meal	1.457	1.400	1.387		
Maize 75% with rice 25%	1.540	1.540	1.540	1.533	1.527
Maize 50% with rice 50%	1.540	1.513	1.510	1.507	1.497
Maize 25% with rice 75%	1.540	1.540	1.540	1.537	1.527
Maize 75% with oat, Pegaz 25%	1.517	1.517	1.510	1.510	1.510
Maize 50% with oat, Pegaz 50%	1.493	1.507	1.520	1.500	1.500
Maize 25% with oat, Pegaz 75%	1.493	1.507	1.507	1.507	1.480
Maize 75% with wheat, Alba 25%	1.543	1.540	1.530	1.507	1.503
Maize 50% with wheat, Alba 50%	1.540	1.540	1.533	1.520	1.503
Maize 25% with wheat, Alba 75%	1.540	1.540	1.533	1.513	1.507
Maize 75% with soybean 25%	1.510	1.513	1.517	1.510	1.530
Maize 50% with soybean 50%	1.497	1.517	1.497	1.503	1.480
Maize 25% with soybean 75%	1.490	1.503	1.503	1.500	1.463
Rice 75% with soybean 25%	1.507	1.513	1.527	1.517	1.507
Rice 50% with soybean 50%	1.507	1.500	1.510	1.520	1.510
Rice 25% with soybean 75%	1.483	1.503	1.497	1.517	1.503
Maize 50%, rice 25% and soybean 25%	1.557	1.547	1.540	1.540	1.533
Maize 25%, rice 50% and soybean 25%	1.590	1.580	1.560	1.560	1.553
Maize 25%, rice 25% and soybean 50%	1.520	1.520	1.503	1.503	1.503

Table III-51. Mean agglomerate densities, ρ_k (g cm^{-3}), at different moisture levels; ZD40 press, $F_c = 100$ kN

Material	Moisture content				
	10%	12%	14%	16%	18%
Maize meal	1.193	1.247	1.240	1.220	1.170
Rice	1.260	1.277	1.287	1.263	1.213
Wheat, cv. Alba	1.190	1.217	1.250	1.260	1.240
Wheat, cv. Jara	1.250	1.267	1.283	1.270	1.247
Wheat, cv. Almary	1.212	1.278	1.312	1.312	1.274
Oat, cv. Dragon	1.136	1.142	1.183	1.184	1.171
Oat, cv. Pegaz	1.073	1.120	1.070	0.990	0.980
Barley, cv. Aramir	1.187	1.227	1.230	1.230	1.210
Barley, cv. Ars	1.195	1.173	1.185	1.195	1.233
Barley, cv. Edgar	1.184	1.207	1.229	1.222	1.202
Barley, cv. Klimek	1.160	1.198	1.222	1.227	1.211
Barley, cv. Kos	1.150	1.178	1.217	1.222	1.224
Rye cv. Amilo	1.265	1.286	1.288	1.273	1.251
Rye cv. Dańkowskie Nowe	1.246	1.272	1.293	1.265	1.259
Rye cv. Dańkowskie Złote	1.265	1.296	1.280	1.287	1.261
Rye cv. Warko	1.222	1.258	1.282	1.273	1.261
Faba bean cv. Nadwiślański	1.338	1.338	1.322	1.323	1.274
Pea, cv. Fidelia	1.289	1.305	1.319	1.343	1.319
Lupine, cv. Emir	1.168	1.170	1.192	1.202	1.211
Vetch, cv. Szelejewska	1.281	1.331	1.319	1.332	1.340
Dry plant matter (alfalfa)	1.073	1.053	1.020	1.010	0.903
Meat-bone flour	1.467	1.477	1.507	1.507	1.513
Soybean meal	1.120	1.100	1.103		
Maize 75% with rice 25%	1.163	1.223	1.227	1.247	1.160
Maize 50% with rice 50%	1.237	1.250	1.237	1.230	1.213
Maize 25% with rice 75%	1.257	1.260	1.270	1.260	1.160
Maize 75% with oat, Pegaz 25%	1.163	1.207	1.213	1.183	1.120
Maize 50% with oat, Pegaz 50%	1.130	1.153	1.170	1.150	1.083
Maize 25% with oat, Pegaz 75%	1.117	1.147	1.153	1.130	1.060
Maize 75% with wheat, Alba 25%	1.203	1.230	1.227	1.227	1.190
Maize 50% with wheat, Alba 50%	1.207	1.230	1.243	1.213	1.193
Maize 25% with wheat, Alba 75%	1.227	1.240	1.250	1.227	1.167
Maize 75% with soybean 25%	1.200	1.203	1.220	1.193	1.177
Maize 50% with soybean 50%	1.163	1.157	1.143	1.150	1.147
Maize 25% with soybean 75%	1.130	1.130	1.140	1.123	1.103
Rice 75% with soybean 25%	1.260	1.267	1.260	1.263	1.233
Rice 50% with soybean 50%	1.217	1.217	1.223	1.220	1.220
Rice 25% with soybean 75%	1.193	1.157	1.157	1.147	1.150
Maize 50%, rice 25% and soybean 25%	1.230	1.233	1.233	1.217	1.190
Maize 25%, rice 50% and soybean 25%	1.240	1.240	1.230	1.227	1.217
Maize 25%, rice 25% and soybean 50%	1.203	1.210	1.213	1.193	1.170

Table III-52. Mean agglomerate densities after 24 hours, ρ_{k1} (g cm^{-3}), at different moisture levels; ZD40 press, F_c = 100 kN

Material	Moisture content				
	10%	12%	14%	16%	18%
Maize meal	1.117	1.140	1.127	1.077	0.980
Rice	1.203	1.207	1.210	1.173	1.113
Wheat, cv. Alba	1.107	1.150	1.177	1.170	1.123
Wheat, cv. Jara	1.157	1.207	1.207	1.177	1.113
Wheat, cv. Almary	1.233	1.232	1.244	1.214	1.191
Oat, cv. Dragon	1.049	1.057	1.077	1.051	1.033
Oat, cv. Pegaz	0.957	0.983	0.943	0.827	0.790
Barley, cv. Aramir	1.140	1.150	1.163	1.143	1.087
Barley, cv. Ars	1.134	1.148	1.137	1.150	1.098
Barley, cv. Edgar	1.105	1.168	1.167	1.136	1.053
Barley, cv. Klimek	1.109	1.096	1.143	1.123	1.075
Barley, cv. Kos	1.140	1.149	1.159	1.156	1.069
Rye cv. Amilo	1.204	1.236	1.228	1.168	1.118
Rye cv. Dańkowskie Nowe	1.180	1.209	1.223	1.182	1.129
Rye cv. Dańkowskie Złote	1.211	1.234	1.236	1.223	1.129
Rye cv. Warko	1.162	1.205	1.216	1.184	1.120
Faba bean cv. Nadwiślański	1.261	1.252	1.259	1.277	1.237
Pea, cv. Fidelia	1.236	1.245	1.243	1.286	1.260
Lupine, cv. Emir	1.048	1.105	1.102	1.052	1.020
Vetch, cv. Szelejewska	1.244	1.254	1.245	1.256	1.273
Dry plant matter (alfalfa)	0.953	0.910	0.833	0.820	0.707
Meat-bone flour	1.400	1.413	1.483	1.487	1.487
Soybean meal	0.963	0.940	0.913		
Maize 75% with rice 25%	1.077	1.103	1.167	1.127	0.967
Maize 50% with rice 50%	1.163	1.177	1.163	1.130	1.060
Maize 25% with rice 75%	1.180	1.183	1.193	1.160	1.057
Maize 75% with oat, Pegaz 25%	1.040	1.057	1.050	0.997	0.907
Maize 50% with oat, Pegaz 50%	0.980	1.003	1.010	0.963	0.880
Maize 25% with oat, Pegaz 75%	0.960	1.000	0.997	0.953	0.887
Maize 75% with wheat, Alba 25%	1.070	1.103	1.103	1.073	0.983
Maize 50% with wheat, Alba 50%	1.107	1.123	1.113	1.087	0.990
Maize 25% with wheat, Alba 75%	1.147	1.153	1.140	1.093	0.983
Maize 75% with soybean 25%	1.050	1.053	1.080	1.053	1.040
Maize 50% with soybean 50%	1.047	1.040	1.047	1.017	1.017
Maize 25% with soybean 75%	1.040	1.027	0.970	0.973	0.963
Rice 75% with soybean 25%	1.203	1.183	1.173	1.167	1.143
Rice 50% with soybean 50%	1.150	1.127	1.133	1.123	1.090
Rice 25% with soybean 75%	1.030	1.027	1.010	1.010	1.007
Maize 50%, rice 25% and soybean 25%	1.127	1.130	1.113	1.100	1.077
Maize 25%, rice 50% and soybean 25%	1.180	1.147	1.133	1.123	1.090
Maize 25%, rice 25% and soybean 50%	1.093	1.100	1.090	1.070	1.073

Table III-53. Mean pressures at B point, P_b (MPa), at different moisture levels; ZD40 press, F_c = 100 kN

Material	Moisture content (%)				
	10	12	14	16	18
Maize meal	118	107	94	79	57
Rice	121	119	116	110	86
Wheat, cv. Alba	113	105	92	84	66
Wheat, cv. Jara	126	115	106	94	75
Wheat, cv. Almary	144	124	110	96	82
Oat, cv. Dragon	103	100	93	78	63
Oat, cv. Pegaz	98	90	70	45	39
Barley, cv. Aramir	135	125	103	96	77
Barley, cv. Ars	145	141	135	128	120
Barley, cv. Edgar	131	120	118	106	97
Barley, cv. Klimek	138	126	116	112	98
Barley, cv. Kos	136	128	123	113	104
Rye cv. Amilo	132	127	109	102	89
Rye cv. Dańkowskie Nowe	138	128	115	109	93
Rye cv. Dańkowskie Złote	122	116	109	105	88
Rye cv. Warko	131	127	108	104	86
Faba bean cv. Nadwiślański	134	117	107	89	69
Pea, cv. Fidelia	145	134	112	103	93
Lupine, cv. Emir	116	90	69	40	28
Vetch, cv. Szelejewska	127	108	100	85	64
Dry plant matter (alfalfa)	124	116	110	105	90
Meat-bone flour	34	24	15	10	9
Soybean meal	30	20	9		
Maize 75% with rice 25%	119	107	103	83	59
Maize 50% with rice 50%	121	109	104	92	66
Maize 25% with rice 75%	116	113	109	103	80
Maize 75% with oat, Pegaz 25%	115	101	90	65	55
Maize 50% with oat, Pegaz 50%	113	102	84	62	52
Maize 25% with oat, Pegaz 75%	109	100	79	57	49
Maize 75% with wheat, Alba 25%	114	106	93	81	64
Maize 50% with wheat, Alba 50%	116	106	91	82	64
Maize 25% with wheat, Alba 75%	116	106	92	84	66
Maize 75% with soybean 25%	97	71	69	58	49
Maize 50% with soybean 50%	72	48	33	30	21
Maize 25% with soybean 75%	44	21	17	13	9
Rice 75% with soybean 25%	104	98	72	62	54
Rice 50% with soybean 50%	78	70	36	31	25
Rice 25% with soybean 75%	46	34	20	15	10
Maize 50%, rice 25% and soybean 25%	112	102	87	72	55
Maize 25%, rice 50% and soybean 25%	115	105	94	74	57
Maize 25%, rice 25% and soybean 50%	75	73	58	53	44

Table III-54. Mean specific compression energies corresponding to B point, L_b' (J g^{-1}), at different moisture levels; ZD40 press, $F_c = 100$ kN

Material	Moisture content (%)				
	10	12	14	16	18
Maize meal	10.93	9.21	7.86	5.97	3.55
Rice	12.17	10.47	10.02	8.80	6.45
Wheat, cv. Alba	9.93	8.97	7.44	5.84	5.12
Wheat, cv. Jara	11.37	9.65	7.89	6.51	5.63
Wheat, cv. Almary	10.98	8.72	7.75	6.30	5.47
Oat, cv. Dragon	7.63	7.20	6.27	4.77	3.93
Oat, cv. Pegaz	7.81	6.38	4.27	2.05	1.61
Barley, cv. Aramir	10.50	9.17	7.81	6.29	5.19
Barley, cv. Ars	12.15	11.53	10.63	9.47	8.88
Barley, cv. Edgar	9.18	8.22	7.83	7.13	6.87
Barley, cv. Klimek	10.53	9.17	8.02	7.58	6.53
Barley, cv. Kos	9.78	8.92	8.40	7.62	7.10
Rye cv. Amilo	8.88	7.75	6.55	5.98	5.27
Rye cv. Dańkowskie Nowe	11.63	9.40	7.85	6.75	5.60
Rye cv. Dańkowskie Złote	8.77	7.75	7.05	6.35	5.37
Rye cv. Warko	9.77	8.82	6.98	6.57	5.20
Faba bean cv. Nadwiślański	10.38	8.47	7.47	5.73	5.03
Pea, cv. Fidelia	12.98	10.82	7.22	6.15	5.22
Lupine, cv. Emir	11.22	7.77	4.60	2.50	1.50
Vetch, cv. Szelejewska	11.18	9.40	7.97	6.57	4.75
Dry plant matter (alfalfa)	11.23	8.69	7.65	6.80	5.28
Meat-bone flour	1.84	1.09	0.94	0.69	0.62
Soybean meal	3.41	1.17	0.45		
Maize 75% with rice 25%	11.13	9.53	8.11	6.19	4.08
Maize 50% with rice 50%	11.60	9.69	8.58	6.55	4.43
Maize 25% with rice 75%	12.03	10.42	9.31	8.11	5.71
Maize 75% with oat, Pegaz 25%	9.43	8.00	6.04	4.71	3.37
Maize 50% with oat, Pegaz 50%	8.77	7.44	5.32	4.21	3.14
Maize 25% with oat, Pegaz 75%	8.59	7.07	5.16	4.11	2.97
Maize 75% with wheat, Alba 25%	10.63	9.05	7.77	6.02	4.35
Maize 50% with wheat, Alba 50%	10.40	8.95	7.68	6.04	4.51
Maize 25% with wheat, Alba 75%	10.26	8.87	7.67	6.07	4.89
Maize 75% with soybean 25%	8.56	5.57	5.12	3.79	3.04
Maize 50% with soybean 50%	6.48	3.68	2.53	1.80	1.53
Maize 25% with soybean 75%	4.80	1.68	1.07	0.72	0.48
Rice 75% with soybean 25%	10.27	9.25	6.16	4.77	3.88
Rice 50% with soybean 50%	7.12	3.95	2.63	2.21	1.91
Rice 25% with soybean 75%	5.40	2.29	0.99	0.74	0.56
Maize 50%, rice 25% and soybean 25%	12.30	9.29	7.89	6.02	3.42
Maize 25%, rice 50% and soybean 25%	12.48	9.89	8.09	6.05	3.71
Maize 25%, rice 25% and soybean 50%	8.16	7.60	5.89	4.48	3.23

Table III-55. Mean specific compaction energies, L_s' (J g^{-1}), (from B to C point), at different moisture levels; ZD40 press, F_c = 100 kN

Material	Moisture content (%)				
	10	12	14	16	18
Maize meal	2.70	2.77	3.37	3.93	3.97
Rice	4.03	5.00	4.23	3.37	3.27
Wheat, cv. Alba	2.97	2.43	1.67	2.67	3.10
Wheat, cv. Jara	2.20	2.10	2.20	2.83	3.00
Wheat, cv. Almary	4.07	3.30	3.38	3.53	3.87
Oat, cv. Dragon	4.62	4.63	4.63	5.03	5.47
Oat, cv. Pegaz	3.57	3.77	4.70	5.23	5.33
Barley, cv. Aramir	2.93	2.47	2.87	2.70	3.37
Barley, cv. Ars	3.08	2.92	2.90	2.90	2.87
Barley, cv. Edgar	3.13	3.10	2.85	3.20	3.17
Barley, cv. Klimek	3.55	3.30	3.33	3.13	3.35
Barley, cv. Kos	3.55	3.13	2.92	3.00	3.13
Rye cv. Amilo	3.62	3.17	3.13	3.28	3.47
Rye cv. Dańkowskie Nowe	3.95	3.23	3.22	3.10	3.53
Rye cv. Dańkowskie Złote	4.53	3.32	3.20	3.22	3.60
Rye cv. Warko	4.10	3.23	3.08	3.15	3.48
Faba bean cv. Nadwiślański	3.98	3.83	3.90	3.68	3.93
Pea, cv. Fidelia	4.58	3.32	3.32	3.40	3.63
Lupine, cv. Emir	3.37	3.98	5.53	6.22	7.27
Vetch, cv. Szelejewska	4.90	4.77	4.20	3.88	4.15
Dry plant matter (alfalfa)	3.00	2.70	2.17	2.57	1.70
Meat-bone flour	5.23	5.57	5.70	5.80	4.80
Soybean meal	5.32	5.72	5.85		
Maize 75% with rice 25%	2.77	3.13	3.63	3.80	4.00
Maize 50% with rice 50%	2.53	3.07	3.37	3.73	4.13
Maize 25% with rice 75%	2.80	2.70	3.03	2.67	3.43
Maize 75% with oat, Pegaz 25%	2.97	3.00	3.73	4.20	3.93
Maize 50% with oat, Pegaz 50%	3.03	3.20	4.23	4.63	4.03
Maize 25% with oat, Pegaz 75%	2.77	3.20	4.13	4.40	4.20
Maize 75% with wheat, Alba 25%	2.83	2.53	2.73	2.70	3.47
Maize 50% with wheat, Alba 50%	2.83	2.63	2.47	2.60	3.23
Maize 25% with wheat, Alba 75%	2.77	2.57	2.10	2.43	2.87
Maize 75% with soybean 25%	3.41	3.87	3.87	4.11	4.32
Maize 50% with soybean 50%	5.01	5.52	6.36	5.72	5.75
Maize 25% with soybean 75%	5.49	5.52	5.85	6.08	6.14
Rice 75% with soybean 25%	3.65	3.73	3.80	4.00	4.23
Rice 50% with soybean 50%	4.29	5.01	5.32	5.71	5.00
Rice 25% with soybean 75%	6.00	6.99	8.03	7.26	6.09
Maize 50%, rice 25% and soybean 25%	2.46	2.73	3.49	3.52	3.80
Maize 25%, rice 50% and soybean 25%	2.30	3.03	3.43	3.58	3.69
Maize 25%, rice 25% and soybean 50%	3.87	4.35	5.27	5.10	3.87

Table III-56. Mean total specific compression energies, L_c' (J g^{-1}), (corresponding to the C point of compression characteristic) at different moisture levels; ZD40 press, F_c = 100 kN

Material	Moisture content (%)				
	10	12	14	16	18
Maize meal	13.60	12.00	11.20	9.92	7.55
Rice	16.17	15.43	14.27	12.17	9.72
Wheat, cv. Alba	12.87	11.37	9.09	8.48	8.20
Wheat, cv. Jara	13.57	11.80	10.12	9.33	8.64
Wheat, cv. Almary	15.05	12.02	11.13	9.83	9.33
Oat, cv. Dragon	12.25	11.83	10.90	9.80	9.40
Oat, cv. Pegaz	11.33	10.13	8.93	7.28	6.94
Barley, cv. Aramir	13.43	11.67	10.67	8.97	8.59
Barley, cv. Ars	15.23	14.45	13.53	12.37	11.75
Barley, cv. Edgar	12.32	11.32	10.68	10.33	10.03
Barley, cv. Klimek	14.08	12.47	11.35	10.72	9.88
Barley, cv. Kos	13.33	12.05	11.32	10.62	10.23
Rye cv. Amilo	12.50	10.92	9.68	9.27	8.73
Rye cv. Dańkowskie Nowe	15.58	12.63	11.07	9.85	9.13
Rye cv. Dańkowskie Złote	13.30	11.07	10.25	9.57	8.97
Rye cv. Warko	13.87	12.05	10.07	9.72	8.68
Faba bean cv. Nadwiślański	14.37	12.30	11.37	9.42	8.97
Pea, cv. Fidelia	17.57	14.13	10.53	9.55	8.85
Lupine, cv. Emir	14.58	11.75	10.13	8.72	8.77
Vetch, cv. Szelejewska	16.08	14.17	12.17	10.45	8.90
Dry plant matter (alfalfa)	14.23	11.37	9.80	9.39	6.95
Meat-bone flour	7.08	6.64	6.62	6.49	5.41
Soybean meal	8.73	6.89	6.30		
Maize 75% with rice 25%	13.90	12.67	11.73	10.00	8.09
Maize 50% with rice 50%	14.13	12.80	11.93	10.27	8.57
Maize 25% with rice 75%	14.80	13.07	12.37	10.80	9.17
Maize 75% with oat, Pegaz 25%	12.40	11.00	9.75	8.92	7.29
Maize 50% with oat, Pegaz 50%	11.80	10.67	9.53	8.87	7.13
Maize 25% with oat, Pegaz 75%	11.37	10.27	9.28	8.50	7.14
Maize 75% with wheat, Alba 25%	13.43	11.83	10.50	8.72	7.81
Maize 50% with wheat, Alba 50%	13.23	11.57	10.15	8.64	7.75
Maize 25% with wheat, Alba 75%	13.00	11.43	9.79	8.50	7.75
Maize 75% with soybean 25%	11.97	9.44	8.99	7.89	7.36
Maize 50% with soybean 50%	11.49	9.20	8.89	7.52	6.95
Maize 25% with soybean 75%	10.29	7.20	6.92	6.80	6.62
Rice 75% with soybean 25%	13.92	12.99	9.96	8.80	8.11
Rice 50% with soybean 50%	11.41	8.95	7.95	7.92	6.91
Rice 25% with soybean 75%	11.40	9.28	9.01	8.00	6.65
Maize 50%, rice 25% and soybean 25%	14.76	12.02	11.39	9.54	7.22
Maize 25%, rice 50% and soybean 25%	14.78	12.92	11.52	9.16	7.40
Maize 25%, rice 25% and soybean 50%	12.03	11.95	11.52	9.58	7.10

Table III-57. Mean agglomerate compressive strength, σ_n (MPa), at different moisture levels; ZD40 press, F_c = 100 kN

Material	Moisture content (%)				
	10	12	14	16	18
Maize meal	0.30	1.49	1.84	1.22	0.21
Rice	0.31	0.44	0.52	0.49	0.30
Wheat, cv. Alba	0.84	1.62	2.26	2.45	1.73
Wheat, cv. Jara	0.26	0.62	0.77	0.84	0.54
Wheat, cv. Almary	0.30	0.85	1.56	1.57	1.57
Oat, cv. Dragon	6.35	6.13	6.28	5.92	4.86
Oat, cv. Pegaz	11.14	11.69	11.30	6.83	2.86
Barley, cv. Aramir	1.45	2.25	2.78	2.72	2.08
Barley, cv. Ars	2.44	2.26	3.80	4.15	3.18
Barley, cv. Edgar	0.43	1.42	2.34	2.33	1.37
Barley, cv. Klimek	0.63	1.49	2.81	3.21	2.73
Barley, cv. Kos	0.36	1.09	2.25	2.72	2.43
Rye cv. Amilo	0.22	0.82	1.11	1.07	0.77
Rye cv. Dańkowskie Nowe	0.38	0.65	1.13	0.91	0.68
Rye cv. Dańkowskie Złote	0.34	1.10	1.39	1.85	0.88
Rye cv. Warko	0.35	0.73	1.50	1.53	1.14
Faba bean cv. Nadwiślański	0.97	1.77	2.67	3.98	3.30
Pea, cv. Fidelia	1.26	1.71	3.63	5.84	5.06
Lupine, cv. Emir	0.29	0.42	0.78	1.05	0.85
Vetch, cv. Szelejewska	1.48	2.03	3.62	5.06	4.25
Dry plant matter (alfalfa)					
Meat-bone flour	2.43	1.86	0.66	0.47	0.31
Soybean meal					
Maize 75% with rice 25%	0.54	0.64	1.16	0.69	0.13
Maize 50% with rice 50%	0.27	0.44	0.65	0.63	0.27
Maize 25% with rice 75%	0.21	0.31	0.48	0.43	0.14
Maize 75% with oat, Pegaz 25%	1.63	3.37	2.93	1.95	0.46
Maize 50% with oat, Pegaz 50%	4.67	6.42	5.60	4.67	1.84
Maize 25% with oat, Pegaz 75%	8.14	8.52	7.77	7.18	6.11
Maize 75% with wheat, Alba 25%	0.82	1.63	2.14	1.72	0.56
Maize 50% with wheat, Alba 50%	1.02	1.80	2.07	1.64	0.62
Maize 25% with wheat, Alba 75%	1.24	1.88	1.95	1.56	0.68
Maize 75% with soybean 25%	0.63	1.20	1.74	1.74	0.79
Maize 50% with soybean 50%	0.95	0.96	1.15	1.05	0.99
Maize 25% with soybean 75%	0.70	0.76	0.82	1.15	0.97
Rice 75% with soybean 25%	0.80	0.86	0.94	1.20	1.04
Rice 50% with soybean 50%	0.83	0.85	1.04	1.01	0.87
Rice 25% with soybean 75%	0.28	0.41	0.49	0.44	0.41
Maize 50%, rice 25% and soybean 25%	2.26	2.61	2.77	1.98	1.17
Maize 25%, rice 50% and soybean 25%	2.57	3.21	2.43	1.62	0.90
Maize 25%, rice 25% and soybean 50%	2.74	2.80	2.50	1.52	0.94

Table III-58. Mean values of the material compression ability coefficient, k_1 (MPa^{-1}), at different moisture levels; ZD40 press, $F_c = 100$ kN

Material	Moisture content (%)				
	10	12	14	16	18
Maize meal	0.022	0.023	0.026	0.031	0.043
Rice	0.016	0.016	0.016	0.018	0.023
Wheat, cv. Alba	0.025	0.028	0.032	0.034	0.042
Wheat, cv. Jara	0.018	0.019	0.022	0.024	0.031
Wheat, cv. Almary	0.017	0.018	0.021	0.024	0.029
Oat, cv. Dragon	0.041	0.041	0.044	0.053	0.067
Oat, cv. Pegaz	0.045	0.046	0.062	0.094	0.111
Barley, cv. Aramir	0.020	0.022	0.027	0.029	0.037
Barley, cv. Ars	0.020	0.021	0.022	0.023	0.025
Barley, cv. Edgar	0.022	0.023	0.024	0.027	0.030
Barley, cv. Klimek	0.021	0.023	0.024	0.026	0.030
Barley, cv. Kos	0.020	0.021	0.022	0.025	0.027
Rye cv. Amilo	0.018	0.019	0.022	0.024	0.028
Rye cv. Dańkowskie Nowe	0.016	0.017	0.020	0.022	0.025
Rye cv. Dańkowskie Złote	0.018	0.019	0.022	0.023	0.027
Rye cv. Warko	0.019	0.020	0.023	0.025	0.030
Faba bean cv. Nadwiślański	0.014	0.016	0.018	0.023	0.031
Pea, cv. Fidelia	0.013	0.015	0.018	0.021	0.024
Lupine, cv. Emir	0.022	0.028	0.037	0.064	0.094
Vetch, cv. Szelejewska	0.015	0.017	0.020	0.024	0.035
Dry plant matter (alfalfa)	0.065	0.071	0.075	0.084	0.097
Meat-bone flour	0.082	0.105	0.168	0.262	0.289
Soybean meal	0.081	0.109	0.233		
Maize 75% with rice 25%	0.020	0.022	0.023	0.028	0.041
Maize 50% with rice 50%	0.019	0.020	0.021	0.024	0.034
Maize 25% with rice 75%	0.018	0.018	0.019	0.020	0.026
Maize 75% with oat, Pegaz 25%	0.024	0.027	0.031	0.042	0.049
Maize 50% with oat, Pegaz 50%	0.026	0.028	0.035	0.048	0.056
Maize 25% with oat, Pegaz 75%	0.034	0.035	0.045	0.062	0.073
Maize 75% with wheat, Alba 25%	0.024	0.025	0.029	0.034	0.043
Maize 50% with wheat, Alba 50%	0.023	0.025	0.030	0.033	0.043
Maize 25% with wheat, Alba 75%	0.023	0.026	0.030	0.033	0.041
Maize 75% with soybean 25%	0.026	0.034	0.036	0.042	0.052
Maize 50% with soybean 50%	0.035	0.051	0.072	0.093	0.111
Maize 25% with soybean 75%	0.059	0.113	0.133	0.169	0.248
Rice 75% with soybean 25%	0.020	0.021	0.029	0.035	0.041
Rice 50% with soybean 50%	0.029	0.031	0.059	0.071	0.094
Rice 25% with soybean 75%	0.053	0.066	0.115	0.154	0.245
Maize 50%, rice 25% and soybean 25%	0.022	0.023	0.027	0.034	0.045
Maize 25%, rice 50% and soybean 25%	0.021	0.022	0.025	0.031	0.041
Maize 25%, rice 25% and soybean 50%	0.033	0.033	0.041	0.045	0.055

Table III-59. Mean values of k_2 coefficient, (J g^{-1}/g cm^{-3}), at different moisture levels; ZD40 press, F_c = 100 kN

Material	Moisture content (%)				
	10	12	14	16	18
Maize meal	12.05	10.35	8.82	6.92	4.09
Rice	16.24	14.47	14.02	12.48	8.76
Wheat, cv. Alba	10.05	8.86	7.44	5.98	5.40
Wheat, cv. Jara	13.33	11.37	9.17	7.56	6.49
Wheat, cv. Almary	12.51	10.21	9.04	7.28	6.33
Oat, cv. Dragon	6.80	6.44	5.71	4.29	3.57
Oat, cv. Pegaz	6.96	5.85	3.90	1.86	1.46
Barley, cv. Aramir	11.05	9.54	8.10	6.53	5.33
Barley, cv. Ars	12.13	11.42	10.50	9.64	8.89
Barley, cv. Edgar	9.34	8.51	8.02	7.30	7.12
Barley, cv. Klimek	10.49	9.18	8.20	7.59	6.59
Barley, cv. Kos	10.25	9.41	8.76	7.97	7.40
Rye cv. Amilo	10.15	8.47	7.57	6.85	6.00
Rye cv. Dańkowskie Nowe	14.03	11.16	9.10	7.81	6.67
Rye cv. Dańkowskie Złote	10.55	9.30	7.93	7.11	6.20
Rye cv. Warko	10.94	9.54	7.72	7.08	5.66
Faba bean cv. Nadwiślański	14.50	11.91	10.22	7.51	6.43
Pea, cv. Fidelia	17.84	14.51	9.53	7.52	6.22
Lupine, cv. Emir	12.55	8.75	5.19	2.89	1.74
Vetch, cv. Szelejewska	15.55	13.56	10.78	8.73	5.91
Dry plant matter (alfalfa)	8.46	6.46	5.67	4.97	3.96
Meat-bone flour	1.74	1.11	1.03	0.74	0.66
Soybean meal	4.31	1.69	0.69		
Maize 75% with rice 25%	12.73	11.06	9.46	7.26	4.81
Maize 50% with rice 50%	13.74	11.88	10.86	8.26	5.54
Maize 25% with rice 75%	15.47	13.55	12.05	10.51	7.38
Maize 75% with oat, Pegaz 25%	10.01	8.63	6.56	5.17	3.72
Maize 50% with oat, Pegaz 50%	8.92	7.64	5.50	4.39	3.33
Maize 25% with oat, Pegaz 75%	7.98	6.65	4.89	3.94	2.86
Maize 75% with wheat, Alba 25%	11.11	9.69	8.30	6.41	4.64
Maize 50% with wheat, Alba 50%	10.90	9.41	8.09	6.39	4.81
Maize 25% with wheat, Alba 75%	10.74	9.43	8.12	6.53	5.34
Maize 75% with soybean 25%	9.80	6.66	5.93	4.40	3.48
Maize 50% with soybean 50%	7.62	4.36	3.15	2.24	2.01
Maize 25% with soybean 75%	5.63	2.17	1.41	1.04	0.67
Rice 75% with soybean 25%	13.39	12.12	8.04	6.25	4.99
Rice 50% with soybean 50%	8.86	5.15	3.48	2.85	2.46
Rice 25% with soybean 75%	6.58	2.97	1.30	0.97	0.71
Maize 50%, rice 25% and soybean 25%	13.87	10.85	9.16	6.90	3.87
Maize 25%, rice 50% and soybean 25%	13.87	11.38	9.52	7.15	4.38
Maize 25%, rice 25% and soybean 50%	9.34	9.01	7.10	5.40	3.90

Table III-60. Mean values of k_3 coefficient, (J g^{-1}/g cm^{-3}), at different moisture levels; ZD40 press, F_c = 100 kN

Material	Moisture content (%)				
	10	12	14	16	18
Maize meal	14.46	12.99	11.94	10.79	8.17
Rice	21.20	20.82	19.17	16.36	12.68
Wheat, cv. Alba	12.49	10.93	8.75	8.35	8.22
Wheat, cv. Jara	15.40	13.36	11.25	10.29	9.32
Wheat, cv. Almary	16.12	13.29	12.22	10.66	10.03
Oat, cv. Dragon	10.27	9.94	9.35	8.18	7.88
Oat, cv. Pegaz	9.62	8.81	7.74	6.30	6.03
Barley, cv. Aramir	13.70	11.86	10.73	9.03	8.51
Barley, cv. Ars	14.54	13.77	12.85	12.08	11.29
Barley, cv. Edgar	11.97	11.19	10.50	10.09	9.89
Barley, cv. Klimek	13.36	11.89	11.05	10.25	9.47
Barley, cv. Kos	13.27	12.13	11.30	10.61	10.16
Rye cv. Amilo	13.48	11.33	10.62	10.03	9.36
Rye cv. Dańkowskie Nowe	17.64	14.18	12.14	10.81	10.21
Rye cv. Dańkowskie Złote	14.80	12.53	10.91	10.12	9.71
Rye cv. Warko	14.52	12.40	10.58	9.95	8.90
Faba bean cv. Nadwiślański	18.57	16.02	14.38	11.42	10.59
Pea, cv. Fidelia	22.30	17.81	13.01	10.96	9.84
Lupine, cv. Emir	15.47	12.39	10.40	8.91	8.75
Vetch, cv. Szelejewska	20.41	18.49	15.10	12.81	10.14
Dry plant matter (alfalfa)	10.09	8.06	6.94	6.49	4.94
Meat-bone flour	5.74	5.82	5.83	5.88	4.88
Soybean meal	9.64	8.31	7.92		
Maize 75% with rice 25%	15.20	14.01	12.95	11.07	8.78
Maize 50% with rice 50%	16.22	15.27	14.29	12.40	10.12
Maize 25% with rice 75%	18.14	16.19	15.19	13.31	11.18
Maize 75% with oat, Pegaz 25%	12.56	11.26	9.97	9.10	7.42
Maize 50% with oat, Pegaz 50%	11.61	10.47	9.22	8.70	6.95
Maize 25% with oat, Pegaz 75%	10.27	9.28	8.38	7.63	6.50
Maize 75% with wheat, Alba 25%	13.75	12.27	10.92	9.13	8.13
Maize 50% with wheat, Alba 50%	13.52	11.84	10.42	8.92	8.05
Maize 25% with wheat, Alba 75%	13.21	11.57	9.93	8.74	8.00
Maize 75% with soybean 25%	12.87	10.45	9.71	8.58	7.75
Maize 50% with soybean 50%	12.27	9.93	9.70	8.15	7.64
Maize 25% with soybean 75%	10.83	7.80	7.50	7.39	7.41
Rice 75% with soybean 25%	17.04	15.97	12.05	10.52	9.36
Rice 50% with soybean 50%	13.02	10.53	9.35	9.00	7.68
Rice 25% with soybean 75%	12.62	10.39	10.17	8.83	7.21
Maize 50%, rice 25% and soybean 25%	15.76	13.11	12.54	10.26	7.74
Maize 25%, rice 50% and soybean 25%	15.73	14.06	12.66	10.58	8.10
Maize 25%, rice 25% and soybean 50%	12.94	13.13	12.90	10.73	7.78

Table III-61. Mean values of the shape retention ability coefficient, k_4, at different moisture levels; ZD40 press, $F_c = 100$ kN

Material	Moisture content (%)				
	10	12	14	16	18
Maize meal	0.002	0.014	0.020	0.016	0.004
Rice	0.002	0.004	0.004	0.004	0.004
Wheat, cv. Alba	0.007	0.016	0.025	0.029	0.026
Wheat, cv. Jara	0.002	0.005	0.007	0.009	0.007
Wheat, cv. Almary	0.002	0.007	0.014	0.016	0.019
Oat, cv. Dragon	0.061	0.061	0.068	0.076	0.077
Oat, cv. Pegaz	0.114	0.130	0.164	0.150	0.074
Barley, cv. Aramir	0.011	0.018	0.027	0.028	0.027
Barley, cv. Ars	0.017	0.016	0.028	0.032	0.027
Barley, cv. Edgar	0.003	0.012	0.020	0.022	0.014
Barley, cv. Klimek	0.004	0.012	0.024	0.028	0.028
Barley, cv. Kos	0.003	0.009	0.018	0.024	0.023
Rye cv. Amilo	0.001	0.007	0.010	0.010	0.009
Rye cv. Dańkowskie Nowe	0.003	0.005	0.010	0.009	0.008
Rye cv. Dańkowskie Złote	0.003	0.009	0.013	0.018	0.010
Rye cv. Warko	0.003	0.006	0.014	0.015	0.013
Faba bean cv. Nadwiślański	0.007	0.015	0.025	0.044	0.048
Pea, cv. Fidelia	0.009	0.013	0.033	0.057	0.054
Lupine, cv. Emir	0.002	0.005	0.011	0.026	0.030
Vetch, cv. Szelejewska	0.011	0.019	0.036	0.060	0.066
Dry plant matter (alfalfa)					
Meat-bone flour	0.072	0.079	0.045	0.049	0.035
Soybean meal					
Maize 75% with rice 25%	0.005	0.006	0.011	0.008	0.002
Maize 50% with rice 50%	0.002	0.004	0.006	0.007	0.004
Maize 25% with rice 75%	0.002	0.003	0.004	0.004	0.002
Maize 75% with oat, Pegaz 25%	0.014	0.033	0.033	0.030	0.008
Maize 50% with oat, Pegaz 50%	0.042	0.063	0.067	0.076	0.036
Maize 25% with oat, Pegaz 75%	0.075	0.085	0.099	0.127	0.125
Maize 75% with wheat, Alba 25%	0.007	0.015	0.023	0.021	0.009
Maize 50% with wheat, Alba 50%	0.009	0.017	0.022	0.020	0.009
Maize 25% with wheat, Alba 75%	0.011	0.018	0.021	0.019	0.010
Maize 75% with soybean 25%	0.007	0.017	0.025	0.030	0.016
Maize 50% with soybean 50%	0.013	0.020	0.035	0.035	0.047
Maize 25% with soybean 75%	0.016	0.037	0.048	0.089	0.107
Rice 75% with soybean 25%	0.008	0.009	0.013	0.019	0.019
Rice 50% with soybean 50%	0.011	0.012	0.029	0.032	0.036
Rice 25% with soybean 75%	0.006	0.012	0.024	0.030	0.043
Maize 50%, rice 25% and soybean 25%	0.020	0.026	0.032	0.027	0.021
Maize 25%, rice 50% and soybean 25%	0.022	0.031	0.026	0.022	0.016
Maize 25%, rice 25% and soybean 50%	0.037	0.039	0.043	0.029	0.021

Table III-62. Mean material densities at B point, ρ_b (g cm^{-3}); ZD40 press, F_c = 100 kN

Material	No.	Mean	Std. Dev.	Std. Err.	95% confidence interval
Maize meal	15	1.48	0.020	0.005	1.46-1.49
Rice	15	1.50	0.009	0.002	1.49-1.51
Wheat, cv. Alba	15	1.51	0.021	0.005	1.49-1.52
Wheat, cv. Jara	15	1.53	0.013	0.003	1.52-1.54
Wheat, cv. Almary	15	1.52	0.015	0.004	1.50-1.52
Oat, cv. Dragon	15	1.46	0.013	0.003	1.45-1.47
Oat, cv. Pegaz	15	1.43	0.016	0.004	1.42-1.44
Barley, cv. Aramir	15	1.50	0.013	0.003	1.49-1.51
Barley, cv. Ars	15	1.51	0.012	0.003	1.50-1.52
Barley, cv. Edgar	15	1.50	0.014	0.004	1.49-1.51
Barley, cv. Klimek	15	1.52	0.018	0.005	1.50-1.53
Barley, cv. Kos	15	1.51	0.015	0.004	1.50-1.52
Rye cv. Amilo	15	1.51	0.025	0.007	1.49-1.52
Rye cv. Dańkowskie Nowe	15	1.50	0.019	0.005	1.49-1.51
Rye cv. Dańkowskie Złote	15	1.52	0.018	0.005	1.50-1.53
Rye cv. Warko	15	1.51	0.018	0.005	1.49-1.52
Faba bean cv. Nadwiślański	15	1.50	0.017	0.004	1.48-1.50
Pea, cv. Fidelia	15	1.51	0.020	0.005	1.49-1.52
Lupine, cv. Emir	15	1.45	0.033	0.009	1.42-1.46
Vetch, cv. Szelejewska	15	1.47	0.011	0.003	1.46-1.48
Dry plant matter (alfalfa)	15	1.53	0.023	0.006	1.51-1.54
Meat-bone flour	15	1.58	0.062	0.016	1.54-1.61
Soybean meal	9	1.28	0.046	0.015	1.24-1.32
Maize 75% with rice 25%	15	1.49	0.018	0.005	1.47-1.49
Maize 50% with rice 50%	15	1.49	0.025	0.007	1.47-1.50
Maize 25% with rice 75%	15	1.50	0.011	0.003	1.49-1.50
Maize 75% with oat, Pegaz 25%	15	1.47	0.016	0.004	1.46-1.48
Maize 50% with oat, Pegaz 50%	15	1.47	0.020	0.005	1.45-1.48
Maize 25% with oat, Pegaz 75%	15	1.47	0.022	0.006	1.45-1.48
Maize 75% with wheat, Alba 25%	15	1.50	0.016	0.004	1.49-1.51
Maize 50% with wheat, Alba 50%	15	1.50	0.016	0.004	1.49-1.51
Maize 25% with wheat, Alba 75%	15	1.50	0.023	0.006	1.49-1.51
Maize 75% with soybean 25%	15	1.45	0.007	0.002	1.44-1.45
Maize 50% with soybean 50%	15	1.39	0.036	0.009	1.37-1.40
Maize 25% with soybean 75%	15	1.33	0.048	0.012	1.30-1.35
Rice 75% with soybean 25%	15	1.45	0.019	0.005	1.43-1.46
Rice 50% with soybean 50%	15	1.41	0.017	0.005	1.40-1.43
Rice 25% with soybean 75%	15	1.38	0.013	0.003	1.37-1.38
Maize 50%, rice 25% and soybean 25%	15	1.49	0.018	0.005	1.48-1.50
Maize 25%, rice 50% and soybean 25%	15	1.51	0.026	0.007	1.49-1.52
Maize 25%, rice 25% and soybean 50%	15	1.44	0.019	0.005	1.43-1.45

Table III-63. Mean material densities at C point, ρ_c (g cm^{-3}); ZD40 press, F_c = 100 kN

Material	No.	Mean	Std. Dev.	Std. Err.	95% confidence interval
Maize meal	15	1.52	0.014	0.004	1.516-1.531
Rice	15	1.53	0.004	0.001	1.526-1.530
Wheat, cv. Alba	15	1.55	0.017	0.005	1.540-1.559
Wheat, cv. Jara	15	1.57	0.000	0.000	1.570-1.570
Wheat, cv. Almary	15	1.57	0.010	0.003	1.567-1.578
Oat, cv. Dragon	15	1.54	0.013	0.003	1.533-1.547
Oat, cv. Pegaz	15	1.49	0.013	0.003	1.487-1.501
Barley, cv. Aramir	15	1.53	0.011	0.003	1.522-1.534
Barley, cv. Ars	15	1.55	0.013	0.003	1.544-1.558
Barley, cv. Edgar	15	1.55	0.014	0.004	1.539-1.553
Barley, cv. Klimek	15	1.57	0.017	0.005	1.558-1.577
Barley, cv. Kos	15	1.56	0.016	0.004	1.546-1.564
Rye cv. Amilo	15	1.56	0.024	0.006	1.548-1.574
Rye cv. Dańkowskie Nowe	15	1.55	0.017	0.004	1.543-1.562
Rye cv. Dańkowskie Złote	15	1.57	0.015	0.004	1.564-1.580
Rye cv. Warko	15	1.56	0.019	0.005	1.548-1.569
Faba bean cv. Nadwiślański	15	1.56	0.017	0.004	1.546-1.564
Pea, cv. Fidelia	15	1.56	0.017	0.004	1.555-1.572
Lupine, cv. Emir	15	1.54	0.010	0.003	1.529-1.540
Vetch, cv. Szelejewska	15	1.54	0.013	0.003	1.533-1.547
Dry plant matter (alfalfa)	15	1.60	0.036	0.009	1.580-1.620
Meat-bone flour	15	1.76	0.059	0.015	1.725-1.790
Soybean meal	9	1.41	0.033	0.011	1.389-1.440
Maize 75% with rice 25%	15	1.53	0.006	0.002	1.523-1.529
Maize 50% with rice 50%	15	1.52	0.016	0.004	1.514-1.532
Maize 25% with rice 75%	15	1.53	0.008	0.002	1.522-1.531
Maize 75% with oat, Pegaz 25%	15	1.51	0.007	0.002	1.509-1.516
Maize 50% with oat, Pegaz 50%	15	1.50	0.018	0.005	1.494-1.514
Maize 25% with oat, Pegaz 75%	15	1.50	0.021	0.005	1.487-1.510
Maize 75% with wheat, Alba 25%	15	1.53	0.018	0.005	1.515-1.534
Maize 50% with wheat, Alba 50%	15	1.53	0.015	0.004	1.519-1.535
Maize 25% with wheat, Alba 75%	15	1.53	0.015	0.004	1.518-1.535
Maize 75% with soybean 25%	15	1.52	0.014	0.004	1.508-1.523
Maize 50% with soybean 50%	15	1.50	0.016	0.004	1.490-1.507
Maize 25% with soybean 75%	15	1.49	0.018	0.005	1.482-1.501
Rice 75% with soybean 25%	15	1.51	0.012	0.003	1.507-1.520
Rice 50% with soybean 50%	15	1.51	0.011	0.003	1.503-1.515
Rice 25% with soybean 75%	15	1.50	0.014	0.004	1.493-1.508
Maize 50%, rice 25% and soybean 25%	15	1.54	0.018	0.005	1.534-1.553
Maize 25%, rice 50% and soybean 25%	15	1.57	0.016	0.004	1.560-1.577
Maize 25%, rice 25% and soybean 50%	15	1.51	0.016	0.004	1.501-1.518

Table III-64. Mean agglomerate densities, ρ_k (g cm^{-3}); ZD40 press, F_c = 100 kN

Material	No.	Mean	Std. Dev.	Std. Err.	95% confidence interval
Maize meal	15	1.21	0.031	0.008	1.197-1.231
Rice	15	1.26	0.028	0.007	1.245-1.275
Wheat, cv. Alba	15	1.23	0.028	0.007	1.216-1.246
Wheat, cv. Jara	15	1.26	0.018	0.005	1.253-1.273
Wheat, cv. Almary	15	1.28	0.043	0.011	1.254-1.301
Oat, cv. Dragon	15	1.16	0.023	0.006	1.151-1.176
Oat, cv. Pegaz	15	1.05	0.068	0.018	1.009-1.084
Barley, cv. Aramir	15	1.22	0.019	0.005	1.206-1.227
Barley, cv. Ars	15	1.20	0.023	0.006	1.184-1.209
Barley, cv. Edgar	15	1.21	0.020	0.005	1.198-1.219
Barley, cv. Klimek	15	1.20	0.026	0.007	1.190-1.218
Barley, cv. Kos	15	1.20	0.031	0.008	1.181-1.215
Rye cv. Amilo	15	1.27	0.015	0.004	1.264-1.281
Rye cv. Dańkowskie Nowe	15	1.27	0.018	0.005	1.257-1.277
Rye cv. Dańkowskie Złote	15	1.28	0.018	0.005	1.258-1.287
Rye cv. Warko	15	1.26	0.023	0.006	1.246-1.271
Faba bean cv. Nadwiślański	15	1.32	0.029	0.007	1.303-1.334
Pea, cv. Fidelia	15	1.32	0.021	0.005	1.304-1.326
Lupine, cv. Emir	15	1.19	0.023	0.006	1.176-1.201
Vetch, cv. Szelejewska	15	1.32	0.023	0.006	1.308-1.333
Dry plant matter (alfalfa)	15	1.01	0.063	0.016	0.977-1.046
Meat-bone flour	15	1.49	0.021	0.005	1.482-1.505
Soybean meal	9	1.11	0.017	0.006	1.095-1.121
Maize 75% with rice 25%	15	1.21	0.054	0.014	1.182-1.241
Maize 50% with rice 50%	15	1.23	0.015	0.004	1.225-1.241
Maize 25% with rice 75%	15	1.24	0.045	0.012	1.216-1.266
Maize 75% with oat, Pegaz 25%	15	1.18	0.037	0.010	1.157-1.197
Maize 50% with oat, Pegaz 50%	15	1.14	0.032	0.008	1.120-1.154
Maize 25% with oat, Pegaz 75%	15	1.12	0.036	0.009	1.101-1.141
Maize 75% with wheat, Alba 25%	15	1.22	0.018	0.005	1.205-1.225
Maize 50% with wheat, Alba 50%	15	1.22	0.019	0.005	1.207-1.228
Maize 25% with wheat, Alba 75%	15	1.22	0.030	0.008	1.205-1.238
Maize 75% with soybean 25%	15	1.20	0.017	0.004	1.189-1.208
Maize 50% with soybean 50%	15	1.15	0.012	0.003	1.145-1.158
Maize 25% with soybean 75%	15	1.13	0.020	0.005	1.115-1.136
Rice 75% with soybean 25%	15	1.26	0.016	0.004	1.248-1.265
Rice 50% with soybean 50%	15	1.22	0.016	0.004	1.211-1.228
Rice 25% with soybean 75%	15	1.16	0.023	0.006	1.148-1.173
Maize 50%, rice 25% and soybean 25%	15	1.22	0.022	0.006	1.207-1.230
Maize 25%, rice 50% and soybean 25%	15	1.23	0.010	0.003	1.225-1.236
Maize 25%, rice 25% and soybean 50%	15	1.20	0.018	0.005	1.188-1.207

Table III-65. Mean agglomerate densities after 24 hours, ρ_{k1} (g cm^{-3}); ZD40 press, F_c = 100 kN

Material	No.	Mean	Std. Dev.	Std. Err.	95% confidence interval
Maize meal	15	1.09	0.061	0.016	1.054-1.121
Rice	15	1.18	0.038	0.010	1.161-1.202
Wheat, cv. Alba	15	1.15	0.029	0.007	1.129 -1.161
Wheat, cv. Jara	15	1.17	0.037	0.010	1.152-1.192
Wheat, cv. Almary	15	1.22	0.021	0.005	1.211-1.234
Oat, cv. Dragon	15	1.05	0.017	0.005	1.044-1.063
Oat, cv. Pegaz	15	0.90	0.084	0.022	0.854-0.946
Barley, cv. Aramir	15	1.14	0.032	0.008	1.119-1.154
Barley, cv. Ars	15	1.13	0.021	0.005	1.122-1.144
Barley, cv. Edgar	15	1.13	0.045	0.012	1.101-1.150
Barley, cv. Klimek	15	1.11	0.025	0.006	1.096-1.122
Barley, cv. Kos	15	1.14	0.036	0.009	1.115-1.154
Rye cv. Amilo	15	1.19	0.045	0.012	1.166-1.215
Rye cv. Dańkowskie Nowe	15	1.19	0.034	0.009	1.166-1.203
Rye cv. Dańkowskie Złote	15	1.21	0.042	0.011	1.183-1.229
Rye cv. Warko	15	1.18	0.036	0.009	1.157-1.197
Faba bean cv. Nadwiślański	15	1.26	0.016	0.004	1.249-1.265
Pea, cv. Fidelia	15	1.25	0.020	0.005	1.243-1.264
Lupine, cv. Emir	15	1.07	0.035	0.009	1.046-1.084
Vetch, cv. Szelejewska	15	1.25	0.013	0.003	1.247-1.261
Dry plant matter (alfalfa)	15	0.85	0.089	0.023	0.796-0.893
Meat-bone flour	15	1.45	0.042	0.011	1.431-1.477
Soybean meal	7	0.94	0.029	0.011	0.912-0.965
Maize 75% with rice 25%	15	1.09	0.076	0.020	1.046-1.130
Maize 50% with rice 50%	15	1.14	0.045	0.012	1.114-1.163
Maize 25% with rice 75%	15	1.16	0.054	0.014	1.125-1.184
Maize 75% with oat, Pegaz 25%	15	1.01	0.059	0.015	0.977-1.042
Maize 50% with oat, Pegaz 50%	15	0.97	0.049	0.013	0.940-0.994
Maize 25% with oat, Pegaz 75%	15	0.96	0.044	0.011	0.935-0.983
Maize 75% with wheat, Alba 25%	15	1.07	0.046	0.012	1.041-1.092
Maize 50% with wheat, Alba 50%	15	1.08	0.051	0.013	1.056-1.112
Maize 25% with wheat, Alba 75%	15	1.10	0.066	0.017	1.066-1.139
Maize 75% with soybean 25%	15	1.06	0.023	0.006	1.043-1.067
Maize 50% with soybean 50%	15	1.03	0.019	0.005	1.023-1.043
Maize 25% with soybean 75%	15	1.00	0.050	0.013	0.967-1.022
Rice 75% with soybean 25%	15	1.17	0.024	0.006	1.161-1.187
Rice 50% with soybean 50%	15	1.13	0.034	0.009	1.106-1.143
Rice 25% with soybean 75%	15	1.02	0.040	0.010	0.995-1.038
Maize 50%, rice 25% and soybean 25%	15	1.11	0.023	0.006	1.096-1.122
Maize 25%, rice 50% and soybean 25%	15	1.14	0.031	0.008	1.117-1.151
Maize 25%, rice 25% and soybean 50%	15	1.09	0.015	0.004	1.077-1.093

Table III-66. Mean pressure at B point, P_b (MPa); ZD40 press, F_c = 100 kN

Material	No.	Mean	Std. Dev.	Std. Err.	95% confidence interval
Maize meal	15	90.9	22.29	5.76	78-103
Rice	15	110	13.67	3.53	102-117
Wheat, cv. Alba	15	92.2	17.21	4.44	82-101
Wheat, cv. Jara	15	103	18.37	4.74	93-113
Wheat, cv. Almary	15	111	22.56	5.82	98-123
Oat, cv. Dragon	15	87.6	15.63	4.04	78-96
Oat, cv. Pegaz	15	68.3	24.43	6.31	54-81
Barley, cv. Aramir	15	107	21.39	5.52	95-119
Barley, cv. Ars	15	133	9.50	2.45	128-139
Barley, cv. Edgar	15	114	12.35	3.19	107-121
Barley, cv. Klimek	15	118	14.57	3.76	110-126
Barley, cv. Kos	15	120	12.15	3.14	114-127
Rye cv. Amilo	15	111	16.94	4.37	102-120
Rye cv. Dańkowskie Nowe	15	116	16.29	4.21	107-125
Rye cv. Dańkowskie Złote	15	108	12.44	3.21	101-114
Rye cv. Warko	15	111	16.92	4.37	101-120
Faba bean cv. Nadwiślański	15	103	23.44	6.05	90-116
Pea, cv. Fidelia	15	117	20.68	5.34	105-128
Lupine, cv. Emir	15	68.6	33.51	8.65	50-87
Vetch, cv. Szelejewska	15	96.9	22.25	5.74	84-109
Dry plant matter (alfalfa)	15	109	12.38	3.20	102-115
Meat-bone flour	15	18.2	9.70	2.51	12-23
Soybean meal	9	19.9	9.16	3.05	12-26
Maize 75% with rice 25%	15	94.0	21.71	5.61	81-106
Maize 50% with rice 50%	15	98.1	19.45	5.02	87-108
Maize 25% with rice 75%	15	104	13.60	3.51	96-111
Maize 75% with oat, Pegaz 25%	15	85.2	22.86	5.90	72-97
Maize 50% with oat, Pegaz 50%	15	82.5	24.09	6.22	69-95
Maize 25% with oat, Pegaz 75%	15	78.8	24.23	6.25	65-92
Maize 75% with wheat, Alba 25%	15	91.7	18.63	4.81	81-102
Maize 50% with wheat, Alba 50%	15	91.7	18.75	4.84	81-102
Maize 25% with wheat, Alba 75%	15	92.8	18.05	4.66	82-102
Maize 75% with soybean 25%	15	68.9	17.06	4.41	59-78
Maize 50% with soybean 50%	15	40.9	18.47	4.77	30-51
Maize 25% with soybean 75%	15	20.8	12.58	3.25	13-27
Rice 75% with soybean 25%	15	77.9	20.48	5.29	66-89
Rice 50% with soybean 50%	15	48.0	22.40	5.78	35-60
Rice 25% with soybean 75%	15	24.9	13.93	3.60	17-32
Maize 50%, rice 25% and soybean 25%	15	85.8	21.22	5.48	74-97
Maize 25%, rice 50% and soybean 25%	15	89.2	22.03	5.69	76-101
Maize 25%, rice 25% and soybean 50%	15	60.5	12.47	3.22	53-67

Table III-67. Mean specific compression energies corresponding to B point, L_b' (J g^{-1}); ZD40 press, F_c = 100 kN

Material	No.	Mean	Std. Dev.	Std. Err.	95% confidence interval
Maize meal	15	7.51	2.66	0.69	6.03-8.99
Rice	15	9.58	2.02	0.52	8.46-10.70
Wheat, cv. Alba	15	7.46	1.94	0.50	6.38-8.53
Wheat, cv. Jara	15	8.21	2.18	0.56	7.00-9.41
Wheat, cv. Almary	15	7.84	2.01	0.52	6.73-8.95
Oat, cv. Dragon	15	5.96	1.47	0.38	5.14-6.77
Oat, cv. Pegaz	15	4.42	2.51	0.65	3.03-5.81
Barley, cv. Aramir	15	7.80	2.00	0.52	6.68-8.90
Barley, cv. Ars	15	10.53	1.28	0.33	9.82-11.24
Barley, cv. Edgar	15	7.85	0.88	0.23	7.36-8.33
Barley, cv. Klimek	15	8.37	1.48	0.38	7.55-9.18
Barley, cv. Kos	15	8.36	1.01	0.26	7.80-8.92
Rye cv. Amilo	15	6.89	1.35	0.35	6.14-7.63
Rye cv. Dańkowskie Nowe	15	8.25	2.19	0.57	7.03-9.46
Rye cv. Dańkowskie Złote	15	7.06	1.22	0.32	6.38-7.73
Rye cv. Warko	15	7.47	1.70	0.44	6.52-8.40
Faba bean cv. Nadwiślański	15	7.42	2.00	0.52	6.30-8.52
Pea, cv. Fidelia	15	8.48	3.08	0.80	6.76-10.18
Lupine, cv. Emir	15	5.52	3.70	0.95	3.47-7.56
Vetch, cv. Szelejewska	15	7.97	2.33	0.60	6.68-9.26
Dry plant matter (alfalfa)	15	7.93	2.09	0.54	6.77-9.09
Meat-bone flour	15	1.04	0.47	0.12	0.77-1.29
Soybean meal	9	1.68	1.42	0.47	0.59-2.76
Maize 75% with rice 25%	15	7.81	2.58	0.67	6.38-9.23
Maize 50% with rice 50%	15	8.17	2.58	0.67	6.74-9.60
Maize 25% with rice 75%	15	9.11	2.24	0.58	7.87-10.3
Maize 75% with oat, Pegaz 25%	15	6.31	2.27	0.59	5.05-7.56
Maize 50% with oat, Pegaz 50%	15	5.78	2.14	0.55	4.59-6.96
Maize 25% with oat, Pegaz 75%	15	5.58	2.10	0.54	4.41-6.73
Maize 75% with wheat, Alba 25%	15	7.56	2.29	0.59	6.29-8.83
Maize 50% with wheat, Alba 50%	15	7.52	2.19	0.57	6.30-8.72
Maize 25% with wheat, Alba 75%	15	7.55	2.01	0.52	6.44-8.66
Maize 75% with soybean 25%	15	5.22	1.98	0.51	4.11-6.31
Maize 50% with soybean 50%	15	3.21	1.88	0.49	2.16-4.24
Maize 25% with soybean 75%	15	1.75	1.64	0.42	0.84-2.65
Rice 75% with soybean 25%	15	6.87	2.59	0.67	5.43-8.30
Rice 50% with soybean 50%	15	3.56	2.01	0.52	2.45-4.67
Rice 25% with soybean 75%	15	2.00	1.88	0.49	0.95-3.03
Maize 50%, rice 25% and soybean 25%	15	7.79	3.11	0.84	6.06-9.50
Maize 25%, rice 50% and soybean 25%	15	8.04	3.05	0.81	6.29-9.78
Maize 25%, rice 25% and soybean 50%	15	5.87	1.96	0.51	4.78-6.95

Table III-68. Mean specific compaction energies, L_s' (Jg^{-1}), (from B to C point); ZD40 press, $F_c = 100$ kN

Material	No.	Mean	Std. Dev.	Std. Err.	95% confidence interval
Maize meal	15	3.35	0.66	0.17	2.98-3.70
Rice	15	3.98	0.79	0.20	3.54-4.41
Wheat, cv. Alba	15	2.57	0.67	0.17	2.19-2.93
Wheat, cv. Jara	15	2.47	0.47	0.12	2.20-2.72
Wheat, cv. Almary	15	3.63	0.32	0.08	3.45-3.80
Oat, cv. Dragon	15	4.88	0.38	0.10	4.66-5.08
Oat, cv. Pegaz	15	4.52	0.85	0.22	4.05-4.98
Barley, cv. Aramir	15	2.87	0.42	0.11	2.63-3.09
Barley, cv. Ars	15	2.93	0.15	0.04	2.84-3.01
Barley, cv. Edgar	15	3.09	0.17	0.04	2.99-3.18
Barley, cv. Klimek	15	3.33	0.27	0.07	3.18-3.48
Barley, cv. Kos	15	3.15	0.26	0.07	3.00-3.29
Rye cv. Amilo	15	3.33	0.23	0.06	3.20-3.45
Rye cv. Dańkowskie Nowe	15	3.41	0.36	0.09	3.20-3.60
Rye cv. Dańkowskie Złote	15	3.57	0.55	0.14	3.27-3.87
Rye cv. Warko	15	3.41	0.42	0.11	3.17-3.64
Faba bean cv. Nadwiślański	15	3.87	0.22	0.06	3.74-3.98
Pea, cv. Fidelia	15	3.65	0.59	0.15	3.32-3.97
Lupine, cv. Emir	15	5.27	1.50	0.39	4.44-6.10
Vetch, cv. Szelejewska	15	4.38	0.45	0.12	4.13-4.63
Dry plant matter (alfalfa)	15	2.43	0.54	0.14	2.12-2.72
Meat-bone flour	15	5.42	0.51	0.13	5.13-2.70
Soybean meal	9	5.63	0.40	0.13	5.32-5.93
Maize 75% with rice 25%	15	3.47	0.53	0.14	3.17-3.75
Maize 50% with rice 50%	15	3.37	0.62	0.16	3.02-3.70
Maize 25% with rice 75%	15	2.93	0.48	0.12	2.66-3.19
Maize 75% with oat, Pegaz 25%	15	3.57	0.60	0.15	3.24-3.88
Maize 50% with oat, Pegaz 50%	15	3.83	0.69	0.18	3.44-4.20
Maize 25% with oat, Pegaz 75%	15	3.74	0.74	0.19	3.33-4.14
Maize 75% with wheat, Alba 25%	15	2.85	0.42	0.11	2.61-3.08
Maize 50% with wheat, Alba 50%	15	2.75	0.55	0.14	2.45-3.05
Maize 25% with wheat, Alba 75%	15	2.55	0.50	0.13	2.26-2.83
Maize 75% with soybean 25%	15	3.92	0.40	0.10	3.69-4.13
Maize 50% with soybean 50%	15	5.67	0.64	0.16	5.32-6.02
Maize 25% with soybean 75%	15	5.82	0.38	0.10	5.60-6.02
Rice 75% with soybean 25%	15	3.88	0.40	0.10	3.66-4.10
Rice 50% with soybean 50%	15	5.07	0.71	0.18	4.67-5.45
Rice 25% with soybean 75%	15	6.87	0.87	0.23	6.39-7.35
Maize 50%, rice 25% and soybean 25%	15	3.20	0.66	0.17	2.83-3.56
Maize 25%, rice 50% and soybean 25%	15	3.21	0.66	0.17	2.83-3.57
Maize 25%, rice 25% and soybean 50%	15	4.49	0.79	0.20	4.05-4.92

Table III-69. Mean total specific compression energies, L_c' (J g^{-1}) (corresponding to C point of the compression characteristic; ZD40 press, F_c = 100 kN

Material	No.	Mean	Std. Dev.	Std. Err.	95% confidence interval
Maize meal	15	10.85	2.13	0.55	9.67-12.0
Rice	15	13.55	2.52	0.65	12.15-14.9
Wheat, cv. Alba	15	10.00	1.92	0.50	8.93-11.0
Wheat, cv. Jara	15	10.69	1.86	0.48	9.66-11.7
Wheat, cv. Almary	15	11.47	2.10	0.54	10.3-12.6
Oat, cv. Dragon	15	10.84	1.16	0.30	10.1-11.4
Oat, cv. Pegaz	15	8.92	1.78	0.46	7.93-9.99
Barley, cv. Aramir	15	10.67	1.89	0.49	9.61-11.7
Barley, cv. Ars	15	13.47	1.34	0.35	12.7-14.2
Barley, cv. Edgar	15	10.94	0.85	0.22	10.4-11.4
Barley, cv. Klimek	15	11.70	1.54	0.40	10.8-12.5
Barley, cv. Kos	15	11.51	1.15	0.30	10.8-12.1
Rye cv. Amilo	15	10.22	1.40	0.36	9.44-10.9
Rye cv. Dańkowskie Nowe	15	11.65	2.38	0.62	10.3-12.9
Rye cv. Dańkowskie Złote	15	10.63	1.57	0.41	9.76-11.4
Rye cv. Warko	15	10.88	1.95	0.50	9.79-11.9
Faba bean cv. Nadwiślański	15	11.28	2.05	0.53	10.1-12.4
Pea, cv. Fidelia	15	12.13	3.43	0.89	10.2-14.0
Lupine, cv. Emir	15	10.79	2.29	0.59	9.52-12.0
Vetch, cv. Szelejewska	15	12.35	2.69	0.70	10.8-13.8
Dry plant matter (alfalfa)	15	10.35	2.53	0.65	8.94-11.7
Meat-bone flour	15	6.45	0.65	0.17	6.08-6.80
Soybean meal	9	7.31	1.22	0.41	6.37-8.24
Maize 75% with rice 25%	15	11.28	2.13	0.55	10.0-12.4
Maize 50% with rice 50%	15	11.54	2.03	0.52	10.4-12.6
Maize 25% with rice 75%	15	12.04	2.02	0.52	10.9-13.1
Maize 75% with oat, Pegaz 25%	15	9.87	1.82	0.47	8.86-10.8
Maize 50% with oat, Pegaz 50%	15	9.60	1.66	0.43	8.68-10.5
Maize 25% with oat, Pegaz 75%	15	9.31	1.54	0.40	8.46-10.1
Maize 75% with wheat, Alba 25%	15	10.46	2.12	0.55	9.28-11.6
Maize 50% with wheat, Alba 50%	15	10.27	2.08	0.54	9.11-11.4
Maize 25% with wheat, Alba 75%	15	10.10	2.01	0.52	8.98-11.2
Maize 75% with soybean 25%	15	9.13	1.68	0.44	8.19-10.0
Maize 50% with soybean 50%	15	8.81	1.67	0.43	7.88-9.73
Maize 25% with soybean 75%	15	7.57	1.44	0.37	6.76-8.36
Rice 75% with soybean 25%	15	10.76	2.40	0.62	9.42-12.0
Rice 50% with soybean 50%	15	8.63	1.65	0.43	7.71-9.54
Rice 25% with soybean 75%	15	8.87	1.66	0.43	7.95-9.78
Maize 50%, rice 25% and soybean 25%	15	10.99	2.64	0.68	9.52-12.4
Maize 25%, rice 50% and soybean 25%	15	11.25	2.68	0.69	9.76-12.7
Maize 25%, rice 25% and soybean 50%	15	10.43	2.01	0.52	9.32-11.5

Table III-70. Mean agglomerate compressive strength, σ_n (MPa); ZD40 press, $F_c = 100$ kN

Material	No.	Mean	Std. Dev.	Std. Err.	95% confidence interval
Maize meal	15	1.01	0.69	0.18	0.63-1.39
Rice	15	0.41	0.11	0.03	0.35-0.47
Wheat, cv. Alba	15	1.78	0.60	0.16	1.44-2.11
Wheat, cv. Jara	15	0.61	0.22	0.06	0.48-0.72
Wheat, cv. Almary	15	1.17	0.56	0.15	0.85-1.47
Oat, cv. Dragon	15	5.91	0.93	0.24	5.39-6.42
Oat, cv. Pegaz	15	8.76	3.74	0.97	6.69-10.8
Barley, cv. Aramir	15	2.26	0.51	0.13	1.97-2.53
Barley, cv. Ars	15	3.17	0.79	0.20	2.73-3.60
Barley, cv. Edgar	15	1.58	0.75	0.20	1.16-1.99
Barley, cv. Klimek	15	2.17	1.01	0.26	1.61-2.73
Barley, cv. Kos	15	1.77	0.95	0.24	1.24-2.29
Rye cv. Amilo	15	0.80	0.33	0.09	0.61-0.98
Rye cv. Dańkowskie Nowe	15	0.75	0.27	0.07	0.59-0.89
Rye cv. Dańkowskie Złote	15	1.11	0.53	0.14	0.81-1.40
Rye cv. Warko	15	1.05	0.47	0.12	0.79-1.31
Faba bean cv. Nadwiślański	15	2.54	1.12	0.29	1.91-3.16
Pea, cv. Fidelia	15	3.50	1.87	0.48	2.46-4.53
Lupine, cv. Emir	15	0.68	0.30	0.08	0.51-0.84
Vetch, cv. Szelejewska	15	3.29	1.40	0.36	2.51-4.06
Dry plant matter (alfalfa)					
Meat-bone flour	15	1.15	0.88	0.23	0.66-1.63
Soybean meal					
Maize 75% with rice 25%	15	0.63	0.35	0.09	0.43-0.82
Maize 50% with rice 50%	15	0.45	0.18	0.05	0.35-0.54
Maize 25% with rice 75%	15	0.31	0.14	0.04	0.23-0.38
Maize 75% with oat, Pegaz 25%	15	2.07	1.11	0.29	1.45-2.69
Maize 50% with oat, Pegaz 50%	15	4.64	1.70	0.44	3.70-5.58
Maize 25% with oat, Pegaz 75%	15	7.55	1.23	0.32	6.86-8.22
Maize 75% with wheat, Alba 25%	15	1.37	0.62	0.16	1.03-1.71
Maize 50% with wheat, Alba 50%	15	1.43	0.55	0.14	1.12-1.73
Maize 25% with wheat, Alba 75%	15	1.46	0.49	0.13	1.19-1.73
Maize 75% with soybean 25%	15	1.22	0.49	0.13	0.94-1.49
Maize 50% with soybean 50%	15	1.02	0.10	0.03	0.96-1.07
Maize 25% with soybean 75%	15	0.88	0.21	0.06	0.76-0.99
Rice 75% with soybean 25%	15	0.97	0.17	0.04	0.87-1.06
Rice 50% with soybean 50%	15	0.92	0.12	0.03	0.85-0.98
Rice 25% with soybean 75%	15	0.41	0.11	0.03	0.34-0.46
Maize 50%, rice 25% and soybean 25%	15	2.16	0.61	0.16	1.82-2.49
Maize 25%, rice 50% and soybean 25%	15	2.15	0.86	0.22	1.67-2.62
Maize 25%, rice 25% and soybean 50%	15	2.10	0.79	0.21	1.65-2.53

Table III-71. Mean values of the material compression ability coefficient, k_1 (MPa^{-1}); ZD40 press, F_c=100kN

Material	No.	Mean	Std. Dev.	Std. Err.	95% confidence interval
Maize meal	15	0.029	0.0082	0.0021	0.025-0.033
Rice	15	0.018	0.0028	0.0007	0.016-0.019
Wheat, cv. Alba	15	0.032	0.0062	0.0016	0.029-0.035
Wheat, cv. Jara	15	0.023	0.0050	0.0013	0.020-0.025
Wheat, cv. Almary	15	0.022	0.0047	0.0012	0.193-0.224
Oat, cv. Dragon	15	0.049	0.0102	0.0026	0.044-0.054
Oat, cv. Pegaz	15	0.072	0.0278	0.0072	0.056-0.087
Barley, cv. Aramir	15	0.027	0.0064	0.0017	0.024-0.030
Barley, cv. Ars	15	0.022	0.0018	0.0005	0.021-0.023
Barley, cv. Edgar	15	0.025	0.0030	0.0008	0.024-0.026
Barley, cv. Klimek	15	0.025	0.0033	0.0009	0.023-0.026
Barley, cv. Kos	15	0.023	0.0028	0.0007	0.021-0.024
Rye cv. Amilo	15	0.022	0.0039	0.0010	0.020-0.024
Rye cv. Dańkowskie Nowe	15	0.020	0.0034	0.0009	0.018-0.022
Rye cv. Dańkowskie Złote	15	0.022	0.0032	0.0008	0.020-0.023
Rye cv. Warko	15	0.023	0.0043	0.0011	0.021-0.025
Faba bean cv. Nadwiślański	15	0.021	0.0062	0.0016	0.017-0.023
Pea, cv. Fidelia	15	0.018	0.0043	0.0011	0.015-0.020
Lupine, cv. Emir	15	0.049	0.0279	0.0072	0.034-0.064
Vetch, cv. Szelejewska	15	0.022	0.0072	0.0019	0.018-0.026
Dry plant matter (alfalfa)	15	0.078	0.0118	0.0030	0.072-0.084
Meat-bone flour	15	0.181	0.0866	0.0224	0.133-0.229
Soybean meal	9	0.141	0.0705	0.0235	0.087-0.195
Maize 75% with rice 25%	15	0.027	0.0077	0.0020	0.023-0.031
Maize 50% with rice 50%	15	0.024	0.0058	0.0015	0.021-0.026
Maize 25% with rice 75%	15	0.020	0.0031	0.0008	0.019-0.022
Maize 75% with oat, Pegaz 25%	15	0.035	0.0098	0.0025	0.029-0.039
Maize 50% with oat, Pegaz 50%	15	0.039	0.0119	0.0031	0.032-0.045
Maize 25% with oat, Pegaz 75%	15	0.050	0.0160	0.0041	0.041-0.058
Maize 75% with wheat, Alba 25%	15	0.031	0.0073	0.0019	0.027-0.034
Maize 50% with wheat, Alba 50%	15	0.031	0.0071	0.0018	0.027-0.034
Maize 25% with wheat, Alba 75%	15	0.030	0.0063	0.0016	0.027-0.033
Maize 75% with soybean 25%	15	0.038	0.0092	0.0024	0.033-0.042
Maize 50% with soybean 50%	15	0.070	0.0271	0.0070	0.055-0.084
Maize 25% with soybean 75%	15	0.144	0.0655	0.0169	0.108-0.180
Rice 75% with soybean 25%	15	0.029	0.0081	0.0021	0.025-0.033
Rice 50% with soybean 50%	15	0.057	0.0261	0.0067	0.042-0.071
Rice 25% with soybean 75%	15	0.127	0.0724	0.0187	0.087-0.166
Maize 50%, rice 25% and soybean 25%	15	0.030	0.0087	0.0023	0.025-0.034
Maize 25%, rice 50% and soybean 25%	15	0.028	0.0077	0.0020	0.024-0.032
Maize 25%, rice 25% and soybean 50%	15	0.041	0.0086	0.0022	0.036-0.046

Table III-72. Mean values of k_2 coefficient, (J g^{-1}/g cm^{-3}); ZD40 press, F_c = 100 kN

Material	No.	Mean	Std. Dev.	Std. Err.	95% confidence interval
Maize meal	15	8.45	2.87	0.74	6.85-10.03
Rice	15	13.22	2.71	0.70	11.71-14.71
Wheat, cv. Alba	15	7.55	1.85	0.48	6.52-8.56
Wheat, cv. Jara	15	9.58	2.61	0.67	8.14-11.02
Wheat, cv. Almary	15	9.07	2.27	0.59	7.81-10.33
Oat, cv. Dragon	15	5.36	1.23	0.33	4.64-6.07
Oat, cv. Pegaz	15	4.01	2.25	0.58	2.75-5.25
Barley, cv. Aramir	15	8.11	2.14	0.55	6.92-9.29
Barley, cv. Ars	15	10.52	1.23	0.32	9.83-11.19
Barley, cv. Edgar	15	8.06	0.87	0.23	7.57-8.54
Barley, cv. Klimek	15	8.41	1.44	0.37	7.61-9.20
Barley, cv. Kos	15	8.76	1.07	0.28	8.16-9.35
Rye cv. Amilo	15	7.81	1.50	0.39	6.97-8.63
Rye cv. Dańkowskie Nowe	15	9.75	2.71	0.70	8.25-11.25
Rye cv. Dańkowskie Złote	15	8.22	1.62	0.42	7.32-9.11
Rye cv. Warko	15	8.19	1.94	0.50	7.11-9.26
Faba bean cv. Nadwiślański	15	10.11	3.05	0.79	8.42-11.80
Pea, cv. Fidelia	15	11.12	4.59	1.19	8.57-13.66
Lupine, cv. Emir	15	6.22	4.11	1.06	3.94-8.49
Vetch, cv. Szelejewska	15	10.90	3.56	0.92	8.93-12.87
Dry plant matter (alfalfa)	15	5.90	1.60	0.41	5.02-6.78
Meat-bone flour	15	1.06	0.41	0.11	0.82-1.28
Soybean meal	9	2.23	1.73	0.58	0.90-3.55
Maize 75% with rice 25%	15	9.06	2.90	0.75	7.45-10.67
Maize 50% with rice 50%	15	10.06	2.98	0.77	8.40-11.70
Maize 25% with rice 75%	15	11.79	2.88	0.74	10.19-13.38
Maize 75% with oat, Pegaz 25%	15	6.82	2.36	0.61	5.51-8.12
Maize 50% with oat, Pegaz 50%	15	5.96	2.13	0.55	4.77-7.13
Maize 25% with oat, Pegaz 75%	15	5.26	1.91	0.49	4.20-6.32
Maize 75% with wheat, Alba 25%	15	8.03	2.39	0.62	6.70-9.35
Maize 50% with wheat, Alba 50%	15	7.92	2.26	0.58	6.66-9.17
Maize 25% with wheat, Alba 75%	15	8.03	2.04	0.53	6.90-9.15
Maize 75% with soybean 25%	15	6.06	2.27	0.59	4.79-7.31
Maize 50% with soybean 50%	15	3.88	2.14	0.55	2.68-5.06
Maize 25% with soybean 75%	15	2.19	1.87	0.48	1.15-3.22
Rice 75% with soybean 25%	15	8.96	3.40	0.88	7.07-10.84
Rice 50% with soybean 50%	15	4.56	2.47	0.64	3.19-5.92
Rice 25% with soybean 75%	15	2.51	2.22	0.59	1.24-3.76
Maize 50%, rice 25% and soybean 25%	15	8.93	3.55	0.92	6.96-10.89
Maize 25%, rice 50% and soybean 25%	15	9.26	3.43	0.89	7.35-11.15
Maize 25%, rice 25% and soybean 50%	15	6.95	2.20	0.57	5.73-8.17

Table III-73. Mean values of k_3 coefficient, (J g^{-1}/g cm^{-3}); ZD40 press, F_c = 100 kN

Material	No.	Mean	Std. Dev.	Std. Err.	95% confidence interval
Maize meal	15	11.67	2.24	0.58	10.4-12.9
Rice	15	18.05	3.41	0.88	16.1-19.9
Wheat, cv. Alba	15	9.75	1.80	0.46	8.75-10.7
Wheat, cv. Jara	15	11.93	2.28	0.59	10.6-13.1
Wheat, cv. Almary	15	12.47	2.24	0.58	11.2-13.7
Oat, cv. Dragon	15	9.12	0.99	0.26	8.57-9.69
Oat, cv. Pegaz	15	7.70	1.49	0.39	6.87-8.52
Barley, cv. Aramir	15	10.77	2.01	0.52	9.65-11.8
Barley, cv. Ars	15	12.91	1.22	0.31	12.2-13.5
Barley, cv. Edgar	15	10.73	0.82	0.21	10.2-11.1
Barley, cv. Klimek	15	11.20	1.44	0.37	10.4-12.0
Barley, cv. Kos	15	11.49	1.16	0.30	10.8-12.1
Rye cv. Amilo	15	10.96	1.48	0.38	10.1-11.7
Rye cv. Dańkowskie Nowe	15	13.00	2.80	0.72	11.4-14.5
Rye cv. Dańkowskie Złote	15	11.61	1.94	0.50	10.5-12.6
Rye cv. Warko	15	11.27	2.08	0.54	10.1-12.4
Faba bean cv. Nadwiślański	15	14.20	3.06	0.79	12.4-15.8
Pea, cv. Fidelia	15	14.79	4.88	1.26	12.0-17.4
Lupine, cv. Emir	15	11.18	2.62	0.68	9.73-12.6
Vetch, cv. Szelejewska	15	15.39	3.88	1.00	13.2-17.5
Dry plant matter (alfalfa)	15	7.30	1.81	0.47	6.31-8.30
Meat-bone flour	15	5.63	0.47	0.12	5.37-5.88
Soybean meal	9	8.62	1.11	0.34	7.84-9.40
Maize 75% with rice 25%	15	12.40	2.36	0.61	11.0-13.7
Maize 50% with rice 50%	15	13.66	2.28	0.59	12.4-14.9
Maize 25% with rice 75%	15	14.80	2.51	0.65	13.4-16.1
Maize 75% with oat, Pegaz 25%	15	10.06	1.84	0.49	9.04-11.0
Maize 50% with oat, Pegaz 50%	15	9.39	1.65	0.43	8.47-10.3
Maize 25% with oat, Pegaz 75%	15	8.41	1.39	0.36	7.64-9.18
Maize 75% with wheat, Alba 25%	15	10.84	2.12	0.55	9.66-12.0
Maize 50% with wheat, Alba 50%	15	10.55	2.08	0.54	9.39-11.6
Maize 25% with wheat, Alba 75%	15	10.29	1.99	0.51	9.18-11.3
Maize 75% with soybean 25%	15	9.87	1.85	0.48	8.84-10.8
Maize 50% with soybean 50%	15	9.54	1.72	0.44	8.58-10.4
Maize 25% with soybean 75%	15	8.19	1.41	0.36	7.40-8.9
Rice 75% with soybean 25%	15	12.99	3.14	0.81	11.2-14.7
Rice 50% with soybean 50%	15	9.92	1.93	0.50	8.85-10.9
Rice 25% with soybean 75%	15	9.84	1.90	0.49	8.79-10.8
Maize 50%, rice 25% and soybean 25%	15	11.88	2.87	0.74	10.2-13.4
Maize 25%, rice 50% and soybean 25%	15	12.23	2.80	0.72	10.6-13.7
Maize 25%, rice 25% and soybean 50%	15	11.50	2.20	0.57	10.2-12.7

Table III-74. Mean values of the shape retention ability coefficients, k_4; ZD40 press, $F_c = 100$ kN

Material	No.	Mean	Std. Dev.	Std. Err.	95% confidence interval
Maize meal	15	0.011	0.0074	0.0019	0.007-0.015
Rice	15	0.004	0.0010	0.0003	0.003-0.004
Wheat, cv. Alba	15	0.021	0.0085	0.0022	0.016-0.025
Wheat, cv. Jara	15	0.006	0.0025	0.0006	0.005-0.007
Wheat, cv. Almary	15	0.012	0.0066	0.0017	0.008-0.015
Oat, cv. Dragon	15	0.069	0.0110	0.0028	0.062-0.074
Oat, cv. Pegaz	15	0.126	0.0369	0.0095	0.106-0.146
Barley, cv. Aramir	15	0.022	0.0071	0.0018	0.018-0.026
Barley, cv. Ars	15	0.024	0.0069	0.0018	0.020-0.027
Barley, cv. Edgar	15	0.014	0.0069	0.0018	0.010-0.018
Barley, cv. Klimek	15	0.019	0.0100	0.0026	0.014-0.024
Barley, cv. Kos	15	0.016	0.0089	0.0023	0.010-0.020
Rye cv. Amilo	15	0.008	0.0035	0.0009	0.006-0.009
Rye cv. Dańkowskie Nowe	15	0.007	0.0027	0.0007	0.005-0.008
Rye cv. Dańkowskie Złote	15	0.011	0.0051	0.0013	0.008-0.013
Rye cv. Warko	15	0.010	0.0050	0.0013	0.007-0.012
Faba bean cv. Nadwiślański	15	0.028	0.0165	0.0043	0.019-0.037
Pea, cv. Fidelia	15	0.033	0.0209	0.0054	0.021-0.044
Lupine, cv. Emir	15	0.015	0.0119	0.0031	0.008-0.021
Vetch, cv. Szelejewska	15	0.039	0.0226	0.0058	0.026-0.051
Dry plant matter (alfalfa)					
Meat-bone flour	15	0.056	0.0183	0.0047	0.046-0.066
Soybean meal					
Maize 75% with rice 25%	15	0.007	0.0033	0.0009	0.005-0.008
Maize 50% with rice 50%	15	0.005	0.0018	0.0005	0.004-0.005
Maize 25% with rice 75%	15	0.003	0.0013	0.0003	0.002-0.003
Maize 75% with oat, Pegaz 25%	15	0.024	0.0116	0.0030	0.017-0.030
Maize 50% with oat, Pegaz 50%	15	0.057	0.0172	0.0044	0.047-0.066
Maize 25% with oat, Pegaz 75%	15	0.102	0.0247	0.0064	0.088-0.115
Maize 75% with wheat, Alba 25%	15	0.015	0.0068	0.0018	0.011-0.018
Maize 50% with wheat, Alba 50%	15	0.016	0.0057	0.0015	0.012-0.018
Maize 25% with wheat, Alba 75%	15	0.016	0.0047	0.0012	0.013-0.018
Maize 75% with soybean 25%	15	0.019	0.0087	0.0023	0.014-0.023
Maize 50% with soybean 50%	15	0.030	0.0126	0.0032	0.023-0.036
Maize 25% with soybean 75%	15	0.059	0.0369	0.0095	0.039-0.079
Rice 75% with soybean 25%	15	0.014	0.0054	0.0014	0.011-0.016
Rice 50% with soybean 50%	15	0.024	0.0113	0.0029	0.018-0.030
Rice 25% with soybean 75%	15	0.023	0.0141	0.0036	0.015-0.030
Maize 50%, rice 25% and soybean 25%	15	0.025	0.0047	0.0012	0.023-0.027
Maize 25%, rice 50% and soybean 25%	15	0.023	0.0055	0.0014	0.020-0.026
Maize 25%, rice 25% and soybean 50%	15	0.034	0.0088	0.0023	0.029-0.038

Table III-75a. Mean values of confined compression parameters, (at F_{max} = 100 kN), for the materials pelleted on CLM press

Material	W (%)	ρ_b (g cm^{-3})	ρ_c (g cm^{-3})	ρ_k (g cm^{-3})	ρ_{k1} (g cm^{-3})	P_b (MPa)	L_b' (J g^{-1})	L_s' (J g^{-1})	L_c' (J g^{-1})
Maize	11.9	1.49	1.54	1.22	1.15	115.4	8.45	3.05	11.50
Barley	12.7	1.50	1.55	1.20	1.15	127.1	9.83	3.13	12.97
Pea	15.5	1.50	1.55	1.28	1.22	113.4	7.03	3.07	10.10
Soybean meal	13.2	1.46	1.51	1.16	1.05	106.0	6.82	3.40	10.22
Wheat	15.1	1.48	1.54	1.25	1.19	104.1	7.08	3.65	10.73
Rapeseed meal	14	1.44	1.50	1.22	1.05	98.9	6.65	4.30	10.95
Lupine	14.2	1.45	1.53	1.23	1.13	87.2	4.68	4.97	9.65
Wheat bran	14.2	1.47	1.53	1.11	1.02	102.6	7.00	3.75	10.75
Dry plant matter	14.5	1.48	1.56	1.10	0.86	128.6	18.24	4.38	22.62

Table III-75b. Mean values of confined compression parameters, (at F_{max} = 100 kN), for the materials submitted to pelleting on CLM press

Material	w (%)	σ_n (MPa)	k_1 (MPa^{-1})	k_2 (J g^{-1}/g cm^{-3})	k_3 (J g^{-1}/g cm^{-3})	k_4
Maize	11.9	0.24	0.020	9.82	12.70	0.002
Barley	12.7	1.97	0.021	10.43	13.13	0.016
Pea	15.5	2.11	0.019	8.75	11.89	0.019
Soybean meal	13.2	0.12	0.021	8.46	11.95	0.001
Wheat	15.1	0.72	0.023	8.27	11.76	0.007
Rapeseed meal	14	0.11	0.028	7.26	11.22	0.001
Lupine	14.2	3.41	0.028	5.50	10.42	0.039
Wheat bran	14.2	6.23	0.047	5.97	8.76	0.061
Dry plant matter	14.5		0.045	14.89	17.41	

Table III-76. Mean material densities at B point, ρ_b (g cm^{-3}), at different moisture levels; Instron, $F_c = 9$ kN

Material	Moisture content (%)				
	10	12	14	16	18
Barley, cv. Ars	1.27	1.27	1.26	1.30	1.35
Barley, cv. Edgar	1.27	1.29	1.31	1.30	1.33
Barley, cv. Klimek	1.22	1.25	1.28	1.30	1.31
Barley, cv. Kos	1.18	1.22	1.25	1.31	1.36
Rye cv. Amilo	1.10	1.12	1.16	1.21	1.31
Rye cv. Dańkowskie Nowe	1.12	1.14	1.15	1.22	1.32
Rye cv. Dańkowskie Złote	1.17	1.18	1.23	1.29	1.33
Rye cv. Warko	1.19	1.22	1.29	1.33	1.36
Faba bean cv. Nadwiślański	1.23	1.22	1.22	1.31	1.41
Pea, cv. Fidelia	1.18	1.25	1.21	1.18	1.30
Lupine, cv. Emir	1.30	1.31	1.39	1.40	1.40
Vetch, cv. Szelejewska	1.25	1.33	1.37	1.33	1.37
Maize	1.16	1.18	1.20	1.21	1.26
Barley	1.24	1.27	1.28	1.28	1.31
Pea	1.14	1.15	1.16	1.27	1.32
Soybean meal	1.13	1.25	1.32	1.33	1.34
Wheat	1.25	1.28	1.27	1.31	1.32
Rapeseed meal	1.20	1.23	1.25	1.30	1.32
Lupine	1.20	1.24	1.28	1.34	1.38
Meat-bone flour	1.04	1.14	1.21	1.28	1.36

Table III-77. Mean material densities at C point, ρ_c (g·cm^{-3}), at different moisture levels; Instron, $F_c = 9$ kN

Material	Moisture content (%)				
	10	12	14	16	18
Barley, cv. Ars	1.34	1.35	1.34	1.40	1.42
Barley, cv. Edgar	1.33	1.36	1.39	1.37	1.40
Barley, cv. Klimek	1.28	1.32	1.35	1.37	1.37
Barley, cv. Kos	1.25	1.29	1.34	1.40	1.42
Rye cv. Amilo	1.15	1.17	1.23	1.28	1.39
Rye cv. Dańkowskie Nowe	1.18	1.21	1.22	1.30	1.40
Rye cv. Dańkowskie Złote	1.21	1.24	1.30	1.37	1.41
Rye cv. Warko	1.26	1.29	1.37	1.41	1.43
Faba bean cv. Nadwiślański	1.27	1.27	1.26	1.38	1.45
Pea, cv. Fidelia	1.24	1.29	1.26	1.23	1.36
Lupine, cv. Emir	1.37	1.40	1.43	1.45	1.46
Vetch, cv. Szelejewska	1.32	1.41	1.47	1.42	1.46
Maize	1.23	1.29	1.31	1.33	1.38
Barley	1.32	1.37	1.38	1.39	1.41
Pea	1.21	1.23	1.25	1.35	1.39
Soybean meal	1.21	1.37	1.40	1.40	1.42
Wheat	1.34	1.37	1.39	1.44	1.46
Rapeseed meal	1.29	1.34	1.37	1.39	1.41
Lupine	1.29	1.36	1.40	1.43	1.47
Meat-bone flour	1.11	1.25	1.32	1.38	1.45

Table III-78. Mean agglomerate densities, ρ_k (g cm^{-3}), at different moisture levels; Instron, $F = 9$ kN

Material	Moisture content (%)				
	10	12	14	16	18
Barley, cv. Ars	1.12	1.11	1.18	1.20	1.19
Barley, cv. Edgar	1.10	1.19	1.21	1.22	1.20
Barley, cv. Klimek	1.11	1.14	1.20	1.20	1.19
Barley, cv. Kos	1.11	1.17	1.21	1.21	1.19
Rye cv. Amilo	1.11	1.16	1.21	1.21	1.20
Rye cv. Dańkowskie Nowe	1.11	1.14	1.20	1.20	1.19
Rye cv. Dańkowskie Złote	1.10	1.17	1.20	1.21	1.20
Rye cv. Warko	1.12	1.11	1.18	1.21	1.19
Faba bean cv. Nadwiślański			1.18	1.18	1.24
Pea, cv. Fidelia			1.18	1.24	1.26
Lupine, cv. Emir		1.06	1.14	1.12	1.10
Vetch, cv. Szelejewska			1.16	1.22	1.25
Maize				1.14	1.13
Barley			1.07	1.09	1.12
Pea		1.12	1.14	1.22	1.25
Soybean meal	1.02	1.03	1.06	1.10	1.09
Wheat			1.08	1.13	1.15
Rapeseed meal					0.87
Lupine	0.98	0.97	1.07	1.11	1.12
Meat-bone flour		1.00	1.00	0.97	0.94

Table III-79. Mean pressures at B point, P_b (MPa), at different moisture levels; Instron, $F_c = 9$ kN

Material	Moisture content (%)				
	10	12	14	16	18
Barley, cv. Ars	34.89	34.02	33.35	32.18	32.99
Barley, cv. Edgar	35.49	34.31	34.00	33.73	33.07
Barley, cv. Klimek	35.18	34.27	33.43	33.57	32.60
Barley, cv. Kos	32.66	31.65	31.64	30.22	30.34
Rye cv. Amilo	34.07	32.26	31.53	30.55	29.06
Rye cv. Dańkowskie Nowe	32.77	31.59	30.75	29.45	28.21
Rye cv. Dańkowskie Złote	33.63	32.36	31.38	31.45	30.65
Rye cv. Warko	33.39	32.59	31.93	31.16	29.88
Faba bean cv. Nadwiślański	39.12	36.71	37.68	35.13	41.26
Pea, cv. Fidelia	40.27	41.93	37.74	34.37	33.63
Lupine, cv. Emir	37.75	34.51	34.93	33.00	28.42
Vetch, cv. Szelejewska	36.87	36.69	33.62	31.62	29.12
Maize	30.96	29.55	28.14	27.80	27.40
Barley	32.29	30.09	29.43	28.88	27.59
Pea	31.69	29.35	28.19	27.39	24.49
Soybean meal	31.30	30.61	29.91	26.15	22.55
Wheat	30.32	28.52	27.18	26.60	27.13
Rapeseed meal	32.15	31.69	31.16	30.86	28.55
Lupine	32.84	29.78	28.89	28.71	26.23
Meat-bone flour	32.80	30.54	30.31	28.93	27.20

Table III-80. Mean specific compression energies corresponding to B point, L_b' (J g^{-1}), at different moisture levels; Instron, $F_c = 9$ kN

Material	Moisture content (%)				
	10	12	14	16	18
Barley, cv. Ars	4.47	4.50	4.29	4.12	4.20
Barley, cv. Edgar	3.83	3.82	3.92	4.04	4.22
Barley, cv. Klimek	3.78	3.94	3.98	4.10	3.73
Barley, cv. Kos	3.39	3.50	3.65	3.54	3.27
Rye cv. Amilo	3.15	2.94	3.05	3.28	3.17
Rye cv. Dańkowskie Nowe	3.47	3.35	3.18	3.28	3.05
Rye cv. Dańkowskie Złote	3.28	3.31	3.34	3.25	3.25
Rye cv. Warko	3.43	3.29	3.43	3.47	3.17
Faba bean cv. Nadwiślański	3.87	3.55	3.48	3.99	4.64
Pea, cv. Fidelia	5.06	5.44	4.59	3.89	3.74
Lupine, cv. Emir	5.23	4.85	4.05	3.69	2.62
Vetch, cv. Szelejewska	4.41	4.58	4.42	4.18	3.74
Maize	3.24	3.24	3.05	3.05	3.06
Barley	3.99	3.76	3.80	3.80	3.58
Pea	3.26	2.92	3.13	3.01	2.31
Soybean meal	4.16	4.48	4.00	2.75	2.15
Wheat	3.12	2.85	2.92	2.97	3.21
Rapeseed meal	4.62	4.55	4.41	4.02	3.37
Lupine	4.03	3.88	3.88	3.59	2.92
Meat-bone flour	3.70	3.89	4.04	3.59	3.02

Table III-81. Mean specific compaction energies, L_s' (J g^{-1}), (from B to C point), at different moisture levels; Instron, $F_c = 9$ kN

Material	Moisture content (%)				
	10	12	14	16	18
Barley, cv. Ars	2.17	2.25	2.31	2.57	1.79
Barley, cv. Edgar	1.73	1.87	1.89	1.88	1.75
Barley, cv. Klimek	1.79	1.90	1.94	1.86	1.48
Barley, cv. Kos	2.00	2.12	2.06	2.03	1.42
Rye cv. Amilo	1.68	1.81	1.90	1.81	1.87
Rye cv. Dańkowskie Nowe	2.07	2.26	2.25	2.18	1.80
Rye cv. Dańkowskie Złote	1.81	1.94	2.00	1.92	1.59
Rye cv. Warko	1.89	1.95	2.03	1.87	1.54
Faba bean cv. Nadwiślański	1.27	1.48	1.34	1.56	0.95
Pea, cv. Fidelia	1.37	1.15	1.43	1.49	1.44
Lupine, cv. Emir	1.70	2.12	0.99	0.94	1.04
Vetch, cv. Szelejewska	1.78	1.86	2.03	1.95	1.72
Maize	2.38	2.64	2.77	2.78	2.73
Barley	2.22	2.47	2.53	2.43	2.22
Pea	2.11	2.40	2.42	1.75	1.40
Soybean meal	2.92	2.69	1.87	1.52	1.51
Wheat	2.19	2.36	2.57	2.68	2.56
Rapeseed meal	2.70	2.80	2.70	2.09	1.86
Lupine	2.34	2.86	2.58	1.81	1.54
Meat-bone flour	2.63	3.03	2.61	2.06	1.73

Table III-82. Mean total specific compression energies, L_c' (J g^{-1}), (corresponding to C point of the compression characteristic), at different moisture levels; Instron, F_c = 9 kN

Material	Moisture content (%)				
	10	12	14	16	18
Barley, cv. Ars	6.63	6.74	6.59	6.70	5.99
Barley, cv. Edgar	5.56	5.69	5.82	5.92	5.96
Barley, cv. Klimek	5.57	5.84	5.93	5.96	5.21
Barley, cv. Kos	5.39	5.62	5.71	5.58	4.69
Rye cv. Amilo	4.83	4.75	4.95	5.09	5.03
Rye cv. Dańkowskie Nowe	5.54	5.61	5.43	5.46	4.85
Rye cv. Dańkowskie Złote	5.09	5.24	5.35	5.17	4.84
Rye cv. Warko	5.32	5.24	5.45	5.34	4.70
Faba bean cv. Nadwiślański	5.14	5.03	4.81	5.56	5.59
Pea, cv. Fidelia	6.43	6.60	6.02	5.38	5.18
Lupine, cv. Emir	6.93	6.96	5.04	4.63	3.66
Vetch, cv. Szelejewska	6.19	6.45	6.45	6.14	5.46
Maize	5.62	5.88	5.82	5.83	5.79
Barley	6.21	6.23	6.32	6.24	5.80
Pea	5.38	5.32	5.55	4.76	3.72
Soybean meal	7.08	7.17	5.87	4.27	3.66
Wheat	5.30	5.21	5.49	5.65	5.77
Rapeseed meal	7.32	7.34	7.11	6.11	5.24
Lupine	6.37	6.74	6.47	5.39	4.46
Meat-bone flour	6.33	6.92	6.66	5.65	4.75

Table III-83. Mean agglomerate compressive strength, σ_n (MPa), at different moisture levels; Instron, F_c = 9 kN

Material	Moisture content (%)				
	10	12	14	16	18
Barley, cv. Ars				3.87	3.51
Barley, cv. Edgar			2.84	2.64	1.40
Barley, cv. Klimek			2.90	2.69	3.19
Barley, cv. Kos			2.98	3.20	2.86
Rye cv. Amilo			1.07	1.62	1.40
Rye cv. Dańkowskie Nowe		0.22	1.00	1.65	1.63
Rye cv. Dańkowskie Złote		0.94	1.65	2.15	1.97
Rye cv. Warko			1.86	2.26	2.26
Faba bean cv. Nadwiślański			0.16	0.49	2.59
Pea, cv. Fidelia			0.43	2.88	3.79
Lupine, cv. Emir		0.50	1.47	1.36	1.91
Vetch, cv. Szelejewska			0.37	1.69	4.04
Maize				0.29	0.54
Barley			1.05	1.70	2.03
Pea		0.32	1.46	4.11	4.74
Soybean meal		0.16	0.67	2.02	2.01
Wheat			0.29	0.68	1.17
Rapeseed meal					2.36
Lupine	0.68	1.44	2.96	4.75	4.36
Meat-bone flour		1.15	1.22	1.26	0.76

Table III-84. Mean values of the material compression ability coefficient, k_1 (MPa^{-1}), at different moisture levels; Instron, $F_c = 9$ kN

Material	Moisture content (%)				
	10	12	14	16	18
Barley, cv. Ars	0.071	0.074	0.075	0.078	0.081
Barley, cv. Edgar	0.067	0.069	0.074	0.074	0.078
Barley, cv. Klimek	0.066	0.068	0.071	0.076	0.079
Barley, cv. Kos	0.064	0.067	0.072	0.080	0.083
Rye cv. Amilo	0.051	0.054	0.057	0.063	0.075
Rye cv. Dańkowskie Nowe	0.051	0.053	0.058	0.065	0.074
Rye cv. Dańkowskie Złote	0.052	0.054	0.061	0.064	0.068
Rye cv. Warko	0.057	0.062	0.067	0.074	0.080
Faba bean cv. Nadwiślański	0.039	0.042	0.042	0.051	0.049
Pea, cv. Fidelia	0.039	0.039	0.042	0.049	0.057
Lupine, cv. Emir	0.059	0.065	0.069	0.076	0.093
Vetch, cv. Szelejewska	0.044	0.046	0.056	0.059	0.071
Maize	0.060	0.063	0.068	0.071	0.077
Barley	0.070	0.076	0.079	0.084	0.091
Pea	0.048	0.052	0.056	0.067	0.081
Soybean meal	0.054	0.061	0.068	0.079	0.096
Wheat	0.062	0.068	0.073	0.078	0.079
Rapeseed meal	0.069	0.071	0.076	0.082	0.092
Lupine	0.059	0.068	0.074	0.079	0.090
Meat-bone flour	0.052	0.054	0.063	0.074	0.086

Table III-85. Mean values of k_2 coefficient, ($\text{J g}^{-1}/\text{g cm}^{-3}$), at different moisture levels; Instron, $F_c = 9$ kN

Material	Moisture content (%)				
	10	12	14	16	18
Barley, cv. Ars	5.91	5.89	5.66	5.24	5.00
Barley, cv. Edgar	5.18	5.11	4.96	5.20	5.17
Barley, cv. Klimek	5.47	5.55	5.40	5.18	4.68
Barley, cv. Kos	5.48	5.44	5.21	4.59	3.99
Rye cv. Amilo	6.75	6.16	5.86	5.68	4.47
Rye cv. Dańkowskie Nowe	7.70	7.30	6.33	5.69	4.46
Rye cv. Dańkowskie Złote	6.57	6.59	5.74	4.99	4.67
Rye cv. Warko	6.01	5.35	4.97	4.59	4.00
Faba bean cv. Nadwiślański	8.95	8.27	7.73	6.82	6.52
Pea, cv. Fidelia	11.91	11.47	10.33	8.15	5.99
Lupine, cv. Emir	7.32	6.67	4.99	4.38	3.00
Vetch, cv. Szelejewska	9.09	8.43	6.92	6.81	5.26
Maize	6.09	6.00	5.34	5.08	4.64
Barley	5.78	5.27	5.19	5.06	4.57
Pea	8.38	7.32	7.29	5.20	3.54
Soybean meal	8.93	7.68	5.99	4.00	2.99
Wheat	5.31	4.62	4.67	4.38	4.56
Rapeseed meal	7.03	6.72	6.08	5.13	4.14
Lupine	6.86	6.22	5.70	4.79	3.66
Meat-bone flour	8.64	8.64	7.00	5.27	3.89

Table III-86. Mean values of k_3 coefficient, (J g^{-1}/g cm^{-3}), at different moisture levels; Instron, $F_c = 9$ kN

Material	Moisture content (%)				
	10	12	14	16	18
Barley, cv. Ars	8.00	8.00	7.83	7.55	6.55
Barley, cv. Edgar	6.97	6.94	6.71	6.97	6.71
Barley, cv. Klimek	7.38	7.52	7.33	6.92	6.08
Barley, cv. Kos	7.84	7.83	7.30	6.47	5.31
Rye cv. Amilo	9.41	8.93	8.50	7.82	6.39
Rye cv. Dańkowskie Nowe	10.81	10.59	9.42	8.27	6.35
Rye cv. Dańkowskie Złote	9.32	9.32	8.13	7.11	6.28
Rye cv. Warko	8.40	7.64	7.05	6.38	5.45
Faba bean cv. Nadwiślański	10.78	10.44	9.69	8.52	7.42
Pea, cv. Fidelia	13.10	12.82	12.19	10.19	7.55
Lupine, cv. Emir	8.84	8.50	5.88	5.21	3.96
Vetch, cv. Szelejewska	11.20	10.33	8.75	8.69	6.83
Maize	9.29	9.05	8.54	8.12	7.40
Barley	8.04	7.65	7.56	7.25	6.53
Pea	11.71	11.16	10.66	7.29	5.15
Soybean meal	12.83	10.28	7.85	5.61	4.59
Wheat	7.82	7.34	7.35	6.96	6.87
Rapeseed meal	9.74	9.26	8.44	6.95	5.78
Lupine	9.42	9.04	8.08	6.42	5.03
Meat-bone flour	12.66	12.39	9.72	7.29	5.51

Table III-87. Mean values of the shape retention ability coefficients, k_4, at different moisture levels; Instron, $F_c = 9$ kN

Material	Moisture content (%)				
	10	12	14	16	18
Barley, cv. Ars				0.120	0.107
Barley, cv. Edgar			0.083	0.078	0.042
Barley, cv. Klimek			0.087	0.080	0.098
Barley, cv. Kos			0.094	0.106	0.095
Rye cv. Amilo			0.034	0.053	0.048
Rye cv. Dańkowskie Nowe		0.007	0.032	0.056	0.058
Rye cv. Dańkowskie Złote		0.029	0.053	0.068	0.064
Rye cv. Warko			0.058	0.072	0.075
Faba bean cv. Nadwiślański			0.004	0.014	0.063
Pea, cv. Fidelia			0.011	0.084	0.113
Lupine, cv. Emir		0.014	0.042	0.041	0.067
Vetch, cv. Szelejewska			0.011	0.054	0.139
Maize				0.010	0.020
Barley	0.000	0.000	0.036	0.059	0.073
Pea		0.011	0.052	0.150	0.194
Soybean meal		0.005	0.022	0.077	0.089
Wheat			0.011	0.025	0.043
Rapeseed meal					0.082
Lupine	0.021	0.048	0.103	0.166	0.166
Meat-bone flour		0.038	0.041	0.044	0.028

Table III-88. Mean material densities at B point, ρ_b (g cm^{-3}); Instron, F_c = 9 kN

Material	No	Mean	Std. Dev.	Std. Err.	95% conf. interval
Barley, cv. Ars	15	1.29	0.040	0.010	1.27-1.31
Barley, cv. Edgar	15	1.30	0.022	0.006	1.29-1.31
Barley, cv. Klimek	15	1.27	0.041	0.011	1.25-1.29
Barley, cv. Kos	15	1.26	0.067	0.017	1.23-1.30
Rye cv. Amilo	15	1.18	0.078	0.020	1.14-1.22
Rye cv. Dańkowskie Nowe	15	1.19	0.078	0.020	1.15-1.23
Rye cv. Dańkowskie Złote	15	1.24	0.067	0.017	1.20-1.28
Rye cv. Warko	15	1.28	0.066	0.017	1.24-1.31
Faba bean cv. Nadwiślański	15	1.28	0.078	0.020	1.23-1.32
Pea, cv. Fidelia	15	1.22	0.053	0.014	1.19-1.25
Lupine, cv. Emir	15	1.36	0.050	0.013	1.33-1.39
Vetch, cv. Szelejewska	15	1.33	0.047	0.012	1.30-1.35
Maize	15	1.20	0.036	0.009	1.18-1.22
Barley	15	1.28	0.027	0.007	1.26-1.29
Pea	15	1.21	0.078	0.020	1.17-1.25
Soybean meal	15	1.27	0.082	0.021	1.23-1.32
Wheat	15	1.29	0.031	0.008	1.27-1.30
Rapeseed meal	15	1.26	0.046	0.012	1.23-1.28
Lupine	15	1.29	0.068	0.018	1.25-1.33
Meat-bone flour	15	1.21	0.117	0.030	1.14-1.27

Table III-89. Mean material densities at C point, ρ_c (g cm^{-3}); Instron, F_c = 9 kN

Material	No	Mean	Std. Dev.	Std. Err.	95% conf. interval
Barley, cv. Ars	15	1.37	0.040	0.010	1.35-1.39
Barley, cv. Edgar	15	1.37	0.027	0.007	1.36-1.39
Barley, cv. Klimek	15	1.34	0.042	0.011	1.31-1.36
Barley, cv. Kos	15	1.34	0.068	0.017	1.30-1.38
Rye cv. Amilo	15	1.24	0.090	0.023	1.19-1.29
Rye cv. Dańkowskie Nowe	15	1.26	0.084	0.022	1.22-1.31
Rye cv. Dańkowskie Złote	15	1.31	0.077	0.020	1.26-1.35
Rye cv. Warko	15	1.35	0.071	0.018	1.31-1.39
Faba bean cv. Nadwiślański	15	1.33	0.079	0.020	1.28-1.37
Pea, cv. Fidelia	15	1.27	0.053	0.014	1.25-1.30
Lupine, cv. Emir	15	1.42	0.037	0.010	1.40-1.44
Vetch, cv. Szelejewska	15	1.41	0.058	0.015	1.38-1.45
Maize	15	1.31	0.051	0.013	1.28-1.34
Barley	15	1.38	0.033	0.008	1.36-1.40
Pea	15	1.29	0.075	0.019	1.24-1.33
Soybean meal	15	1.36	0.078	0.020	1.32-1.40
Wheat	15	1.40	0.047	0.012	1.37-1.43
Rapeseed meal	15	1.36	0.043	0.011	1.34-1.38
Lupine	15	1.39	0.064	0.016	1.36-1.43
Meat-bone flour	15	1.30	0.120	0.031	1.23-1.37

Table III-90. Mean agglomerate densities, ρ_k (g cm^{-3}); Instron, F_c = 9 kN

Material	No	Mean	Std. Dev.	Std Err.	95% conf. interval
Barley, cv. Ars	15	1.16	0.038	0.010	1.139-1.181
Barley, cv. Edgar	15	1.18	0.043	0.011	1.159-1.207
Barley, cv. Klimek	15	1.17	0.040	0.010	1.145-1.190
Barley, cv. Kos	15	1.18	0.040	0.010	1.157-1.202
Rye cv. Amilo	15	1.18	0.041	0.010	1.155-1.200
Rye cv. Dańkowskie Nowe	15	1.17	0.041	0.011	1.146-1.191
Rye cv. Dańkowskie Złote	15	1.17	0.048	0.012	1.148-1.201
Rye cv. Warko	15	1.16	0.040	0.010	1.139-1.183
Faba bean cv. Nadwiślański	9	1.20	0.036	0.012	1.169-1.224
Pea, cv. Fidelia	9	1.23	0.039	0.013	1.197-1.256
Lupine, cv. Emir	12	1.11	0.035	0.010	1.083-1.127
Vetch, cv. Szelejewska	9	1.21	0.059	0.020	1.162-1.253
Maize	6	1.13	0.009	0.004	1.122-1.140
Barley	9	1.09	0.028	0.009	1.070-1.113
Pea	12	1.18	0.059	0.017	1.146-1.220
Soybean meal	15	1.06	0.032	0.008	1.043-1.078
Wheat	9	1.12	0.035	0.012	1.094-1.148
Rapeseed meal	3	0.87	0.014	0.008	0.834-0.903
Lupine	15	1.05	0.069	0.018	1.010-1.086
Meat-bone flour	12	0.98	0.036	0.010	0.953-0.999

Table III-91. Mean pressures at B point, P_b (MPa); Instron, F_c = 9 kN

Material	No	Mean	Std. Dev.	Std Err.	95% conf. interval
Barley, cv. Ars	15	33.49	1.214	0.313	32.81-34.16
Barley, cv. Edgar	15	34.12	0.917	0.237	33.61-34.63
Barley, cv. Klimek	15	33.81	0.927	0.239	33.30-34.32
Barley, cv. Kos	15	31.30	1.269	0.328	30.60-32.00
Rye cv. Amilo	15	31.49	1.762	0.455	30.52-32.47
Rye cv. Dańkowskie Nowe	15	30.55	1.669	0.431	29.63-31.48
Rye cv. Dańkowskie Złote	15	31.89	1.157	0.299	31.25-32.54
Rye cv. Warko	15	31.79	1.322	0.341	31.06-32.52
Faba bean cv. Nadwiślański	15	37.98	2.214	0.572	36.76-39.21
Pea, cv. Fidelia	15	37.59	3.356	0.867	35.73-39.45
Lupine, cv. Emir	15	33.72	3.232	0.834	31.93-35.51
Vetch, cv. Szelejewska	15	33.59	3.115	0.804	31.86-35.31
Maize	15	28.77	1.377	0.356	28.01-29.53
Barley	15	29.66	1.694	0.437	28.72-30.60
Pea	15	28.22	2.521	0.651	26.82-29.62
Soybean meal	15	28.11	3.448	0.890	26.20-30.02
Wheat	15	27.95	1.467	0.379	27.14-28.76
Rapeseed meal	15	30.88	1.344	0.347	30.14-31.63
Lupine	15	29.29	2.263	0.584	28.04-30.54
Meat-bone flour	15	29.96	1.972	0.509	28.86-31.05

Table III-92. Mean specific compression energies corresponding to the B point, L_b' (J g^{-1}); Instron, F_c = 9 kN

Material	No	Mean	Std. Dev.	Std Err.	95% conf. interval
Barley, cv. Ars	15	4.31	0.21	0.05	4.20-4.43
Barley, cv. Edgar	15	3.97	0.17	0.04	3.87-4.06
Barley, cv. Klimek	15	3.91	0.15	0.04	3.82-3.99
Barley, cv. Kos	15	3.47	0.16	0.04	3.38-3.56
Rye cv. Amilo	15	3.12	0.13	0.03	3.05-3.19
Rye cv. Dańkowskie Nowe	15	3.27	0.17	0.04	3.17-3.36
Rye cv. Dańkowskie Złote	15	3.29	0.08	0.02	3.24-3.33
Rye cv. Warko	15	3.36	0.14	0.04	3.28-3.44
Faba bean cv. Nadwiślański	15	3.91	0.44	0.11	3.66-4.15
Pea, cv. Fidelia	15	4.55	0.70	0.18	4.16-4.93
Lupine, cv. Emir	15	4.09	0.96	0.25	3.56-4.62
Vetch, cv. Szelejewska	15	4.27	0.33	0.09	4.08-4.45
Maize	15	3.13	0.11	0.03	3.07-3.19
Barley	15	3.79	0.16	0.04	3.70-3.88
Pea	15	2.93	0.35	0.09	2.73-3.12
Soybean meal	15	3.51	0.93	0.24	3.00-4.02
Wheat	15	3.01	0.16	0.04	2.93-3.10
Rapeseed meal	15	4.19	0.48	0.12	3.93-4.46
Lupine	15	3.66	0.42	0.11	3.43-3.89
Meat-bone flour	15	3.65	0.37	0.10	3.44-3.85

Table III-93. Mean specific compaction energies, L_s' (J g^{-1}), (from B to C point); Instron, F_c = 9 kN

Material	No	Mean	Std. Dev.	Std Err.	95% conf. interval
Barley, cv. Ars	15	2.22	0.29	0.08	2.06-2.38
Barley, cv. Edgar	15	1.82	0.10	0.03	1.77-1.88
Barley, cv. Klimek	15	1.80	0.18	0.05	1.70-1.89
Barley, cv. Kos	15	1.93	0.28	0.07	1.77-2.08
Rye cv. Amilo	15	1.81	0.10	0.03	1.75-1.87
Rye cv. Dańkowskie Nowe	15	2.11	0.18	0.05	2.01-2.21
Rye cv. Dańkowskie Złote	15	1.85	0.16	0.04	1.76-1.94
Rye cv. Warko	15	1.85	0.18	0.05	1.75-1.95
Faba bean cv. Nadwiślański	15	1.32	0.22	0.06	1.20-1.44
Pea, cv. Fidelia	15	1.38	0.13	0.03	1.30-1.45
Lupine, cv. Emir	15	1.36	0.49	0.13	1.09-1.63
Vetch, cv. Szelejewska	15	1.87	0.14	0.04	1.79-1.95
Maize	15	2.66	0.16	0.04	2.57-2.75
Barley	15	2.37	0.15	0.04	2.29-2.46
Pea	15	2.02	0.41	0.11	1.79-2.24
Soybean meal	15	2.10	0.62	0.16	1.76-2.44
Wheat	15	2.47	0.19	0.05	2.37-2.58
Rapeseed meal	15	2.43	0.40	0.10	2.21-2.65
Lupine	15	2.23	0.51	0.13	1.94-2.51
Meat-bone flour	15	2.41	0.48	0.13	2.15-2.68

Table III-94. Mean total specific compression energies, L_c' (J g^{-1}), (corresponding to the C point of compression characteristic); Instron, $F_c = 9$ kN

Material	No.	Mean	Std. Dev.	Std Err.	95% conf. interval
Barley, cv. Ars	15	6.53	0.31	0.08	6.36-6.70
Barley, cv. Edgar	15	5.79	0.17	0.05	5.69-5.89
Barley, cv. Klimek	15	5.70	0.30	0.08	5.53-5.87
Barley, cv. Kos	15	5.40	0.38	0.10	5.18-5.61
Rye cv. Amilo	15	4.93	0.15	0.04	4.85-5.02
Rye cv. Dańkowskie Nowe	15	5.38	0.29	0.08	5.22-5.54
Rye cv. Dańkowskie Złote	15	5.14	0.20	0.05	5.03-5.25
Rye cv. Warko	15	5.21	0.28	0.07	5.05-5.37
Faba bean cv. Nadwiślański	15	5.23	0.33	0.08	5.04-5.41
Pea, cv. Fidelia	15	5.92	0.62	0.16	5.58-6.26
Lupine, cv. Emir	15	5.45	1.36	0.35	4.70-6.20
Vetch, cv. Szelejewska	15	6.14	0.42	0.11	5.91-6.37
Maize	15	5.79	0.11	0.03	5.72-5.85
Barley	15	6.16	0.21	0.06	6.05-6.28
Pea	15	4.94	0.70	0.18	4.56-5.33
Soybean meal	15	5.61	1.49	0.38	4.79-6.43
Wheat	15	5.48	0.24	0.06	5.35-5.61
Rapeseed meal	15	6.62	0.86	0.22	6.15-7.10
Lupine	15	5.89	0.88	0.23	5.40-6.37
Meat-bone flour	15	6.06	0.82	0.21	5.61-6.51

Table III-95. Mean agglomerate compressive strength, σ_n (MPa); Instron, $F_c = 9$ kN

Material	No.	Mean	Std. Dev.	Std Err.	95% conf. interval
Barley, cv. Ars	6	3.69	0.30	0.12	3.38-4.00
Barley, cv. Edgar	9	2.30	0.72	0.24	1.75-2.85
Barley, cv. Klimek	9	2.93	0.59	0.20	2.48-3.38
Barley, cv. Kos	9	3.01	0.24	0.08	2.83-3.20
Rye cv. Amilo	9	1.36	0.31	0.10	1.12-1.60
Rye cv. Dańkowskie Nowe	12	1.12	0.62	0.18	0.73-1.52
Rye cv. Dańkowskie Złote	12	1.68	0.49	0.14	1.37-1.99
Rye cv. Warko	9	2.12	0.28	0.10	1.91-2.34
Faba bean cv. Nadwiślański	9	1.08	1.20	0.40	0.16-2.00
Pea, cv. Fidelia	9	2.37	1.53	0.51	1.19-3.54
Lupine, cv. Emir	12	1.31	0.67	0.19	0.88-1.74
Vetch, cv. Szelejewska	9	2.03	1.70	0.57	0.73-3.33
Maize	6	0.41	0.17	0.07	0.24-0.59
Barley	9	1.59	0.49	0.16	1.22-1.96
Pea	12	2.66	1.91	0.55	1.44-3.87
Soybean meal	12	1.21	0.87	0.25	0.66-1.76
Wheat	9	0.71	0.39	0.13	0.42-1.01
Rapeseed meal	3	2.36	0.50	0.29	1.12-3.60
Lupine	15	2.84	1.66	0.43	1.92-3.76
Meat-bone flour	12	1.10	0.29	0.08	0.91-1.28

Table III-96. Mean values of the material compression ability coefficient, k_1 (MPa^{-1}); Instron, $F_c = 9$ kN

Material	No.	Mean	Std. Dev.	Std Err.	95% conf. interval
Barley, cv. Ars	15	0.076	0.004	0.001	0.074-0.078
Barley, cv. Edgar	15	0.072	0.004	0.001	0.070-0.075
Barley, cv. Klimek	15	0.072	0.005	0.001	0.069-0.075
Barley, cv. Kos	15	0.073	0.008	0.002	0.069-0.078
Rye cv. Amilo	15	0.060	0.009	0.002	0.055-0.065
Rye cv. Dańkowskie Nowe	15	0.060	0.009	0.002	0.055-0.065
Rye cv. Dańkowskie Złote	15	0.060	0.006	0.002	0.056-0.063
Rye cv. Warko	15	0.068	0.009	0.002	0.064-0.073
Faba bean cv. Nadwiślański	15	0.045	0.005	0.001	0.042-0.047
Pea, cv. Fidelia	15	0.045	0.007	0.002	0.041-0.049
Lupine, cv. Emir	15	0.072	0.012	0.003	0.066-0.079
Vetch, cv. Szelejewska	15	0.055	0.010	0.003	0.050-0.061
Maize	15	0.068	0.006	0.002	0.064-0.071
Barley	15	0.080	0.007	0.002	0.076-0.084
Pea	15	0.061	0.012	0.003	0.054-0.068
Soybean meal	15	0.072	0.015	0.004	0.063-0.080
Wheat	15	0.072	0.007	0.002	0.068-0.076
Rapeseed meal	15	0.078	0.009	0.002	0.073-0.083
Lupine	15	0.074	0.011	0.003	0.068-0.080
Meat-bone flour	15	0.066	0.013	0.003	0.058-0.073

Table III-97. Mean values of the k_2 coefficient, (J g^{-1}/g cm^{-3}); Instron, $F_c = 9$ kN

Material	No.	Mean	Std. Dev.	Std Err.	95% conf. interval
Barley, cv. Ars	15	5.54	0.42	0.11	5.31-5.77
Barley, cv. Edgar	15	5.13	0.14	0.04	5.05-5.20
Barley, cv. Klimek	15	5.26	0.37	0.10	5.05-5.46
Barley, cv. Kos	15	4.94	0.61	0.16	4.61-5.28
Rye cv. Amilo	15	5.78	0.79	0.20	5.35-6.22
Rye cv. Dańkowskie Nowe	15	6.30	1.21	0.31	5.63-6.96
Rye cv. Dańkowskie Złote	15	5.71	0.83	0.21	5.25-6.17
Rye cv. Warko	15	4.98	0.72	0.19	4.59-5.38
Faba bean cv. Nadwiślański	15	7.66	0.95	0.25	7.13-8.18
Pea, cv. Fidelia	15	9.57	2.35	0.61	8.27-10.87
Lupine, cv. Emir	15	5.27	1.62	0.42	4.37-6.17
Vetch, cv. Szelejewska	15	7.30	1.42	0.37	6.51-8.08
Maize	15	5.43	0.58	0.15	5.11-5.75
Barley	15	5.17	0.43	0.11	4.94-5.41
Pea	15	6.35	1.81	0.47	5.35-7.35
Soybean meal	15	5.92	2.29	0.59	4.65-7.18
Wheat	15	4.71	0.35	0.09	4.51-4.90
Rapeseed meal	15	5.82	1.10	0.29	5.21-6.43
Lupine	15	5.44	1.17	0.30	4.80-6.09
Meat-bone flour	15	6.69	1.94	0.50	5.61-7.76

Table III-98. Mean values of the k_3 coefficient, (J g^{-1}/g cm^{-3}); Instron, F_c = 9 kN

Material	No.	Mean	Std. Dev.	Std Err.	95% conf. interval
Barley, cv. Ars	15	7.58	0.61	0.16	7.24-7.92
Barley, cv. Edgar	15	6.86	0.17	0.04	6.77-6.95
Barley, cv. Klimek	15	7.05	0.59	0.15	6.72-7.37
Barley, cv. Kos	15	6.95	1.01	0.26	6.39-7.51
Rye cv. Amilo	15	8.21	1.10	0.28	7.60-8.82
Rye cv. Dańkowskie Nowe	15	9.09	1.71	0.44	8.14-10.03
Rye cv. Dańkowskie Złote	15	8.03	1.26	0.32	7.34-8.73
Rye cv. Warko	15	6.99	1.06	0.27	6.40-7.57
Faba bean cv. Nadwiślański	15	9.37	1.30	0.34	8.65-10.09
Pea, cv. Fidelia	15	11.17	2.17	0.56	9.97-12.37
Lupine, cv. Emir	15	6.48	1.97	0.51	5.39-7.57
Vetch, cv. Szelejewska	15	9.16	1.59	0.41	8.28-10.04
Maize	15	8.48	0.71	0.18	8.09-8.87
Barley	15	7.41	0.53	0.14	7.11-7.70
Pea	15	9.19	2.63	0.68	7.74-10.65
Soybean meal	15	8.23	3.13	0.81	6.50-9.97
Wheat	15	7.27	0.37	0.10	7.06-7.47
Rapeseed meal	15	8.03	1.53	0.40	7.19-8.88
Lupine	15	7.60	1.71	0.44	6.65-8.55
Meat-bone flour	15	9.51	2.90	0.75	7.91-11.12

Table III-99. Mean values of the shape retention ability coefficient, k_4; Instron, F_c = 9 kN

Material	No.	Mean	Std. Dev.	Std Err.	95% conf. interval
Barley, cv. Ars	6	0.113	0.011	0.004	0.102-0.125
Barley, cv. Edgar	9	0.068	0.020	0.007	0.052-0.084
Barley, cv. Klimek	9	0.088	0.018	0.006	0.074-0.102
Barley, cv. Kos	9	0.098	0.009	0.003	0.091-0.105
Rye cv. Amilo	9	0.045	0.011	0.004	0.037-0.053
Rye cv. Dańkowskie Nowe	12	0.038	0.022	0.006	0.024-0.052
Rye cv. Dańkowskie Złote	12	0.054	0.016	0.005	0.043-0.064
Rye cv. Warko	9	0.069	0.010	0.003	0.061-0.076
Faba bean cv. Nadwiślański	9	0.027	0.029	0.010	0.005-0.049
Pea, cv. Fidelia	9	0.069	0.046	0.015	0.034-0.105
Lupine, cv. Emir	12	0.041	0.024	0.007	0.026-0.056
Vetch, cv. Szelejewska	9	0.068	0.059	0.020	0.022-0.113
Maize	6	0.015	0.006	0.003	0.008-0.021
Barley	15	0.034	0.032	0.008	0.016-0.051
Pea	12	0.102	0.077	0.022	0.053-0.151
Soybean meal	12	0.048	0.038	0.011	0.025-0.072
Wheat	9	0.026	0.014	0.005	0.015-0.037
Rapeseed meal	3	0.082	0.018	0.010	0.039-0.126
Lupine	15	0.101	0.062	0.016	0.066-0.135
Meat-bone flour	12	0.037	0.009	0.003	0.032-0.043

Address of Authors

Grzegorz Łysiak
Janusz Laskowski
Stanisław Skonecki
Department of Equipment Operation and Maintenance in Food Industry, Agricultural University
ul. Doświadczalna 44, 20-236 Lublin, Poland
tel. +48 81 4610061 fax +48 81 4610689
e-mail: grzegorz.lysiak@ar.lublin.pl