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INVESTIGATION ON THE MECHANICS OF WOOD PELLET PRODUCTION FROM SAWDUST AND CHIPS

Zoltán KOCSIS and Etele CSANÁDY

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INTRODUCTION

The wood – as a complex structured biomechanical system – behavior does not characterized by some physical constants such as in the case of metals. Mechanical properties are not constant, but depend on a variety of factors. Still rises many questions resulting from the above that the wood with the various external and internal forces acting on related behavior. That's why the importance of basic research has appreciated. The result of the wood complexity, during the negotiations of mechanics has to make relatively large number of assumptions and the results obtained are valid only in the given conditions. Often have to resort to empirical methods that we could write to the observed phenomena. Whereas purely theoretical considerations are seldom suitable results therefore the experimental investigations are particularly important. It is very important to evaluate the test that we have to accurately record all the characteristics of the material which influence the results (wood species, moisture content, particle size, density, load, etc.). The high-pressure compaction process of wood chips and dust sets related the domestic and foreign researches are incomplete. In order to facilitate the sequential use of pellets – as a renewable energy source – firstly needed a well-designed state support and incentive system, secondly a targeted basic research.

The mechanical properties of high pressure produced pellets depend on many factors. The most influencing factors are the type of wood, particle size, moisture content, the pressing pressure, the pressing speed, the deformation holding time, the punch diameter and the press temperature. Description of resulting mechanical changes during high pressure compression of wood chips and dust sets stress (σ) - deformation (ε) relationship happen by non-linear rheological methods, because the wood has non-linear viscoelastic property. Consequently, during the compression process greatly increases the elastic modulus of wood chips and dust set, and the resulted pellet at the end of the process suffers residual deformation. The rates of residual deformation determine the properties of pellet, especially density. The research considers it highly important, examining the impact of influencing factors at compression process of wood chips and dust sets and then the development of new mechanical models based on the received results. In the first part of the research we used dimensional analysis to describe the energy consumption of the pressing of pellets resulting in similarity equation. Independently from the species of wood it is possible to calculate the energy consumption of the press. In the following the calculation for the relative friction of the side wall of the channels was worked out. This model was used to determine the component of the modulus of elasticity from the deformation during the compression process. This component causes the side wall friction when the pellets are pushed out. The model is described in a dimensionless form. This friction force gives the counterforce at a given pressure and at different pellet diameters. Finally, we measured and cleared the effects of moisture content of the raw material on the minimum compaction pressure providing stabile pellets. The moisture content of the raw material affects the mechanical stability of the pellets and allows the use of moisture contents in a limited range.

MATERIALS AND METHODS

The quality of the pellet meets the European norms for (EN 14961-1:2011). The optimum diameter (6 mm) and length (20-30 mm) of the pellets are fixed in this norm. We constructed press heads, that had diameter of 6 mm, 8 mm and 16 mm and compressing channel length was 115 mm, this parameters are the same as the industry norm. In measurements we used a universal testing machine (Instron). The pressing velocity was 10 mm/min, which is the same as the industrie norm. We used pressure parameters between 100-140 MPa, but also for special purposes between 30-300 MPa. We controlled and measured the temperature of the press head with a control system. Chips and sawdust are produced from spruce (*Picea abies*) and black locust (*Robinia pseudoacacia*) with 10-12% moisture content. In the final measuring process we changed the moisture content of the raw material between 5-15%. After the post chopping the raw material was put through a sieve vibrating 1.5 mm amplitude at for 10 minutes. This produced 4 different particle sizes: 0.063-0.2mm; 0.2-0.5 mm; 0.5-0.8 mm and 0.8-1.0 mm net. We demonstrate the cumulative curve (spruce and black locust chip) using the lognormal integral distribution on a probability net. Average values were calculated from sieve analysis (Fig. 2 broken line).

Fig. 1 Punch and the temperature control and measurement system

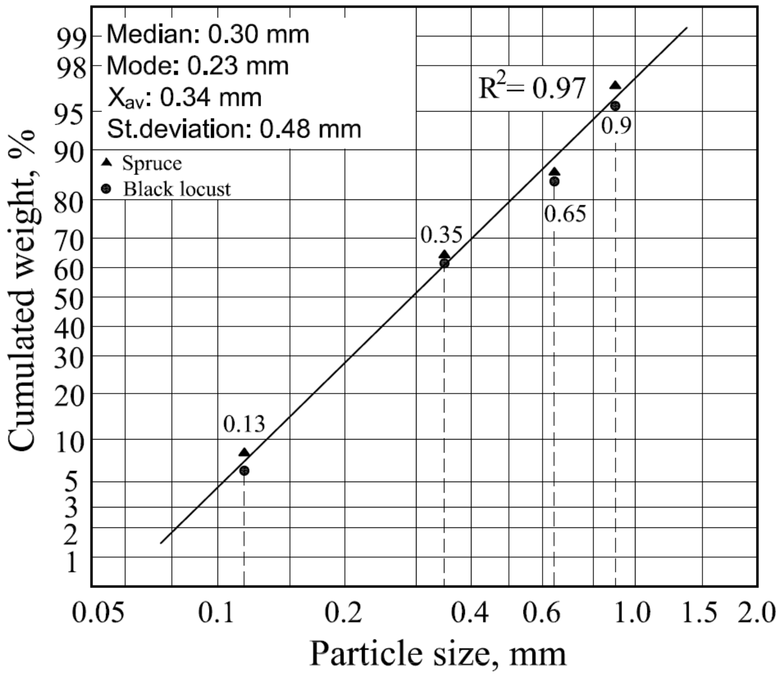

Fig. 2 The particle size distribution on probability net

The predominant fractions are lying between 0.2-0.5 mm. The characteristic distribution parameters are the following: *Median* = 0.3 mm, *Mode* = 0.23 mm, geometric mean $X_{av.}$ = 0.34 mm and the standard deviation σ = 0.48 mm. The anatomical properties (soft and hardwood) influence the elastic- plastic behavior of the compressed material, especially the rebound of the material due to elastic recovery, after the pellet pushed out from the channel. The increase of pellet diameter after recovery is a measure for the stored elastic stresses in the compressed state.

ENERGY CONSUMPTION OF THE COMPACTION PROCESS USING DIMENSIONLESS EQUATION

During the compaction process the density and the modulus of elasticity of the material rapidly increase. Wood materials generally show non-linear viscoelastic-plastic behavior and, therefore, the pressure-deformation relationship is dependent on the loading velocity and on the time during which the material is subjected to constant deformation or load. The energy requirement of pellet production depends on many influencing factors and in such cases the use of dimensionless numbers in the form of similarity equation facilitates the processing of experimental results and the obtained similarity relationship has a more general validity for the users. Various fractions of different wood species were used in these experiments and the pressure, pellet diameter, temperature were also varied. The proposed similarity equation shows a good correlation with the experimental results.

One of the rational utilization of waste products in the wood industry is to make them into pellets. The pelleting reduces the volume of the bulk chip considerably and facilitates its handling (transport, storage, feeding into boiler) fundamentally. At the same time, energy and suitable equipment are needed to perform the pelleting process. The most commonly used pelleting machines utilize a rotating die ring and the material is pressed into the boreholes of the ring by rollers. The first comprehensive analysis of the pelleting process is given in [26]. Especially the working principle of the press rollers, the effect of their operational parameters on the throughput was measured and analyzed. For describing the compaction process a relatively simple empirical relationship was used. Using non-linear rheological models, a more generally valid description of the compaction process was developed and used for sawdust and chips [29; 30] and, furthermore, the non-linear viscoelastic behavior of the material was experimentally mapped in the entire loading velocity range. Some experimental results on the energy requirement of the pelleting process for fodder flours were already summarized in [26] without specifying the measurement conditions and material properties. Later experiments also did not give generally valid relationships for the energy requirement of the pelleting process [7].

The aim of present work is to develop and validate a relationship which takes into account the pressure, the final density of the pellet, pellet diameter, the effect of temperature and material properties. For this purpose the application of similarity equation [6] seems to be the most promising method, similarly to those successful applications made in the last hundred years on the field of heat transfer and fluid flow problems.

Theoretical considerations

Biological materials have very complicated material laws and, in the case of higher volume changes as is the pelleting process, the stress-strain relationship is always highly non-linear. Therefore pure mathematical methods for describing the compaction process in all its details are today hardly available. A more practical and reliable approach is to perform carefully designed experimental measurements and to process these results in such a way that the obtained relationship would be valid with so few constraints as possible. In order to extend the validity of a relationship for different materials, the inclusion of proper material properties seems to be indispensable.

The particles in the ring die channels are loaded by compressive forces and, therefore, the material property may be characterized, as a first approximation, by the compressive strength of the material in question. Concerning the compaction process of wood chips, the following main influencing factors should be treated: material property of wood species, average particle diameter, compaction pressure, temperature of the material, diameter of the pellet, and final density of the pellet and the total specific work of the compaction. There are further influencing factors with limited variability range due to the process itself. For instance, the loading speed has always a definite influence on the compaction process, but in real pelleting machines the loading speed cannot be varied as a process parameter. The moisture content is also an important process parameter, but its range is also limited (optimum 10 to 12%) due to the durability requirement of the pellet [19; 20].

Keeping in mind the above statements, the following formal functional relationship with seven variables may be written:

$$W = f\left(p, \gamma, d, \sigma_C, \vartheta, \vartheta_0\right) \tag{1}$$

where:

p – pressure, N/m^2 ,
W – total specific energy of compaction, Nm/m^3,
γ – final specific weight of the pellet, N/m^3,
d – diameter of the pellet, m,
σ_C– compressive strength of the wood, N/m^2,
ϑ , ϑ_0 – are the pellet temperature and a reference temperature, here taken as ϑ_0=25°C (room temperature).

In order to derive the proper functional form of Eq. (1), the standard dimensional analysis method was used [6; 21]. It yields the following dimensionless numbers

$$\pi_1 = \frac{W}{p}; \quad \pi_2 = \frac{\gamma \cdot d}{\sigma_C}; \quad \pi_3 = \frac{\vartheta}{\vartheta_0}$$

and according to Buckingham's theorem, we may further write

$$\frac{W}{p} = f(\frac{\gamma \cdot d}{\sigma_C}, \frac{\vartheta}{\vartheta_0})$$

or

$$\frac{W}{p} = const \cdot \left(\frac{\gamma \cdot d}{\sigma_C}\right)^n \cdot \left(\frac{\vartheta}{\vartheta_0}\right)^m \tag{2}$$

where the constant and the exponents *n* and *m* should be determined experimentally.

In the above equation the dependent variable is the specific energy consumption *W*, therefore, the dimensionless number π_1 containing the specific energy is placed on the left side of Eq. (2). The other two numbers containing only independent variables are on the right side of Eq. (2). The total work of compaction is determined by the pure compression work and by the work done during pushing out the pellet from the boreholes. The pure compression work is given by integration of the pressure along the displacement. The pressure – strain relationship is strongly non-linear and can be given in the following form [28; 7]:

$$p = A\left(\frac{\varepsilon}{1-\varepsilon}\right)^n \tag{3}$$

where:
A – material dependent constant,
ε – strain,
n – exponent.

The exponent *n* is depending on the size and strength of particles and on the pressure range. Its value varies between 1.5 and 2.5 for various wood chips [28; 16]. Especially the strength of chips influences the course of compaction curve as a function of displacement. Soft particles can be compacted at relatively low pressures and, increasing further the pressure, the curve ascends steep giving a higher exponent. On the contrary, particles of hardwood species with higher individual strength will be compacted more uniformly as a function of displacement resulting in lower exponent *n*. Due to the anatomical structure of wood, the individual strength of particles depends not only on wood species but also on the size of particles. With decreasing particle size the surface – volume ratio increases [8; 3]. The surface of a particle is created by fracture with highly uneven surface and the load-bearing capacity of this near-surface layer is less compared to that of the sound inner part. As a consequence, a smaller particle may behave similarly as it would be originated from a softer wood species. The size effect on the compaction process can only be determined experimentally.

The second main part of the total compaction work is the work done during the push-out of the pellet from the boreholes. This work depends on the friction coefficient between pellet and channel wall, the length of the channel and the elastic-plastic behavior of the material at the given pressure. This work should also be determined experimentally.

Concerning constant deformation velocity, the particular phases of a compaction process is illustrated in Fig. 3. Due to the constant deformation rate, the pressure progressively increases. During constant load or stress, the deformation and compaction continues to grow (creep). After unloading the elastic part of the deformation recovers suddenly following by a retarded rebound. Much of the deformation is retained as permanent deformation ensuring the required pellet density.

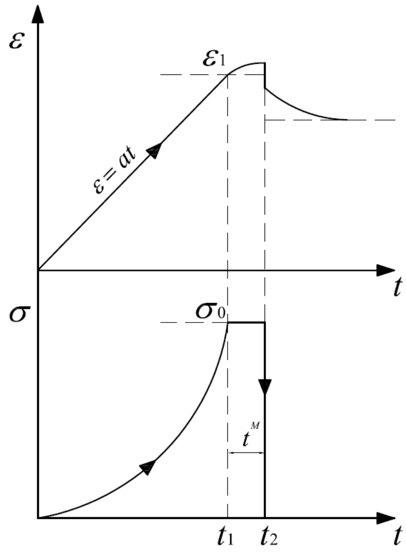

Fig. 3 The time course of the compression process

Results and discussion

Figure 4 shows the total specific work for spruce chips for different pellet diameters using 140 MPa pressure. With increasing diameters the relative contribution of wall friction decreases and therefore the energy requirement also decreases.

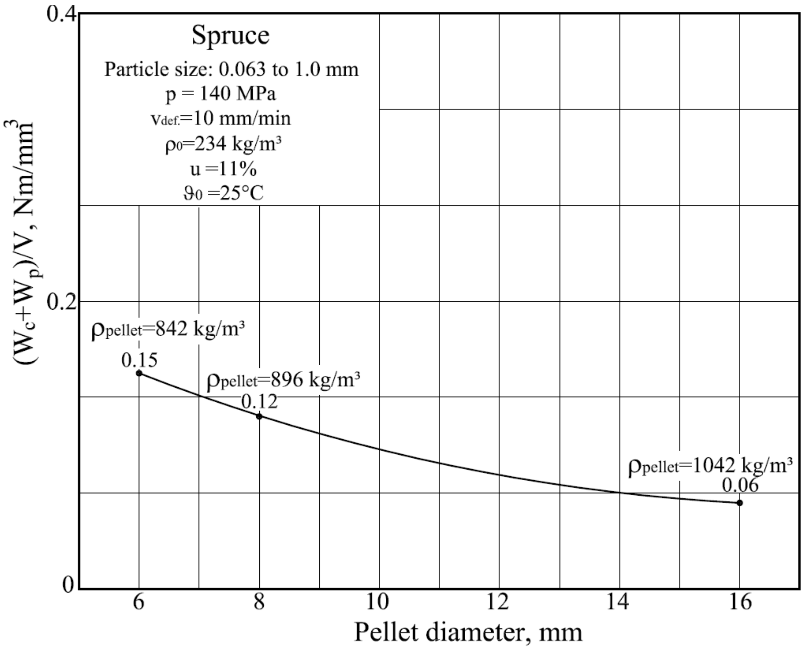

Fig. 4 The change in specific work depending on the diameter of spruce pellets at ambient temperature

Using pellet heating with different temperatures the viscoelastic properties of wood materials considerably changes. Figure 5 shows the effect of pellet temperature on the total specific compaction energy.

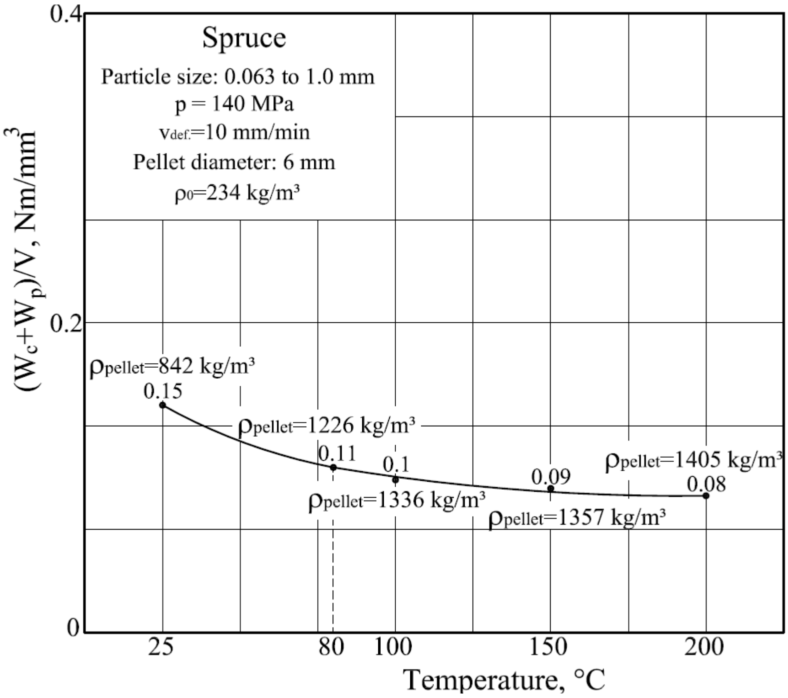

Fig. 5 The change of total specific work depending on pellet temperature using spruce chips

The beneficial effect of heating is more efficient, however only up to 100-110°C, further increase of temperature reduces the energy requirement in a lesser extent. A possible explanation for this may be the reduction in friction coefficient between particles and in the virtual viscosity of the material as the temperature increases. Due to the limiting effect of solid wood density on the compaction process however, the compaction is an asymptotic phenomenon with decreasing effectivity toward high densities. An inspection of Fig. 5 and Fig. 7 clearly shows that the pellet density over 100°C is not far from the solid wood density (~1580 kg/m^3). It should also be remembered that the pellet density, due to the rebound, is always less than the compaction density at maximum pressure.

Similar measurement results are depicted in Figure 6 and 7 for black locust.

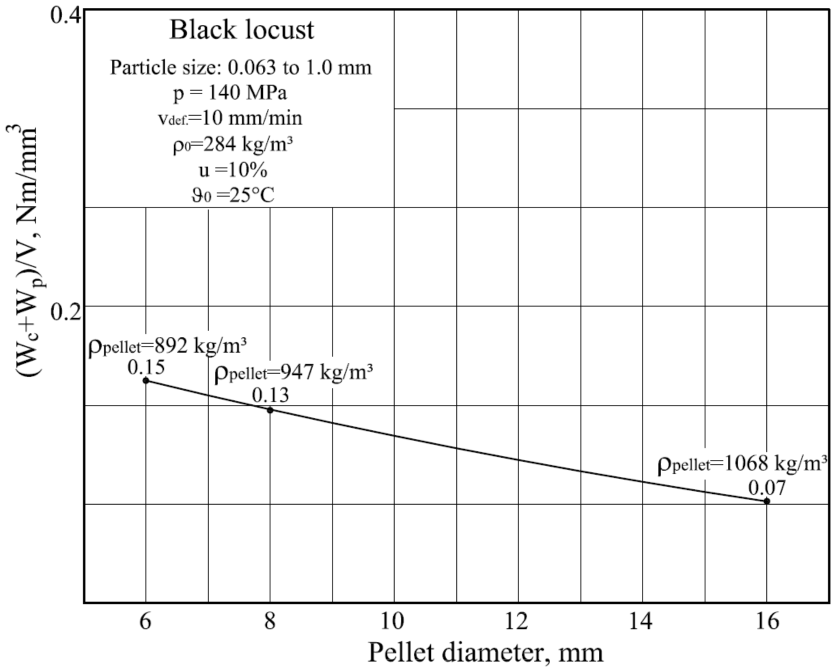

Fig. 6 The change in specific work as a function the punch diameter using black locust samples

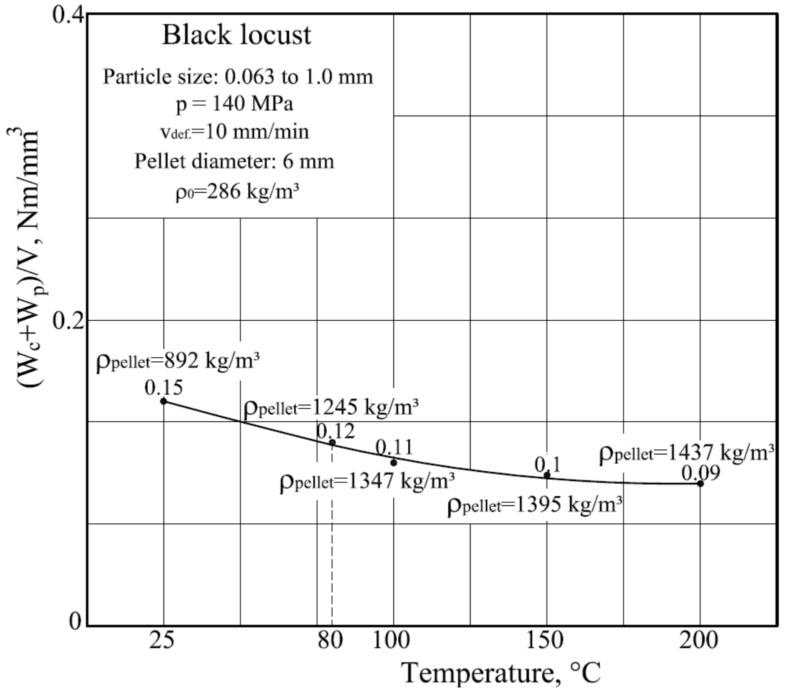

Fig. 7 The change in the specific work as a function of temperature using black locust chips

It is interesting to note that the total energy values of compaction for black locust only slightly differ from those of the spruce although the components are not the same.

In order to calculate the dimensionless numbers the compressive strength of the wood species used are needed. In general this value varies for spruce in the range of 45-55 N/mm^2 and for black locust 60-65 N/mm^2 [22]. It should be noted, however, that the strength ratio for small particles is not exactly the same as for the solid wood. Therefore, a slight correction might be required. The measured and calculated values for spruce and black locust are summarized in Table 1.

Table 1 Summary of research findings in the 100 and 140 MPa pressure range with 0.063 to 1.0 mm particle sized pellets at 25°C

Species	Pressure	Specific energy	Specific energy	**W/p**	Pellet specific gravity	Pellet diameter	σ_C	**$\gamma d/\sigma_C$**
	p	W	W		γ	d		
	N/m^2	Nm/mm^3	Nm/m^3		N/m^3	m	N/m^2	
Black locust	$1,4.10^8$	0,15	$1,5.10^8$	**1,07**	8920	0,006	65.10^6	**$8,93.10^{-7}$**
	$1,4.10^8$	0,13	$1,3.10^8$	**0,93**	9470	0,008	65.10^6	**$11,65.10^{-7}$**
	$1,4.10^8$	0,07	$0,7.10^8$	**0,50**	10680	0,016	65.10^6	**$26,28.10^{-7}$**
	$1,0.10^8$	0,12	$1,2.10^8$	**1,20**	8130	0,006	65.10^6	**$7,50.10^{-7}$**
	$1,0.10^8$	0,10	$1,0.10^8$	**1,00**	8340	0,008	65.10^6	**$10,26.10^{-7}$**
	$1,0.10^8$	0,05	$0,5.10^8$	**0,50**	9720	0,016	65.10^6	**$23,92.10^{-7}$**
Spruce	$1,4.10^8$	0,15	$1,5.10^8$	**1,07**	8420	0,006	55.10^6	**$9,18.10^{-7}$**
	$1,4.10^8$	0,12	$1,2.10^8$	**0,86**	8960	0,008	55.10^6	**$13,03.10^{-7}$**
	$1,4.10^8$	0,06	$0,6.10^8$	**0,43**	10420	0,016	55.10^6	**$30,31.10^{-7}$**
	$1,0.10^8$	0,12	$1,2.10^8$	**1,20**	7030	0,006	55.10^6	**$7,67.10^{-7}$**
	$1,0.10^8$	0,09	$0,9.10^8$	**0,90**	7500	0,008	55.10^6	**$10,90.10^{-7}$**
	$1,0.10^8$	0,05	$0,5.10^8$	**0,50**	8450	0,016	55.10^6	**$24,58.10^{-7}$**

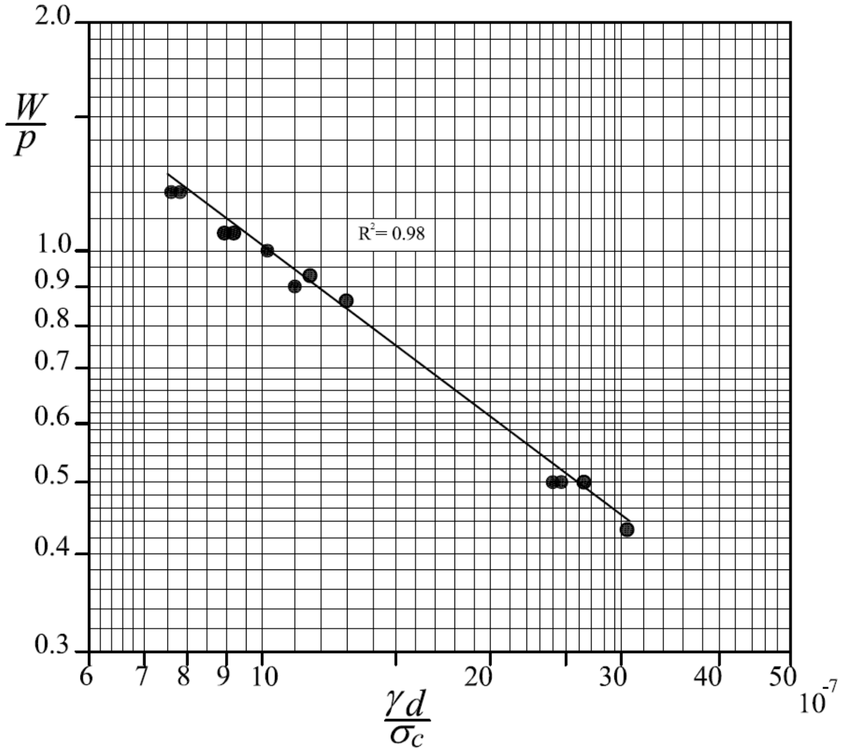

Fig. 8 Dimensionless plot of experimental results for ambient temperature

Plotting the dimensionless numbers has revealed that in our case the selection of compressive strength values of 55 and 65 N/mm^2 for spruce and black locust respectively is appropriate and all measurement points are on the same line as shown in Fig. 8.

We investigated the influence of temperature on specific energy required to produce pellets from spruce and black locust chips and dust at pressures between 100 and 140 MPa. Table 2 shows the results. Fig. 9 summarizes the results in a dimensionless graph.

Table 2 Summary of measured and calculated results at 100 and 140 MPa, 0.063 to 1.0 mm size particles with the effect of the temperature

Species	Pressure	Specific energy	Specific energy	**W/p**	Pellet specific gravity	Pellet diameter	σ_C	$(\frac{\gamma d}{\sigma_C})(\frac{\vartheta}{\vartheta_0})^{0,15}$
	p	W	W		γ	d		
	N/m^2	Nm/mm^3	Nm/m^3		N/m^3	m	N/m^2	
Black locust	$1,4.10^8$	0,12	$1,2.10^8$	**0,86**	12450	0,006	65.10^6	**$13,67.10^{-7}$**
	$1,4.10^8$	0,11	$1,1.10^8$	**0,79**	13470	0,006	65.10^6	**$15,29.10^{-7}$**
	$1,4.10^8$	0,10	$1,0.10^8$	**0,71**	13950	0,006	65.10^6	**$16,74.10^{-7}$**
	$1,4.10^8$	0,09	$0,9.10^8$	**0,64**	14370	0,006	65.10^6	**$18,04.10^{-7}$**
	$1,0.10^8$	0,09	$0,9.10^8$	**0,90**	11200	0,006	65.10^6	**$12,30.10^{-7}$**
	$1,0.10^8$	0,08	$0,8.10^8$	**0,80**	11960	0,006	65.10^6	**$13,58.10^{-7}$**
	$1,0.10^8$	0,07	$0,7.10^8$	**0,70**	12870	0,006	65.10^6	**$15,44.10^{-7}$**
	$1,0.10^8$	0,07	$0,7.10^8$	**0,70**	13110	0,006	65.10^6	**$16,46.10^{-7}$**
Spruce	$1,4.10^8$	0,11	$1,1.10^8$	**0,79**	12260	0,006	55.10^6	**$15,91.10^{-7}$**
	$1,4.10^8$	0,10	$1,0.10^8$	**0,71**	13360	0,006	55.10^6	**$17,92.10^{-7}$**
	$1,4.10^8$	0,09	$0,9.10^8$	**0,64**	13570	0,006	55.10^6	**$19,24.10^{-7}$**
	$1,4.10^8$	0,08	$0,8.10^8$	**0,57**	14050	0,006	55.10^6	**$20,84.10^{-7}$**
	$1,0.10^8$	0,09	$0,9.10^8$	**0,90**	10520	0,006	55.10^6	**$13,65.10^{-7}$**
	$1,0.10^8$	0,08	$0,8.10^8$	**0,80**	11100	0,006	55.10^6	**$14,89.10^{-7}$**
	$1,0.10^8$	0,07	$0,7.10^8$	**0,70**	12360	0,006	55.10^6	**$17,53.10^{-7}$**
	$1,0.10^8$	0,06	$0,6.10^8$	**0,60**	12860	0,006	55.10^6	**$19,08.10^{-7}$**

The exponent m in Eq. (2) should be determined such that the measured points for different pellet temperatures fit the same line properly as given in Fig. 8. Taking $m = 0.15$, all measurement points including also those for heated pellets fit the straight line as shown in Figure 9. Points for elevated temperatures are marked with x.

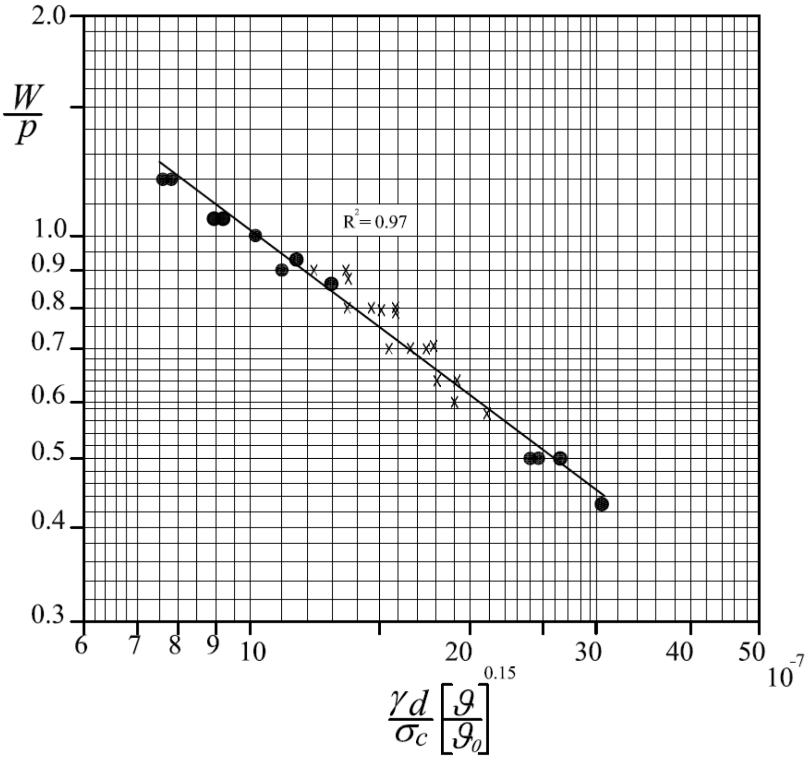

Fig. 9 Measurement points including also those for heated pellets on double logarithmic scale

The scattering zone of measurement points is fully acceptable and it corresponds to a good engineering accuracy. The calculated correlation coefficient is around 0.97.

In the following the effect of particle size on the compression work was examined. For these experiments we have used three fractions of chips for both spruce and black locust. The fractions have the following particle ranges: 0.063 to 0.2 mm, 0.2 to 0.5 mm and 0.8 to 1.0 mm. Which were demonstrated in Fig. 3. The measurement and calculated results are plotted in Figure 10 and 11. It is clearly seen that in both cases the energy requirement changes in a very low extent, although the slight decrease for both wood species has the same tendency. If we use now these additional data in the similarity equation without any correction and plot quite similarly to Figure 8 and 9, we obtain Figure 12 including all measurement points.

The scattering of data points are not much higher and the correlation coefficient also in this case is as high as 0.94. This is due also to the fact that for construction of Figure 8 and 9 the middle fraction from the three was used and therefore, the points of the other two fractions are placed on the opposite sides of the resultant straight line. The final similarity equation is given in the following form:

$$\frac{W}{p} = C \cdot \left(\frac{\gamma \cdot d}{\sigma_C}\right)^{-0,75} \cdot \left(\frac{\vartheta}{\vartheta_0}\right)^{0,15} \tag{4}$$

where the constant C has the value of $3.12 \cdot 10^{-5}$

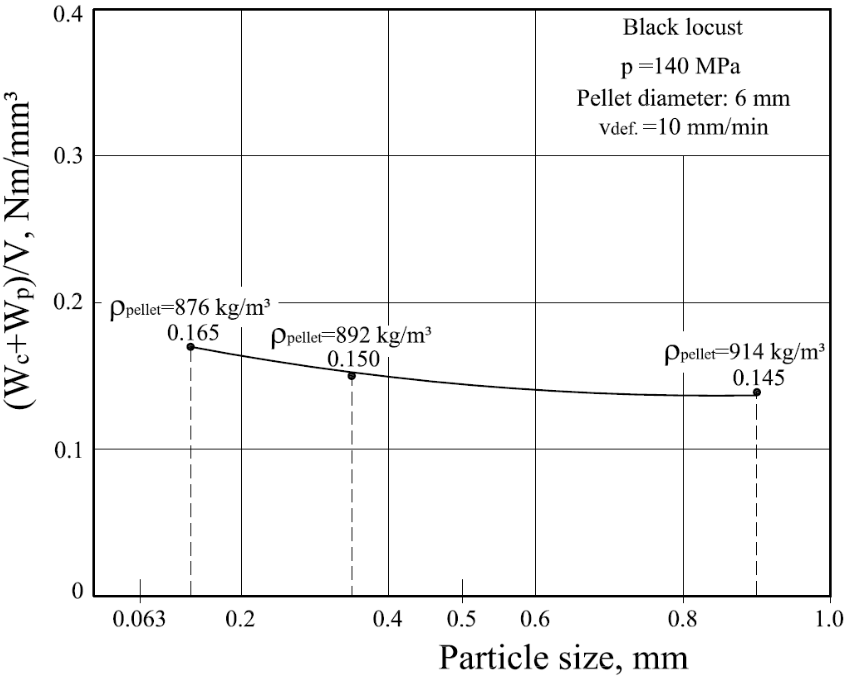

Fig. 10 The change in the specific work as a function of particle size using black locust

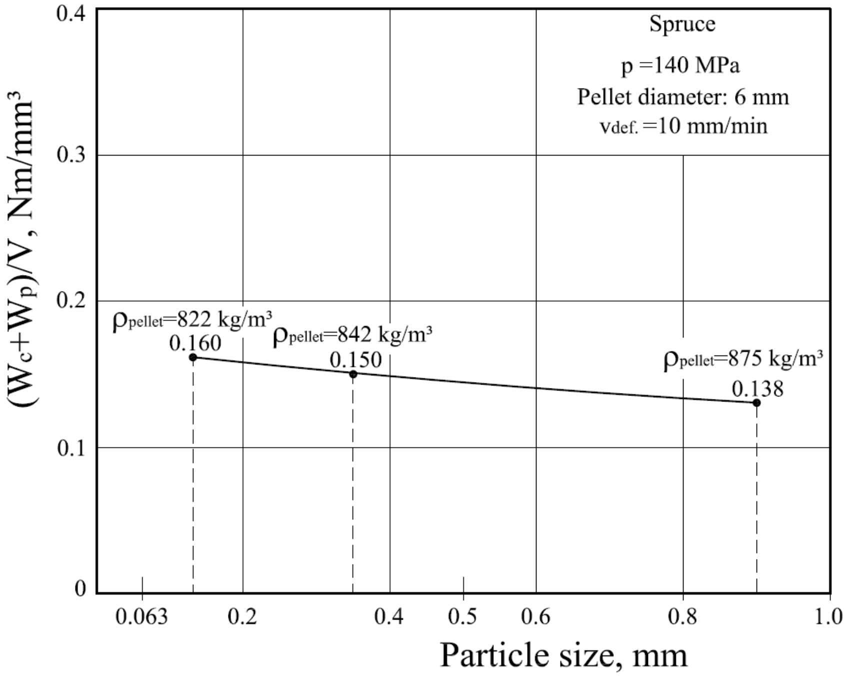

Fig. 11 The change in the specific work as a function of particle size using spruce samples

Table 3 Summary of measurement results at 140 MPa pressure and with three different particle fractions: 0.063 to 0.2 mm, 0.2 to 0.5 mm and 0.8 to 1.0 mm

Species	Pressure	Specific energy	Specific energy	**W/p**	Pellet specific gravity	Pellet diameter	σ_C	**$\gamma d/\sigma_C$**
	p	W	W		γ	d		
	N/m^2	Nm/mm^3	Nm/m^3		N/m^3	m	N/m^2	
black locust	$1,4.10^8$	0,165	$1,65.10^8$	**1,18**	8760	0,006	65.10^6	**$8,08.10^{-7}$**
	$1,4.10^8$	0,150	$1,5.10^8$	**1,07**	8920	0,006	65.10^6	**$8,93.10^{-7}$**
	$1,4.10^8$	0,145	$1,45.10^8$	**1,04**	9140	0,006	65.10^6	**$8,74.10^{-7}$**
spruce	$1,4.10^8$	0,160	$1,6.10^8$	**1,14**	8220	0,006	55.10^6	**$8,96.10^{-7}$**
	$1,4.10^8$	0,150	$1,5.10^8$	**1,07**	8420	0,006	55.10^6	**$9,18.10^{-7}$**
	$1,4.10^8$	0,138	$1,38.10^8$	**0,99**	8750	0,006	55.10^6	**$9,54.10^{-7}$**

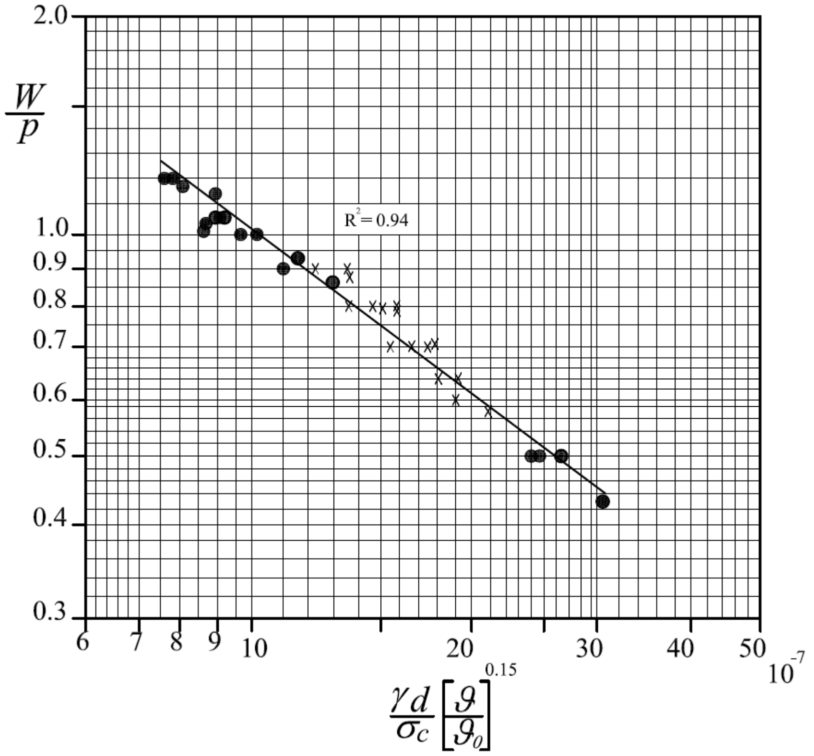

Fig. 12 The final similarity plot of all measurement results

It should finally be noted that in these experiments a plunger with bottom face was used. In practice, however, due to the continuous operation requirement, the chips material will be pressed into the boreholes of a die ring and the counter-force is assured by friction forces on the channel wall. Therefore the push-out force is more or less the same as the maximum compression force. This means that under real conditions somewhat higher specific energy is required.

THE EFFECT OF WALL FRICTION ON PELLET PRODUCTION

The ratio of the channel diameter (*D*) and the channel length (*L*) has significant influence on the pellet density due to the wall friction which is sometimes referred to odometer problem. In rolling presses the counter pressure is ensured by wall friction forces which depend on the channel length. To our best knowledge this problem has not been treated yet in details and, therefore, a theoretical and experimental investigation was undertaken to derive a generally valid relationship so describe the above phenomenon. The obtained relationship in dimensionless form is suitable to determine the necessary channel length to given channel diameter for different pellet densities or required maximum pressure using chips of two wood species. The obtained results are in agreement with real channel diameter/length ratios used in the practice.

Using die-ring pelleting machines, where the lose chip material is compressed by a roller and pressed into the boreholes of the ring a common problem is the not proper selection of the borehole diameter and length ratio for a given wood chip. Various wood species may have quite different physical properties influencing the friction coefficient between channel wall and the pressed material. As a consequence, a given die-ring can produce different pellet densities depending on the chip properties. In the practice, the pellets manufacturers may incorrectly select the die-ring process parameters (wood species, particle size distribution, moisture content, temperature and the required compression pressure). Therefore the results may be a low quality products or increased energy consumption. The compaction process in press channel is a very complicated one due to the varying conditions along the press channel. The modulus of elasticity, the Poisson's ratio and the friction coefficient on the wall are continuously varying along the length of the channel which make a pure theoretical treatment impossible. In the following the brief discussion of the problem is given which facilitates the proper processing of the experimental results and to get useful relationship for practical purposes.

Theoretical considerations

Due to the wall friction, the pressure along the length of press channel is not constant, Poisson's ratio and friction coefficient also vary as a function of length [4; 13; 15; 17]. Concerning the main influencing factors, the length/diameter ratio (*L/D*) plays a distinct role determining the influence of wall friction on the density distribution in the compaction channel. The pressure distribution in the space before a compressing piston can be given by the following equation [24; 27].

$$p_x = p_0 e^{-kx} \tag{5}$$

where:
p_0 - pressure exerted by the piston, N/mm^2,
p_x - pressure at a distance x from the piston, N/mm^2.

and

$$k = \frac{4}{D}\mu\frac{v}{1-v}$$

with
μ – friction coefficient,
v – Poisson's ratio (0.35-0.4).

The constant k in Eq. (5) is affected by ratio of the wall surface area (F_{wall}) to the volume (V) which is

$$k' = \frac{F_{wall}}{V} = \frac{D \cdot \pi \cdot L}{\frac{D^2\pi}{4} \cdot L} = \frac{4}{D}$$

In our experiments piston diameters of 6, 8 and 16 mm have been used. Taking the average values for $\mu=0.6$ and $v=0.4$, the constant k has values of 0.267, 0.2 and 0.1 cm^{-1} respectively. With decreasing k-values the pressure distribution will be more uniform in the press channel. The Poisson's ratio generally slightly increases with higher pressures. In the pellet range values of 0.35 and 0.4 are appropriate. The friction coefficient is influenced by the wood species, moisture content and pressure. An interesting observation was for agricultural materials that, applying high pressure, the water might be pressed out from the material reducing the friction coefficient considerably. The condition for water release is that the loading pressure is greater than the water potential (tension) of the material at given moisture content. In the experiments an average moisture content of 10% was used. It corresponds, using the sorption isotherm and converted to a *pF*-number of 6 or 1000 bar tension. The maximum compression pressure was 1400 bar and, therefore, it may be assumed that some water is released and pressed out to the boundary of the particles. Furthermore, it may also be assumed, although never proved, that this water pressed to the particle boundaries plays an important role in getting durable pellet by providing the necessary bonding forces.

An approximate modelling of the pushing force

As outlined above, the force required for pushing out the pellet from the channel is originated from the side wall friction. This force formally can be simply calculated by the following equation

$$F_p = A \cdot p_w \cdot \mu \tag{6}$$

where:

A – instantaneous contact area of the pellet with the channel wall, mm^2,
p_w– average side pressure, N/mm^2,
μ – friction coefficient.

The side pressure is developed by the stored elastic deformation of the material in the compressed state, the deformation of which is the main problem.

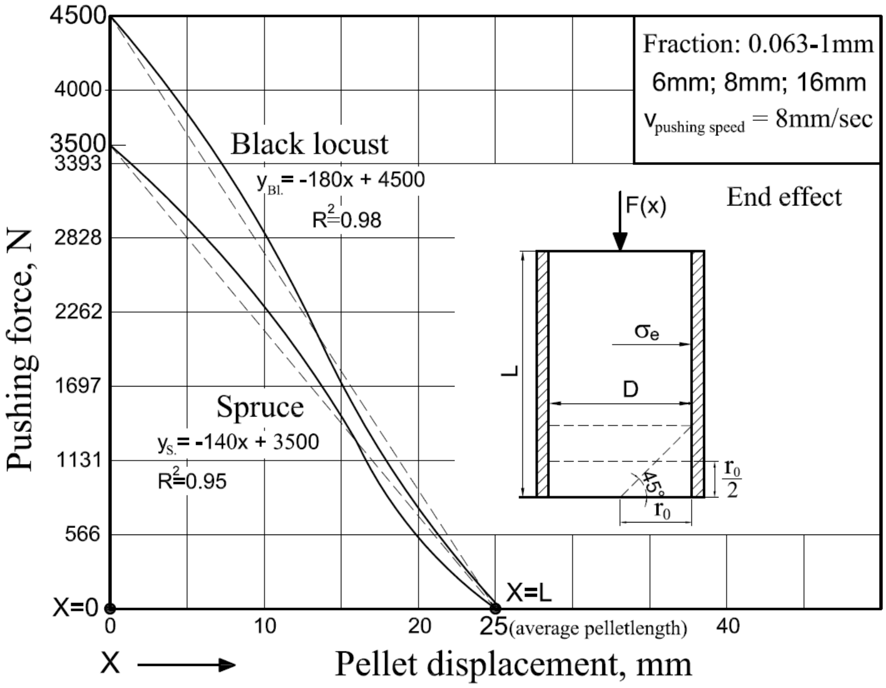

Fig. 13 The reduction of maximum pushing force as a function of free pellet length

Fig. 13 shows the variation of pushing force determined experimentally as a function of displacement for pellets of 25 mm length. Black locust requires somewhat higher force compared to the Spruce. It is interesting to note that pellets with different diameters required practically the same force. Another important observation that the force varied nearly linearly as a function of displacement. Therefore as a first approximation, in the following we calculate with a linear force function along the pellet length. The bottom end of the pellet leaving the channel will undergo an unloading process due to the free expanded part of the pellet (end effect in Fig. 13). For the sake of simplicity this effect will be taken into account with the assumption that the radial stress decreases, starting from the bottom edge of the channel, under 45° to its stationary value [32].

It is interesting to compare the maximum pushing force with the maximum compaction force F_c (1400 bar maximum pressure) for different pellet diameters and wood species ($F_p = 3500$ N and 4500 N for Spruce and Black locust respectively). These F_p/F_c values are summarized in Table 4.

Table 4 F_p/F_c force ratios for the investigated pellets in per cent

	Φ 6 mm	*Φ 8 mm*	*Φ 16 mm*
Spruce	88 %	50 %	12 %
Black locust	114%	64 %	16 %

It is clearly seen that with increasing pellet diameters the share of the push out energy in the total energy of pelleting sharply decreases. During the push-out of a pellet the contact area in Eq. (6) varies according to the following equation:

$$A_x = D\pi(L_{pellet} - x) \tag{7}$$

where:
x – length of the pellet out of the channel, mm.

The instantaneous pushing force is

$$F_{(px)} = A_x \sigma_e \mu \tag{8}$$

where:
σ_e – stress due to the stored elastic deformation (lateral pressure), N/mm^2.

This stress is related to the elastic recovery of the pellet in the following manner

$$\sigma_e = \frac{E}{1-\nu} \cdot \frac{\Delta r}{r_0} \tag{9}$$

where:
Δr – increment of pellet radius due to elastic recovery, mm,
r_0 – channel radius, mm,
E – stored true modulus of elasticity (do not confuse with the deformation modulus of the pellet in compressed state), N/mm^2.

As it is mentioned above, at the lowest end of the channel the stress σ_e declines (end effect) and this effect may be taken into account with the proper correction of the contact surface (see Fig. 13). The ratio of the effective area to the geometric contact area (surface reduction factor) is given by

$$\psi_{end} = \frac{D\pi(L_{pellet} - r_0/2)}{D\pi \cdot L} = \frac{L_{pellet} - r_0/2}{L} \tag{10}$$

L_{pellet} – pellet length, mm.

Keeping in mind the above equations, the instantaneous pushing force is

$$F_{(x)} = 2\pi \frac{E}{1-\nu} \mu \Delta r (L_{pellet} - x) \psi_{end} \tag{11}$$

After pushing out the pellets, their diameters were measured. Because the increment Δr has generally values in the range of tenth of mm, a very accurate measurement is difficult. Average values obtained are summarized in Table 5 for both wood species and for different pellet diameters.

Table 5 Increment of pellet diameters, Δr

	Φ 6 mm	*Φ 8 mm*	*Φ 16 mm*
Spruce	0.25 mm	0.3 mm	0.52 mm
Black locust	0.245 mm	0.3 mm	0.51 mm

Based on our measurements, no significant difference could have been established between the two wood species. Sadly, friction coefficients for wood chips under high pressure conditions are not available at all. The obtained functional relationship (Eq. 11) does not allow separating the effect of friction and lateral pressure on the pushing force. Nevertheless, a good estimate can be done in the following manner.

We possess detailed experimental results on friction properties of wood species for particle size distributions and surfaces [34]. Under low pressure conditions the appropriate values are μ = 0.65 and μ = 0.55 for Spruce and Black locust respectively. If we do not change these values for high pressure conditions then the true modulus of elasticity of the compressed pellet can be calculated. Knowing the pushing force, Eq. (11) is suitable to calculate $E/1-\nu$ values for different pellet diameters. They are summarized in Table 6.

Table 6 Elastic modulus $E/(1-\nu)$ in the compressed pellet

	Φ 6 mm	Φ 8 mm	Φ 16 mm
Spruce	146 N/mm^2	124.2 N/mm^2	78.5 N/mm^2
Black locust	221 N/mm^2	188.7 N/mm^2	119 N/mm^2

It is probably that the friction coefficient under high pressure conditions is somewhat less than the above figures. In this case the elastic module will be higher in the same ratio as the friction coefficients were lowered.

The actual deformation modulus of the pellet is naturally much higher. For comparison, an estimate can be done very easy. Using the nonlinear compaction equation, according to Eq. (3) for Spruce chip compaction (D = 6 mm, p_c = 1400 bar, ε = 0.8) the following equation is valid:

$$p_c = A(\frac{\varepsilon}{1-\varepsilon})^n$$

where:
A= 8.75 N/mm^2 and n=2
Derivation of this equation gives the deformation modulus in the form:

$$E_d = \frac{\partial p_c}{\partial \varepsilon} = A \cdot n \left(\frac{\varepsilon}{1-\varepsilon} \right)^{n-1} /(1-\varepsilon)^2 \qquad (12)$$

Substituting the appropriate values, we get E_d = 1750 N/mm^2 which is one magnitude higher than the true elastic modulus in the compressed pellet. Using Black locust chips, the required strain is somewhat less (ε = 0.75) and the deformation modulus is E_d = 1590 N/mm^2 . The difference in the deformation may be explained by the difference in hardness of the individual particles.

Determination of channel length for a given pressure

Using die-ring pelleting machines with continuous operation, the prescribed maximum compaction pressure (or force) is in equilibrium with friction forces acting on the channel surface. Using Eq. (11), the equilibrium equation has the form (x = 0):

$$p_c = \frac{F_c}{r_0^2 \pi} = \frac{2}{r_0} \frac{E}{1-\nu} \mu \frac{\Delta r}{r_0} L \psi_{end} \qquad (13)$$

It seems to be advisable to transform the above equation into a dimensionless form:

$$\frac{L}{D} = \frac{p_c}{4 \mu \psi_{end} \frac{E}{1-\mu} \cdot \frac{\Delta r}{r_0}} \qquad (14)$$

where:
$D = 2r_0$ – diameter of the channel, mm,
L – channel length, mm,
E – true modulus of elasticity in the compressed pellet, N/mm^2.

Using the measurements results with the three channel diameters, the functional relationship between diameter and channel length is shown in Fig. 13, both for Spruce and Black locust, and for P_c = 1400 bar.

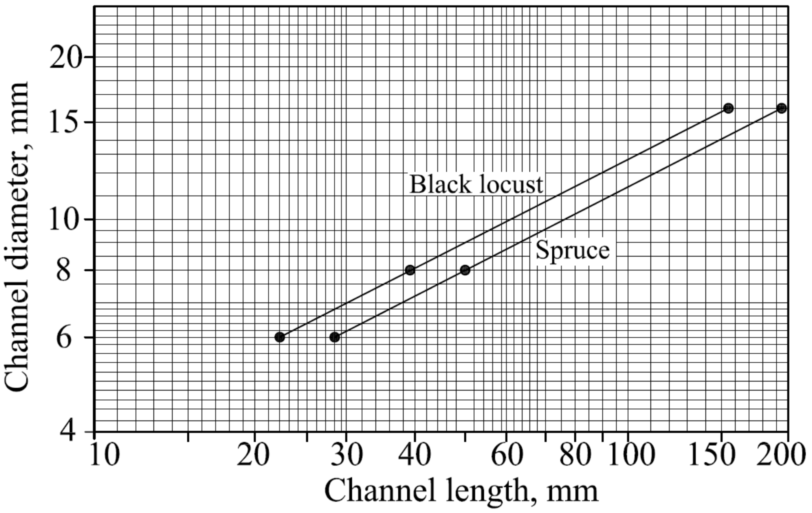

Fig. 14 Relationship between channel diameters an channel length ensuring the required compression pressure

It can be stated that Spruce chip, for the same compaction pressure, requires slightly longer channel compared to Black locust. Therefore using a given die-ring, different compaction pressures may be obtained if chip composition varies. The more generally valid dimensionless plot of experimental results is given in Fig. 15. which is a direct proof of the validity of Eq. (14).

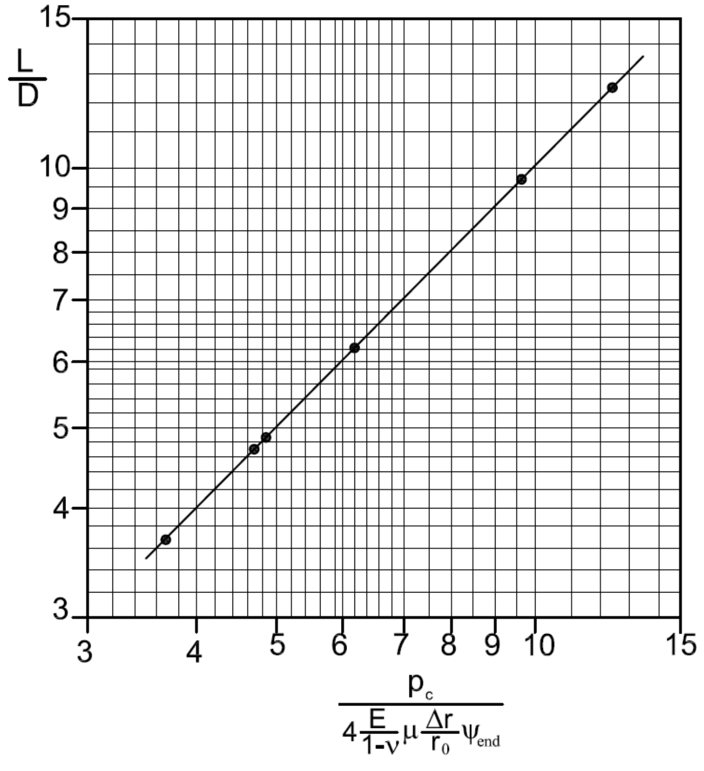

Fig. 15 Representation of Eq. (14) based on experimental results

Obviously, for other wood species and chip particle distributions the experimental determination of E and Δr values is necessary. As table 4 and Fig. 14 clearly suggest, the rotating die ring pelleting method allows to use channel diameters in a very limited range (5-7 mm dia.) due to the rapid increase in the necessary channel length with increasing diameters.

THE INFLUENCE OF MOISTURE CONTENT ON THE MECHANICAL STABILITY OF WOOD PELLETS

Present research examines the possible origins of binding forces and experimental evidences show that also the presence of water on particle surfaces plays a definite role. It also turned out that the water potential curve of timber materials can successfully be used to estimate the relation of compaction pressure to the water tension of the material.

It is well-known from the practice that the deviation of moisture content upwards or downwards in relation to the common values (10-12%) will highly decrease the mechanical stability of pellets, i.e., the binding forces among the particles are sharply decreasing. The detrimental effect of higher moisture contents can easily be explained by the fact that much water in the material hinders the compaction of the material. It is not the case, however, at decreasing water content. Therefore this latter case requires explanation. It is generally assumed that the binding forces among the particles originate from the lignin which is one of the main constituents of wood materials [1; 2; 10; 11]. The lignin is known to be a binding material on the outer surface of the cell walls which support the above assumption [12; 18]. But it is not fully clear why a small decrease in moisture content causes a rapid deterioration of binding forces among the particles and with this the loss of durability. It is therefore reasonable to suppose that the water itself may play also a given role in the development of binding forces.

It is also known that molecular forces exert considerable action on water molecules contacting a surface in one or several layers. The highest force and adhesion will be exerted on the first layer of water molecules which may contribute to the binding forces considerably [5; 9; 14; 23]. A layer of water molecules can appear on the surface of particles only in the case, if the pressure used is somewhat higher than the water potential (tension) of wood material at the given moisture content. Using the theory of wood-water relations, the water potential curve can be constructed and used to check the validity of the above assumption. The aim of present investigation is to solve this problem.

Theoretical considerations

Timber materials are porous and hygroscopic possessing the ability to absorb and desorb water depending on the environmental circumstances. The water content in wood plays an important role in many aspects. Concerning only our subject, it seems to be well-established that the water content of chips plays a decisive role in the development of bonding forces in the pellet. Wood materials tend to be in equilibrium with the surrounding environment which is changing continuously in its temperature and relative humidity. At equilibrium the partial vapour pressure above the surface is equal to the saturated vapour pressure corresponding to the given temperature.

As mentioned above, the wood is a porous material having capillaries of different diameters. On a liquid-gas interface, due to intermolecular forces, the surface tension phenomenon exists. As a consequence, the water rises in the capillary and over the capillary meniscus, depending on the radius of the capillary, the static pressure decreases which corresponds to a decreased relative humidity over the meniscus. This relationship is described by the Thompson equation as follows:

$$\varphi = exp(\frac{2\sigma\rho_v}{p_v\rho_w r}) \tag{15}$$

where:
φ – the relative humidity,
σ – the surface tension of water (0.072 N/m),
p_v – the vapor pressure,
ρ_v, ρ_w – the density of vapor and water, respectively,
r – the radius of capillary.

It is interesting to note that the sap in the wood contains soluble nutrients which decrease the surface tension to about 0.05 N/m. As an example, a capillary radius r = 0.36 nm corresponds to φ = 5% and r = 100 nm to φ = 98%. It means that in the sorption process capillaries over 100 nm radius cannot be filled with water. That means that the sorption isotherm does not characterize the entire moisture range of a saturated wood sample. An approximate distribution of pore radii for a pine wood is represented in Fig. 16 with the corresponding moisture content [29].

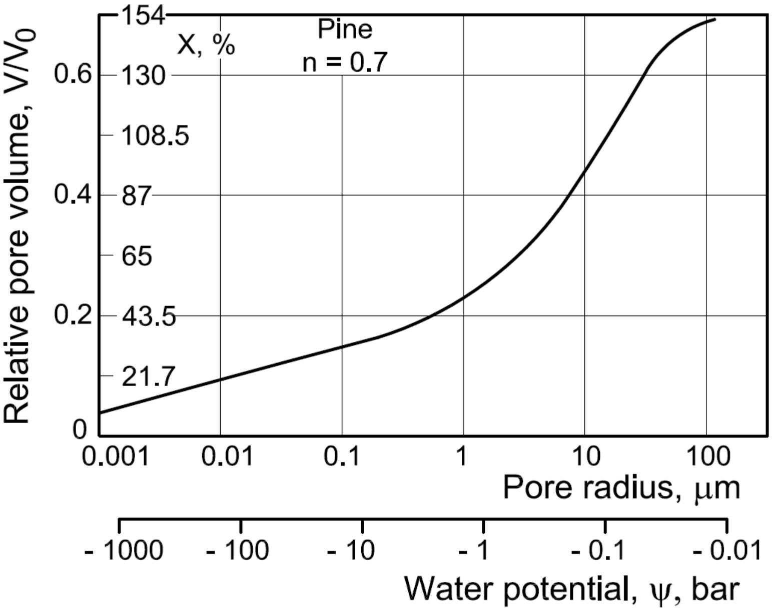

Fig. 16 Relative pore volume of Pinewood as a function of pore radii. The corresponding theoretical water potential values are also given

The water taken up in the sorption process is called the hygroscopic water and the corresponding moisture content is the fiber saturation point [33].

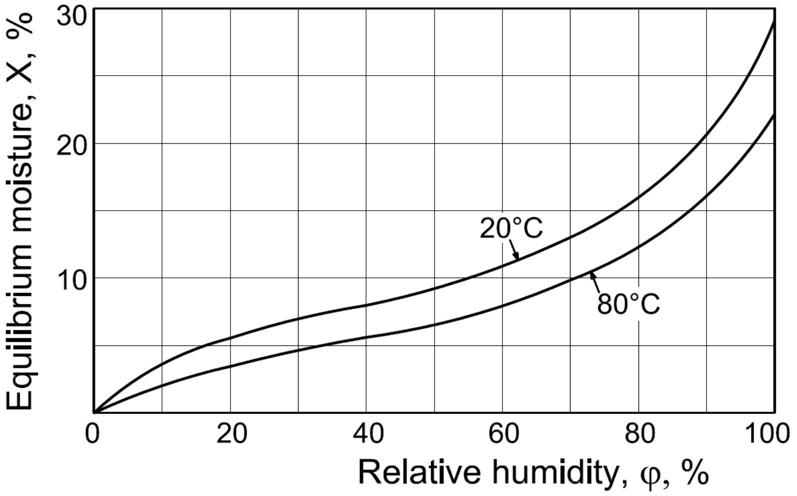

Fig. 17 The equilibrium moisture content of wood for two different temperatures

Measurements on the distribution of micro capillaries in wood have shown that most of the capillaries is in the 0.5 to 1.0 nm range which corresponds to $\varphi = 20\%$ and appr. 5% moisture content [31]. This low relative humidity means a high driving potential or tension which rapidly decreases with increasing capillary radii. This capillary tension is a real driving force which can be expressed in term of water potential as:

$$\psi = \frac{2\sigma \cos\theta}{r} \qquad \text{(Pa)} \tag{16}$$

where:
θ – the contact angle to the wall of the capillary tube.

Due to its relative humidity, the surrounding air has also a driving potential or tension given by the following equation:

$$\psi_a = \frac{RT}{m_w} ln\,\varphi \qquad \text{(bar)} \tag{17}$$

where:
m_w – the molecular volume of water (18 cm^3/mol),
T – the temperature (°K),
R – the gas constant (82 bar.cm^3/mol.°K).

Fig. 17 gives a relationship between the equilibrium moisture content and the relative humidity of air. Therefore, using Eq. (17), the driving potential of the air can be calculated for each equilibrium moisture content. As an example, the air with relative humidity of 90% has water potential or tension of appr. – 140 bar. Using the sorption isotherm given in Fig. 17, the corresponding water potential curves are depicted in Fig. 18.

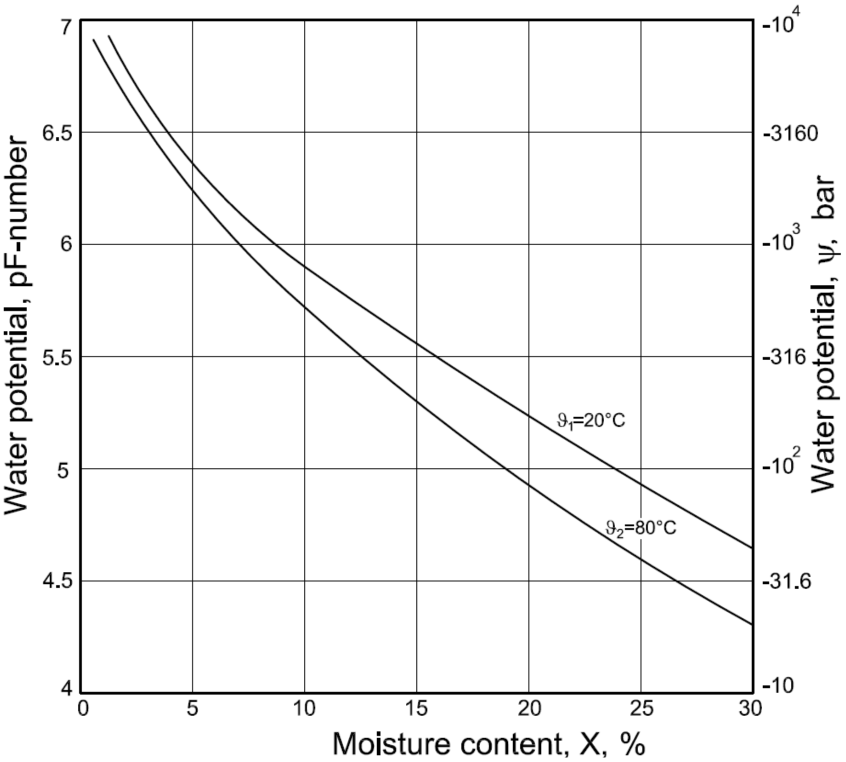

Fig. 18 The pF curve of wood for two different temperatures

The water potential may have different dimensions depending on the choice of dimensions in Eq. (17). If we choice for R = 8.314 kJ/kmol.°K and m_w = 18 kg/kmol, then the water potential has the dimension kJ/kg. For example, taking 50 % relative humidity, it corresponds to nearly 100 kJ/kg and 1000 bar tension. Originally in the soil science, for the characterization of water potential the pF-number has been introduced which is the logarithm of the pressure height expressed in cm [25]. For instance, pF=3 means 1000 cm = 1 bar tension.

Results

For each chosen moisture content a series of measurements was conducted to find the minimum pressure giving stabile pellets. The obtained minimum pressure was then represented in the previously constructed water potential relationship as shown in Fig. 19.

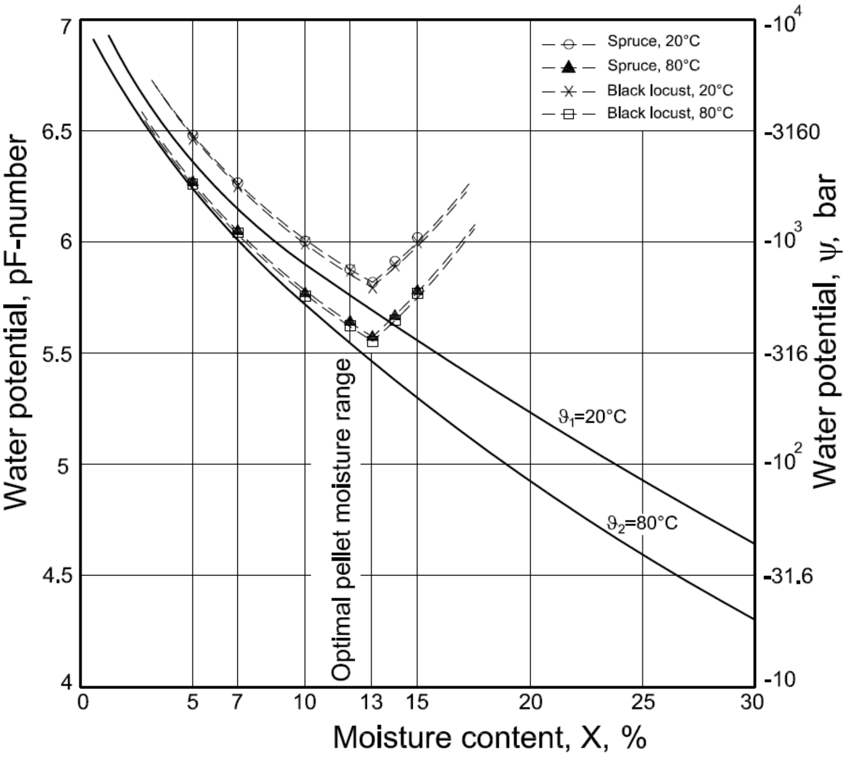

Fig. 19 The measurement results (broken line) and the pF curve of wood (solid line) for two different temperatures

Because the water potential can be expressed in the common pressure unit, for instance in bar, therefore the required minimum pressure can directly be compared to tension holding the water in the material at the given moisture content.

The obtained results are highly interesting. The measurement points are systematically placed slightly above the water potential curves as a function of moisture content. This means that the required compaction pressure should always be higher than the water holding tension at the given moisture content. Increasing the moisture content above 13%, the required pressure rapidly increases. In the presence of excessive water the compactibility of the material is worsening and a thicker water layer among the particles decreases the effect of molecular forces.

Discussion

The measurement results clearly indicate that some water may be pressed out from the material to its surface giving an additional binding force among the particles. In the soil science it is well known long ago that a thin water layer, less than 5 or 6 molecular thickness, on the soil particles makes the water immobile due to molecular forces and this water is not available for plants (wilting point). Similar observation was also presented studying water sorption energies [23]. Therefore it may be assumed that also here the thin water layer on the particle surfaces contributes to the binding forces.

The obtained experimental results prove the practical experience that the optimum moisture content for making pellets is in a narrow range between 10 and 12%. Below and over this moisture range the necessary pressure steeply increases requiring much more compaction energy and additional friction forces for pushing out the pellet from the die.

It is interesting to note, furthermore, that the required minimum pressures for 80°C are somewhat nearer to the water potential curves than for 20°C temperature. The absolute minimum pressure points for both cases, however, are obtained at the same moisture content of 13%. According to these experiments, in the optimum range of moisture content a compaction pressure of 1000 bar supplies stable pellets with sufficient safety.

Based on the above theoretical and experimental results, it can be stated and formulated that hygroscopic materials hold the water by tension. From this statement it follows that the dewatering of a material is possible only by applying a pressure somewhat higher than the tension exerting by the material at a given moisture content. Concerning the pelleting process, the same statement is valid: if the required minimum pressure which ensures a stable pellet is higher than the tension exerted by the material at given moisture content, then some portion of water will be pressed out from the chip particles to their surface. As outlined in the introduction, this thin layer of water may also contribute to the development of bonding forces.

CONCLUSIONS

Based on theoretical and experimental investigations the following main conclusions may be drawn:

- The main influencing factor is the pellet diameter which fundamentally determines the role of wall friction forces in the total energy requirement,
- By heating the material required pressure is reduced by 30 and 35% at 100 degrees compared with 25°C. Over 100°C degrees the rate of reduction declines.
- The chip size distribution has some effects on the energy requirement but, disregarding its effect, it does not cause significant error,
- Using similarity equation is a powerful method to generalize experimental results also for compaction processes. In this way a simple and quick estimation of energy requirement is possible.
- The length and diameter ratio of the press channel considerably influences the stress distribution in the pellet.
- In pellet making a considerable energy is spent on the pushing out of compressed pellet from the channel. In order to determine the main relationships of this process a new model is developed.
- Using the experimental results with two different wood chips, the elastic recovery and the corresponding true modulus of elasticity were determined for several pellet diameters. This true modulus of elasticity is responsible for the lateral pressure on the channel wall and the associated friction forces.
- The maximum compaction pressure is in equilibrium with the friction forces acting on the channel surface. A dimensionless relationship is developed to determine the necessary channel length for a given compaction pressure and pellet diameter.
- The chip mechanical properties may considerably influence the appropriate channel length to ensure the required pressure and pellet quality.
- Moisture has also a definite role in the development of bonding forces in pellets;
- The relation of compaction pressure and water tension in the material can conveniently be followed using the water potential curves;
- In order to minimize the energy consumption of pellet making an accurate control of chip moisture content is essential.

LITERATURE

1. Andrew, C., (2004): Low Carbon Heating with Wood Pellet Fuel, Report, Pp 4-11.
2. Anon, (2009): Pellet deal may herald new era. New Zealand Forestry Bulletin (Winter 2009), New Zealand Forest Owners. p. 2.
3. Akdeniz, R.C.; Haghighat, S., (2013): The effect of die dimensions, raw material moisture content and particle size on pelletizing characteristics of olive cake. Department of Agricultural Machinery, International Conferences Engineering, Agriculture, Waste Management and Green Industry Innovation. Gödöllő, Hungary, 13-19. october, S. 33-41.
4. Biot, M.A., (1954): Theory of stress-strain relations in anisotropic viscoelasticity and relaxation phenomena. Journal of Applied Physics. 25(11):1385-1391. http://dx.doi.org/10.1063/1.1721573
5. Brunauer, S., Emmett, P. H., Teller, E., (1938): Adsorption of gases in multi molecular layers. Journal of the American Chemical Society 60:309-19.
6. Buckingham, E., (1914): On physically similar systems: illustrations of the use of dimensional equations, Physical Review, **4**, S. 345-376. http://dx.doi.org/10.1103/PhysRev.4.345.
7. Carlos, S.; Tore, F.; Geir, S.; Odd-Ivar, L.; Olav, H.; Reidar, B., (2010): Compression rheology and physical quality of wood pellets pre-handled with four different conditions. Annual Transactions of the Nordic Rheology Society, Norwegian, 14:152-168.
8. Csanády, E.; Magoss, E., (2013): Mechanics of Wood Machining. Springer-Verlag Berlin Heidelberg, S. 25-30. http://dx.doi.org/10.1007/978-3-642-29955-1
9. Dent, R. W., (1977): A multilayer theory for gas sorption. Part I. Sorption of a single gas. Textile Research Journal, 47:145-152.
10. Demirbas, A., (2001): "Relationships between lignin contents and heating values of biomass," Energy Conversion and Management, vol. 42, no. 2, Pp 183–188.
11. Dmitry, T., Chander, S., Mathew, L., (2013): Effect of Additives on Wood Pellet Physical and Thermal Characteristics: A Review. Hindawi Publishing Corporation. ISRN Forestry. Volume 2013, Article ID 876939, 6 pages, http://dx.doi.org/10.1155/2013/876939
12. Escort, G., (2009): Wood pellets – a cleaner kind of fuel. NZ Journal of Forestry Volume 53 (No. 4) Pp 18-19.
13. Findley, W.N.; Lai, J.S.; Onaran, K., (1976): Creep and Relaxation of Nonlinear Viscoelastic Materials with an Introduction to Linear Viscoelasticity. Dover Publication, Inc., Mineola, New York. S.55-74.
14. Hailwood, A.J., Horrobin, S., (1946): Absorption by water of polymers. Analysis in terms of a simple model. Trans Faraday Soc 42B:84-92, 94-102.
15. Heiko, T.; Clovis, R.H.; Philip, E.H., (2005): Modelling the physical processes relevant during hot pressing of wood-based composites. Part II. Rheology. 64(2):125–133. http://dx.doi.org/10.1007/s00107-005-0032-5
16. Hofko, B., (2008): „Rheologische Modelle zur Beschreibung des Verformungsverhaltens von Asphalten"; Straße und Autobahn, 2008(5): 253 - 262.
17. Hofko, B., (2006): „Rheologische Modelle zur Beschreibung des Verformungsverhaltens von Asphalten"; Betreuer/in(nen): R. Blab, K. Kappl; Institut für Straßenbau und Straßenerhaltung, 2006; Abschlussprüfung: 24.11.2006.

18. Karwandy, J., (2007): Pellet Production From Sawmill Residue: a Saskatchewan Perspective. Saskatchewan Forest Centre. Forest Development Fund Project 2006-29, Final Report 2006/07.
19. Kocsis, Z., (2015): A fa szemcsés halmazok tömörítésének rheológiája és energetikája a pelletálási tartományban. [The compression rheology and energetics of wood particle sets at pelleting range]. Ph.D. dissertation, Hungary, Sopron, 134 p. http://dx.doi.org/10.13147/NYME.2015.002. (in Hungarian).
20. Kocsis, Z.; Csanády, E. (2015): Study of the energy requirements of wood chip compaction. DRVNA INDUSTRIJA 66(2):163-170. doi:10.5552/drind.2015.1409, ISSN 0012-6772.
21. Langhaar, H., (1951): Dimensional analysis and theory of models. John Wiley London. S. 25-34.
22. Molnár, S., (1999): Faanyagismerettan [Wood material science]. Mezőgazdasági Szaktudás Kiadó, Budapest, pp. 260-292. (in Hungarian).
23. Pizzi, A., Bariska, M., Eaton, N.J., (1987): Theoretical water sorption energies by conformation analysis. Part 2. Amorphous Cellulose and the sorption isotherm. Wood Sci. Technol. 21:317-327.
24. Sacht, H.O., (1967): Über den Verdichtungsvorgang bei landwirtschaftlichen Halmgütern und die dabei auftretende Wandreibung. Grundl. Landtechn. 17(2):47-52.
25. Schofield, R.K., (1935): The pF of the water in soil. In: Transactions, 3rd Internat. Congr. Soil Science 2:34-48.
26. Schwanghart, H., (1969): Messung und Berechnung von Druckverhältnissen und Durchsatz in einer Ringkoller-Strangpresse. Aufbereitungs-Technik. 12:713-722.
27. Sitkei, Gy., (1981): A mezőgazdasági anyagok mechanikája. [Mechanics of Agricultural Materials]. Akadémiai Kiadó, Budapest, pp.126-419. (in Hungarian).
28. Sitkei, Gy., (1994): Non-linear rheological method describing compaction processes. Int. Agrophysics, 8:137-142.
29. Sitkei, G., (1994): A faipari műveletek elmélete [Theory of wood processing]. Mezőgazdasági Szaktudás Kiadó. Budapest, Pp 105-140.
30. Sitkei, Gy., (1997): A non-linear Viscoelastic-Plastic Model Describing Compaction Processes. Proc. of the 2nd Int. Conf. of IMACS/IFAC Budapest, S. 105-112.
31. Stamm, A., (1946): Passage of liquids, vapours and dissolved materials through softwoods. USDA Bull. 929.
32. Timoshenko, S.; Woinowsky-Krieger, S., (1957): Theory of Plates and Shells. McGRAW-HILL Company. S.37-143.
33. Tiemann, H.D., (1906): Effect of moisture upon the strength and stiffness of wood. US Dep Agric For Serv Bull 70, 144 pp.
34. Varga, M., (1983): Por-forgács halmazok mechanikai tulajdonságai, különös tekintettel a tartályból való kifolyásra. [Mechanical properties of bulk wood chips]. Ph.D. dissertation, Hungary, Sopron, pp.74-144. (in Hungarian).