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# Application of Mechanics to Plant Seeds as a Granular or Particulate Material

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Additional information is available at the end of the chapter

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## Abstract

The mechanical behavior of plant seeds as a granular or particulate material dramatically differs from the mechanical behavior of solid materials. This difference is caused by the possibility of partially autonomous movement and rotation of seeds, their mutual contacts, or due to the occurrence of the second fluid phase among the seeds at the stage of their moving or processing. For obtaining the economic effects from the seeds (energy, nutrients, livestock, etc.), seeds must often be subjected to mechanical treatment. In this context application of mechanics as science concerned with the behavior of physical bodies when subjected to forces or displacements is very important and needed. One of the goals of this chapter is therefore to provide an overview for readers who are not primarily concerned with mechanics but who are interested in the behavior of seeds in the context of biology, agriculture, and pharmacy or food industry. This chapter is therefore focused on both an overview of the principles of mechanics of granular or particulate materials and the presentation of experimental results particularly in the area of mechanical extraction of oil from seeds.

**Keywords:** seed, mechanics, granular material, particulate material, rheological model, FEM model, oil extraction

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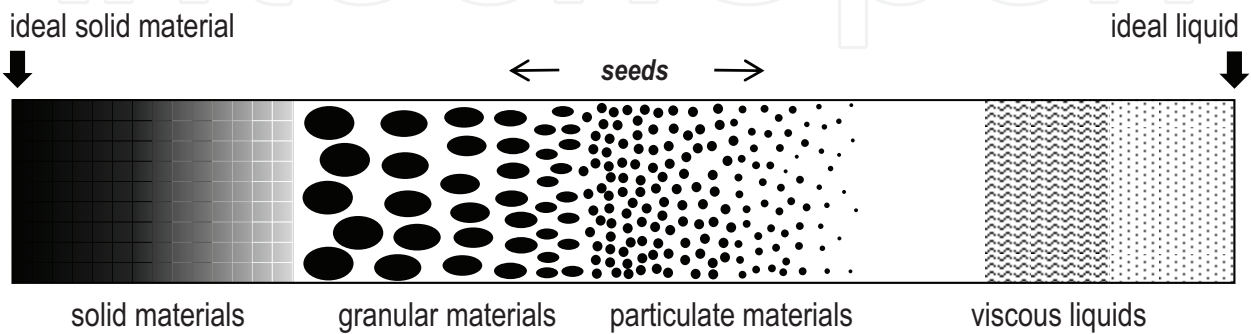
## 1. Introduction

Human life has become dependent on plants for the qualities and developments that they provide, which include agriculture, food production, and chemical industry. Plant seeds are one of the most important agricultural materials which affects billions of people. Seeds are the result of sexual reproduction in plants. Seeds are of immense biological and economic importance. They contain protein, carbohydrate, starch, and oil reserves that help in the early stages of growth and development in a plant. These reserves are what make many plant seeds important

source for a large proportion of the world’s inhabitants. For obtaining the economic effects from the seeds, they must often be subjected to mechanical treatment (manipulation, conveying, separation, hulling, pressing, purification, packaging, etc.). That is why studies of mechanical behavior of seeds are nowadays an important field of science and engineering. The research of how seeds as granular or particulate material are deformed, cracked, or how they flow has big importance for industries as biotechnology, pharmacy, agriculture, or food processing and various nanotechnologies. Results of that research are very important for both proper design of machines or equipment and for technological processes optimization. Current research has shown that seeds mechanical behavior is changing over time within the context of their moisture or oil content, acting forces, geometrical parameters, process of crack formation, porosity, visco-elastic properties, or in connection with the changes in the mutual arrangement or reorganization of the seed layers. The resulting nonlinear mechanical behavior and complex motion or spatial orientation of individual seeds or seed layers are very difficult to study, analyze, describe, and predict. For these scientific and engineering tasks, it is necessary to combine knowledge of basic physical seed characteristics, trivial calculations, modeling with the help of simplified or rheological models, or modeling using numerical methods such as FEM (finite element method) and DEM (discrete element method) and experimentation combined with relevant measurements. Also, special methods utilizing the principle of FEM with variable geometry like FDMs (fictitious domain methods) and IB-BCE (immersed boundary – body conformal enrichment) can be applied. Almost all the physical processes can be solved using numerical methods. The difficulty lies in the time-consuming calculation of highly complex and nonlinear problems. In this case, the calculation time can only be reduced by using supercomputers. The following chapter is therefore divided into several sections dealing with descriptive seed properties, seed mechanics principles, rheological models, and advanced modeling of seeds behavior.

2. Geometrical and mechanical properties of seeds

Seeds can generally be seen as granular or particular material (**Figure 1**). The actual state of the seeds as a material depends on the time from their harvest, moisture/oil content, and on mechanical, thermal, chemical, or other effects induced by the other subjects or by environment. Granular material is composed of small, discrete entities as opposed to being continuous. The granules

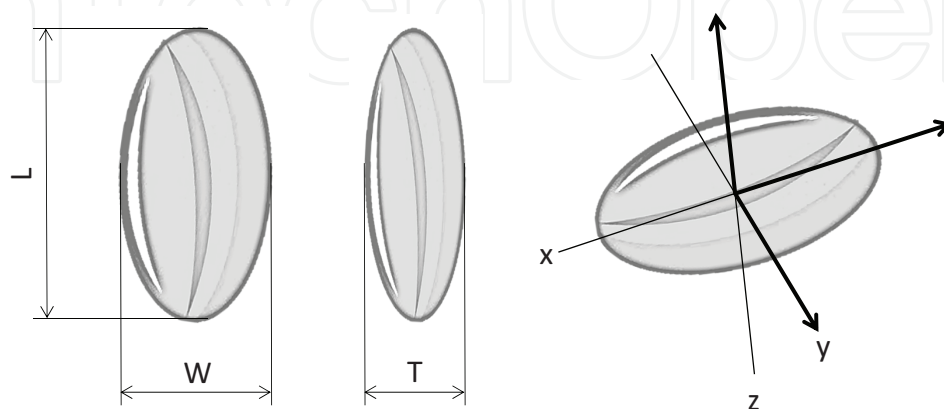


**Figure 1.** Plant seeds as granular or particulate material.

can be characterized as a mathematical set of macroscopic particles defined by their shape. Particulate material is substance composed of mutually contacting solid particles, or structural units, within the liquid and/or the gaseous phase [1]. For various reasons, physical properties of seeds need to be studied. A physical property is any property of matter or energy that can be measured. It is an attribute of matter that can be observed or perceived. The physical properties of seeds can be divided into following categories: geometrical, mechanical, chemical, electrical, optical, and others. For mechanical engineering tasks, geometrical and mechanical properties are most important. Geometrical properties are those that can be derived from the geometry of a seed body. Seeds, however, come in a great variety of shapes and sizes. Seed size varies among species over a range of 10 orders of magnitude with extremes represented by orchids, e.g., *Goodyera repens* (weight 0.000002 g) and by the double coconut palm *Lodoicea maldivica* (weight 18,000–27,000 g) [2]. Seeds may be round, egg-shaped, triangular, long and slender, curved, coiled like a snail or irregular in shape (**Figure 2**). Some have a groove or depression with a ridge along the length; others may be flattened at one or both ends. Moreover, the seed shape may vary in immature or poorly developed seed. Since seed shapes are highly variable, their shapes are simplified (very often on an oval shape), and standardized geometrical parameters are used for the purpose of solving tasks from basic or advanced mechanics and simulation. This simplification is very important as a mean by which the size and shape of an irregular shaped seed can be easily described and quantified whether the seed is treated as an individual unit or as one that is a representative of many seeds in layer or bulk. Selected and often used geometrical properties are illustrated in **Figure 3** and described in **Table 1**. Size of seeds determines the efficiency of processing and storage and the quality of semi-product or final product. For this reason, it is also necessary during mechanical problems



**Figure 2.** Different shapes of seeds.



**Figure 3.** Basic dimensions of seed with oval shape (L—length, W—Width, and T—Thickness).

solving to take into account the stochastic nature of geometrical properties, for example, distinguish size fractions of one type plant seed (most commonly divided into groups of small, medium and large seeds), frequency distribution curves, or coefficient of variation of individual geometrical property. Mechanical properties are physical properties that a material exhibits upon the application of forces. Examples of mechanical properties are the modulus of elasticity, tensile strength, elongation, hardness, and fatigue limit. Mechanical properties occur as a result of the physical properties inherent to each material and are determined through a series of standardized mechanical tests. Some of important mechanical properties of seeds are listed in **Table 2**.

Research on geometrical and mechanical properties has been focused on various types of seeds, such as rapeseed (*Brassica napus* L.) [2], Jatropha (*Jatropha curcas* L.) [4, 5], sunflower

Geometrical property of seed	Nomenclature	Unit	Formula
Length of one seed	L	mm	
Width of seed	W	mm	
Thickness of one seed	T	mm	
Arithmetic mean diameter	D <sub>a</sub>	mm	$D_a = (L + W + T)/3$ (1)
Geometric mean diameter	D <sub>g</sub>	mm	$D_g = (L * B * T)^{1/3}$ (2)
Equivalent diameter	φ	mm	$(4 S_m / \pi)^{1/2} S_m - measured\ area$ (3)
Seed surface area	S	mm <sup>2</sup>	$S = \pi (D_g)^2$ (4)
Sphericity	S <sub>φ</sub>	—	e.g., $S_\phi = D_g / L$ (5)
Volume of one seed	V	mm <sup>3</sup>	e.g., $V = 4/3\pi (L * B * T)$ (6)

**Table 1.** Selected geometrical properties of seeds.

Mechanical property of seed	Nomenclature	Unit
Bulk modulus	K	MPa
Coefficient of friction	μ	—
Compression energy	W <sub>C</sub>	J mm <sup>−3</sup>
Consumed energy at rupture point	W <sub>R</sub>	J
Deformation coefficient of mechanical behavior	B <sub>D</sub>	mm <sup>−1</sup>
Elasticity modulus	E	MPa
Energy used for rupture	E <sub>R</sub>	MPa
Rupture force	R <sub>F</sub>	N
Seed oil dynamic viscosity	η	Pa s
Shear modulus	G	MPa
Stress in the structure	σ <sub>S</sub>	MPa

**Table 2.** Selected mechanical properties of seeds.

Seed	L (mm)	W (mm)	T (mm)	D <sub>g</sub> (mm)	E <sub>R</sub> (Nmm)	R <sub>F</sub> (N)	μ (steel) (–)
<i>Brassica napus</i> (fraction: medium) [3]	2.12 ± 0.108	1.91 ± 0.093				13.53 ± 2.649	
<i>Jatropha curcas</i> L. (var. Kanlueang, nut) [4]	21.02 ± 1.03	11.97 ± 0.30	9.58 ± 0.28	13.40 ± 0.3	124.44 ± 19.95	146.63 ± 14.82	
<i>Helianthus annuus</i> L. (var. Morden, moisture 6.2%) [6]	9.27 ± 0.68	4.78 ± 0.34	3.32 ± 0.27	5.39 ± 0.416)			0.45
<i>Phaseolus vulgaris</i> (var. Hinis) [8]	11.76 ± 0.77	8.85 ± 0.50	7.66 ± 0.58	9.26 ± 0.53	63.79 ± 23.25 (X ax)	145.88 ± 33.54 (X ax)	0.227 ± 0.0038
<i>Dacryodes edulis</i> (moisture 10.3%) [9]	19.00 ± 1.1	12.20 ± 0.8)	10.10 ± 0.8)	13.2 ± 1.4			metal 0.25 ± 0.009

**Table 3.** Selected geometrical and mechanical properties of seeds.

(*Helianthus annuus* L.) [6, 7], bean (e.g., *Phaseolus vulgaris*) [8], arigo seeds (*Dacryodes edulis*) [9], pine (*Pinus pinea*) [10], chia seeds (*Salvia hispanical.*) [11], wild legumes (e.g., *Canavalia cathartica*) [12], melon seeds (*Cucumis melo* L.) [13], tung seed (*Aleurites Fordii*) [14], sugarbeet seed (*Beta vulgaris* L.) [15], sesame (*Sesamum indicum* L.) [16], vetch seeds (*Vicia sativa* L.) [17], green soybean (*Glycine max*) [18], quinoa (*Chenopodium album* L.) [19], hemp (*Cannabis sativa* L.) [20], and so on. Geometrical and mechanical properties of selected seeds types are listed in **Table 3**.

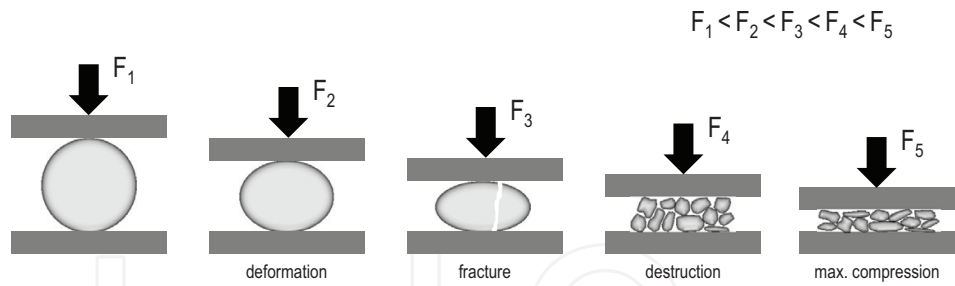
### 3. Mechanical behavior of single seed

When analyzing the mechanical behavior of individual seed, we can identify states similar to the mechanical behavior of the elastic body. Therefore, a model of an idealized flexible body can be used to study and describe the behavior of individual seeds. In this case, the forces and moments of the forces acting on the seed cause its state of strain accompanied by its deformation and fracture (**Figures 4 and 5**)

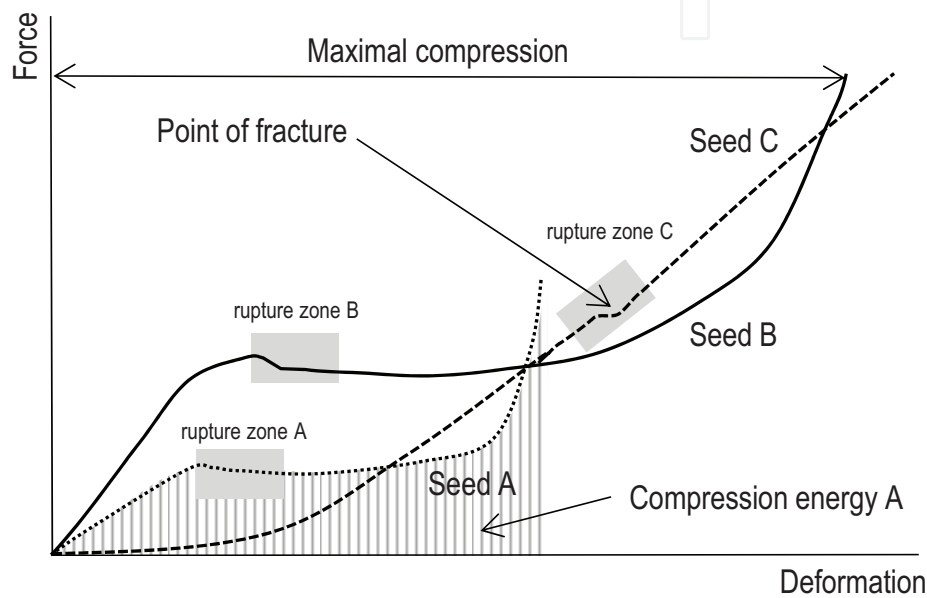
Initially consider the compression of seed as a compression of linear elastic substance and constant side pressure coefficient  $K_0|_{=const.}$ . Then, according to Hook's law:

$$\varepsilon_S^E = \frac{1 - 2\mu}{E_S} (1 + 2K_0) \sigma_S^E \quad (7)$$

where  $\varepsilon_S^E, \sigma_S^E$  are axial deformation and stress in the direction of compression during elastic deformation,  $\mu$  is Poisson's ratio, and  $E_S$  is initial stiffness modulus.



**Figure 4.** Seed deformation at different forces.



**Figure 5.** Selected types of deformation diagrams for different plant seeds.

During an elastic deformation, the structure of the substance does not change, and therefore, initial stiffness modulus will be constant  $E_S|_{=const.}$ . Deformation of single seed is a function of stress  $\sigma_S^E$  which characterizes the intensity of structural changes. Then, Eq. (7) can be overwritten as:

$$d\left(\frac{w}{w_0}\right) = d\left(\frac{V}{V_0}\right) = \frac{d\sigma_S^E}{E_S} \tag{8}$$

where  $w_0$  is the initial seed width.

The stress in the structure of the sample  $\sigma_S$  (MPa) can be resolved into the sum of stresses consisting of the stress elastic component  $\sigma_S^E$  and stress in the plastic component  $\sigma_S^P$ , and which is characterized by oil viscosity component  $\sigma_S^\eta$ . This is responsible for the damping of the structure. Friction component  $\sigma_S^\mu$  of the *seed* sample causes significant permanent deformation with geometrical and physical damage from certain value of strain. By using numerical analysis of the isothermal compression  $T=const.$  for the seed sample, it has been observed that the



elastic component of stress a function which is defined approximately by the Hooke's law [21]. This strain is characterized by a low oiliness point/low point of structure, where the isotropic properties of the structure can be considered. Values of low oiliness point for example tested samples of *J. curcas* L. are shown (Table 4). This area is characterized by a constant volume strain  $\gamma|_{\varepsilon_S \leq 40\% \text{ strain}}$ , which can be defined by Eq. (9), and in principle, it is same as Eq. (8).

$$\gamma = d\left(\frac{V}{V_0}\right) = -\psi \cdot \Delta C \quad (9)$$

where  $V$  is the volume (in an initial position: compression time  $t = 0$ ),  $C$  is the compression pressure, and  $\psi$  the compressibility [22].

$S$  is the projected area of the seed, and  $\varepsilon_{S\text{low}}$  is deformation of the seed (low oiliness point).

This can be visualized as a reversible elastic compression of the Hooke member, which is defined by the initial elastic modulus  $E|_{\varepsilon_S \leq \text{low point of structure}}$  and which can be supplemented by the damping factor of the Newtonian viscous member  $\eta|_{\varepsilon_S \leq \text{low point of structure}}$ . This behavior could be partly described by a generalized Maxwell rheological model (or generalized Maxwell model). The higher compression of the test structure from the point of oiliness or oil point passes the functional dependence of elastic stress in the elastic or plastic or visco-plastic components  $\sigma_S^E = f(\varepsilon_S)|_{\leq \text{low point of structure}} \rightarrow \sigma_S^P = f(\varepsilon_S)|_{\geq \text{low point of structure}}$ . This is reflected in breach of the yield stress of the test sample structure (Figure 5). Here, a comprehensive change in the volumetric strain  $\gamma|_{\geq \text{low point of structure}}$  was reflected and spread with the speed of plastic strain  $\varepsilon_S^P$  which caused increased friction  $\mu = \mu_S$  and creep structure due to extrusion of the oil component from the structure. Functional dependency was reflected in a significant increase in compression strength with a parabolic character which is different to the elastic-plastic deformation of elastic structures. There is a whole range of analytical and empirical relations in the literature that extend the seed deformation description by porosity. Define that the density of the undried seed is  $\rho_S = m_S/V_S$  and the density of the dried seed at 105°C is  $\rho_D = m_S/V_D$ . The pore volume can be then defined by the porosity number:

$$e = \frac{\rho_S - \rho_D}{\rho_D} = e_S - 1 \quad (10)$$

where  $e_S = \rho_S/\rho_D$  is the ratio by which the compression can be defined according to (9).

In principle, it is a semi-logarithmic Walker-Balsin's law applicable to, for example, powder metallurgy:

Maturity stage	T (mm)	S (mm <sup>2</sup> )	$\varepsilon_{S\text{Low}}$ (—)
Ripe	10.0 ± 1.8	180.1 ± 19.3	0.5
Over-ripe	10.2 ± 1.4	181.8 ± 19.5	0.4
Unripe	9.2 ± 1.9	172.2 ± 18.3	0.4

**Table 4.** Dimensions of the seeds prior deformation tests and the coefficients characterizing the deformation of seeds (data in the table are mean ± SD).



$$e_s = (1 + e_0)(1 - C \log \sigma_s) \tag{11}$$

where  $e_0$  is the initial porosity number at  $\sigma_s = \sigma_0$ .

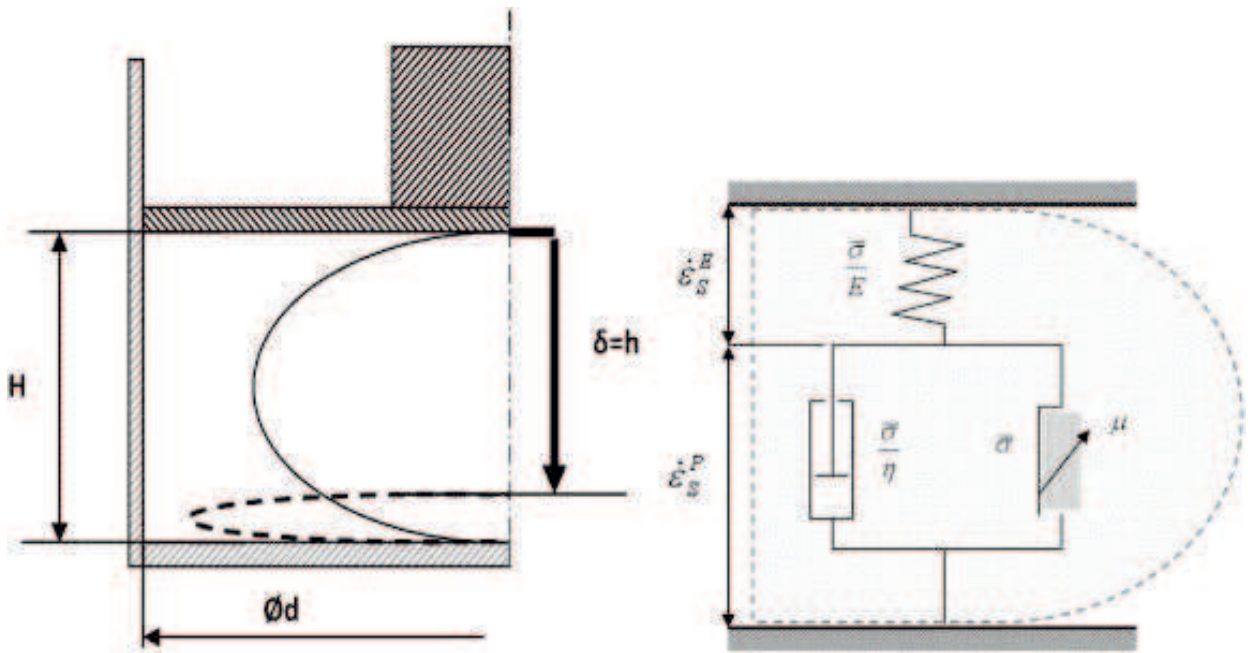
Let us assume a single seed is comprised under pressure  $\sigma_{s1}$  to width  $w_1$  and subsequently comprised under pressure  $\sigma_{s2}$  ( $\sigma_{s1} < \sigma_{s2}$ ) to width  $w_2 < w_1$ . Then, we can introduce Eq. (12), which (in the case  $\sigma_0$  is unit pressure) can be generalized to Eq. (13).

$$\frac{w_1}{w_0} - \frac{w_2}{w_0} = C \left[ \left( \frac{\sigma_0}{\sigma_1} \right)^m - \left( \frac{\sigma_0}{\sigma_2} \right)^m \right] \tag{12}$$

$$\frac{w}{w_0} = C \sigma_s^{-m} \tag{13}$$

For FEM simulation of such anisotropic behavior, we can use equilibrium equations or applications of the constitutive equations of a rheology model with modified parameters like Maxwell model, Kelvin model, Saint-Venant model or Perzyna model. Acceptance of certain seed states as a particulate material leads to the use of rheology in describing its mechanical behavior. The science of rheology is important to the study of the flow behavior of solids suspended in fluids. Rheological models (visco-elastic models) used to characterize seeds are classified as non-Newtonian fluids. For these fluids, no constant of proportionality exists between shear stress and shear rate; their viscosity varies with changing shear rate. For seeds, it is advisable to use the Perzyna rheological model in particular (Figure 6).

The Perzyna model with visco-plastic parameters includes the strain rate, and its rheological behavior is applicable not only for the description of elastic-plastic material damage but also



**Figure 6.** Perzyna rheology model for single *Jatropha curcas* L. seed compression [21].

for the behavior of anisotropic structures of compressed seed samples of different crops (**Figure 6**) in the plastic strain state  $\varepsilon_S^P|_{\geq \text{low point of structure}}$ . The Perzyna model derivation is based on studies of the stress limit description, which was defined by Bingham in 1920 to describe a plastic deformation of elastic materials. It is possible to use this model for quasi-static strain behind yield stress. Also, the model defines the time-dependent response of the structure cohesion, for example, the determination of oil extrusion initiation (so-called low oiliness point), immediate friction, and viscous and elastic parameters as functions or constants. Also, the Perzyna model can be used for modeling of the flow of soil such as clay. The velocity of stress  $\dot{\sigma}_S$  propagation during plastic deformation can be expressed by the constitutive Eq. (14), where the progress of plastic deformations is given by changing of volumetric strain  $\gamma$ , which can assume various values:

$$\dot{\sigma}_S = E_S(\dot{\varepsilon}_S - \dot{\varepsilon}_S^P) \quad (14)$$

where  $\dot{\sigma}_S$  is stress rate of structure,  $E_S$  initial elastic modulus,  $\dot{\varepsilon}_S$  is strain rate of structure, and  $\dot{\varepsilon}_S^P$  is visco-plastic strain rate.

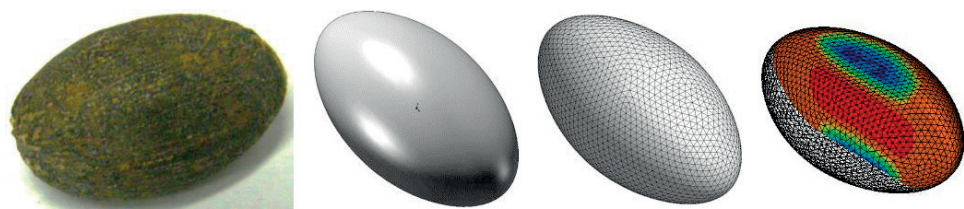
The plastic deformation of material structure denoted by the stress  $\sigma_S$  can be resolved according to Eq. (15) to the sum of the initial yield stress  $\bar{\sigma}_S(\bar{\sigma} \leq \sigma_S^P)$  and product of equivalent visco-plastic strain  $\gamma_S^P$  and function of the strain  $h_S^P$  that describes following condition: if  $h_S^P < 0$ , then a softening of the structure occurs  $h_S^P > 0$ , and then a hardening occurs:

$$\sigma_S = \bar{\sigma}_S + h_S^P \cdot \gamma_S^P \quad (15)$$

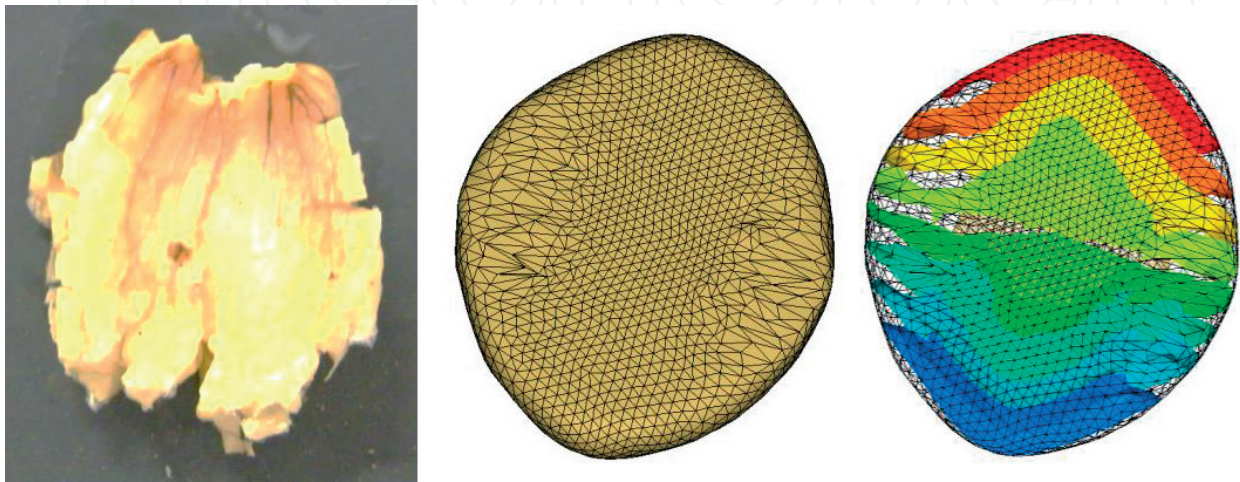
The numerical model can be subsequently designed for isothermal or thermal compression of different seed types. An example is the numerical isothermal study of three samples of *Jatropha* seeds (mature, immature, and precisely mature) with the same initial geometry  $\Omega_{S(\text{ripe})} = \Omega_{S(\text{unripe})} = \Omega_{S(\text{overripe})}|_{t=0}^{T=\text{const.}}$ . Differently mature seeds show different deformation of the original geometry during compression  $t \neq t_0$ , which has been described in detail in [21]. The degree of compression of magnitude  $\delta$  is also the compressibility function  $\psi$  according to Eq. (9). Seed dimensions for the CAD/FEM model for differently mature seeds are based on data listed in the **Table 4**. Modeled seeds had almost ellipsoidal shape with dimensions  $\sim 17 \times 10 \pm 1.8 \times 9.3$  mm, as shown in **Figure 7**.

Compression experiments and simulations of *J. curcas* L. seeds were performed up to plastic deformation (**Figure 8**). The model showed the highest concentration of the main stress on the seed circumference for each level of maturity of tested seeds. This is because the greatest stress is concentrated in the center of the seed and consequently causes the extrusion of the structure from the center toward the periphery. This effect changed and damaged the smallest radius of the seed shape as seen from **Figures 8** and **9**. From this, it can be deduced that the seed is damaged by the internal pressure resulting from external compression forces.

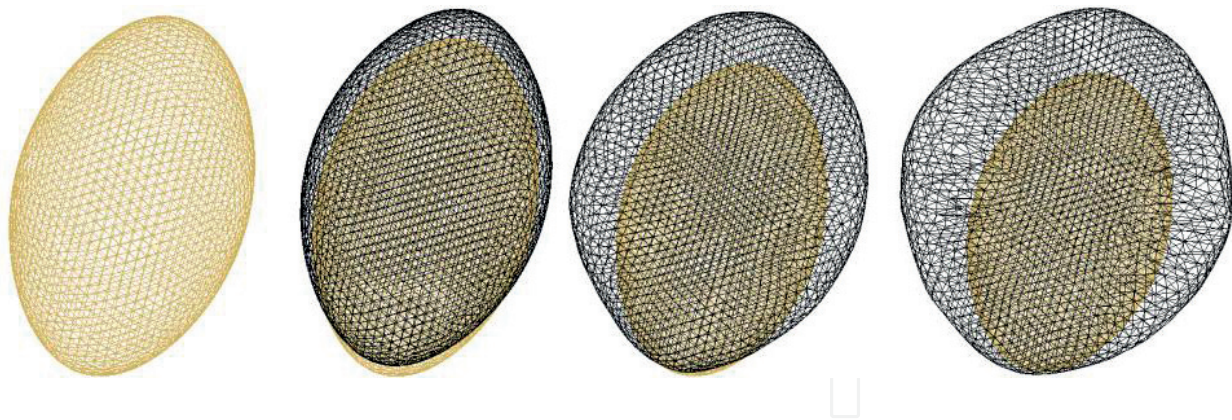
The energetic behavior of individual seeds during compression is shown in the following figures. **Figure 10** shows the comparison of compression forces derived from mathematical



**Figure 7.** *Jatropha curcas* L. seed (CAD model, FEM model, and simulation model).



**Figure 8.** Deformation of *Jatropha curcas* L. seed (real sample, FEM model, vector plot of FEM model).



**Figure 9.** Time response of *Jatropha curcas* L. seed deformation.

equations and forces obtained by numerical models. It can be seen from **Figure 10** that mathematical relationships (7)–(13) do not allow to sufficiently describe the “point of fracture” as they are generally based on the empirical analysis and using graphs of standard mathematical functions (such as a parabola). Point of fracture can be better and more accurately determined from numerical models. Numerical and FEM models can be used to solve a whole range of engineering tasks. For example, using a FEM model, it is possible to determine the compressibility of mature, immature, and overmatured seeds (**Figure 11**) or to effectively assess the



energy intensity of obtaining the oil from the seeds. The results of the experiment also showed differences in the values of the stress of individual seeds, which depend on their maturity.

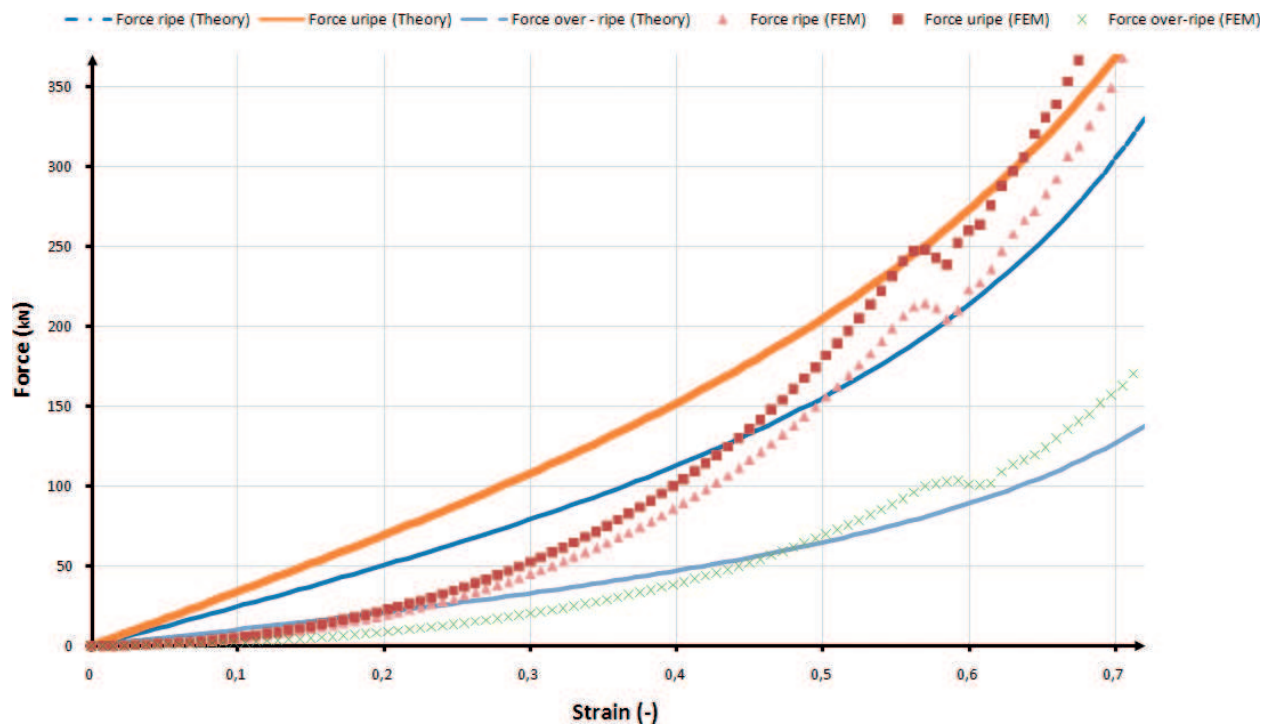


Figure 10. Comparison of theory and FEM model of *Jatropha curcas* L. seed for compressive force.

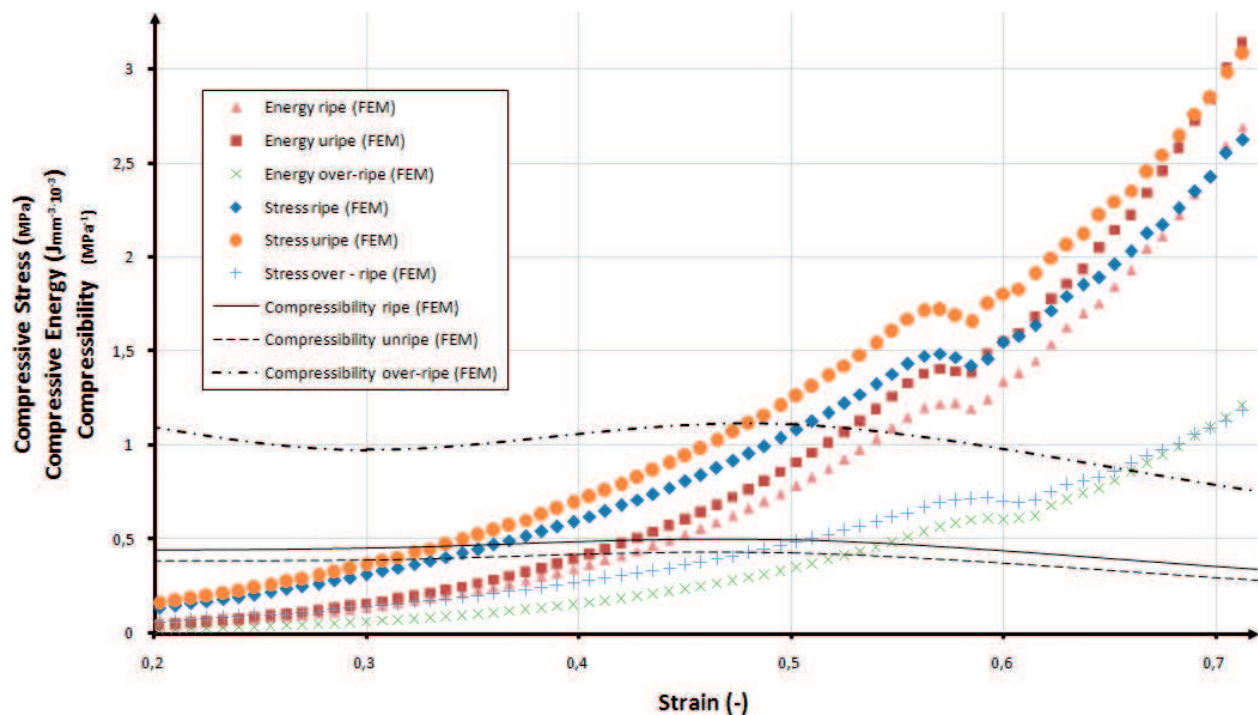


Figure 11. Strain response: compressive stress, compressive energy, compressibility (individual seed).

These findings can be used to find a proper seed position to control orientation of the seed in the press or to optimize the geometry of the press.

#### 4. Mechanical behavior of seeds as a granular or particulate materials

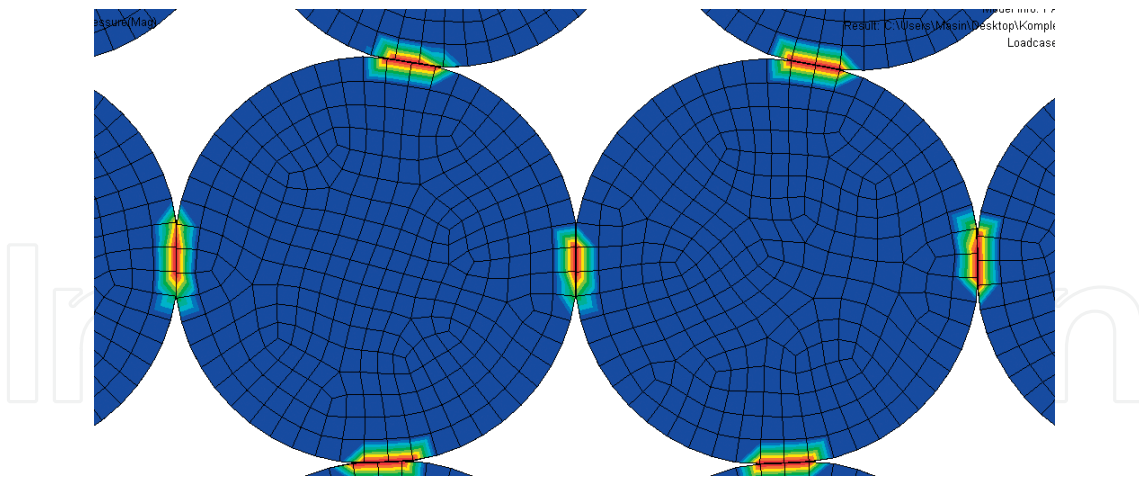
Seeds as a granular or particulate material consists of individual seeds and adjacent voids filled with gas (air) or/and liquid (e.g., oil). Understanding the mechanical behavior of such kind of material, we must therefore take into account the geometrical presentation that describes spatial distribution of seeds and voids, orientation of seeds, and contacts of seeds, etc. Systems composed of seeds consist of mutually contacting phases, which can be solid (geometry, solid structure of seed, etc.), liquid phases (oil component of seed), and gas phases (gaseous environment). The liquid and gas phases fill the pores of the solid skeleton of the seed. In addition to these basic phases, there are mutual bonds between the seeds which, in terms of mechanical properties of the compressed seeds, are mainly frictional. When compressing seeds, we have to study frictional bonds seed-seed, seed-seeds, seeds-container wall, etc. To understand this complex process, we can start on the general theory of friction of solids. The two ideal solid particulate seeds, when moved relative to one another, can either slide or roll in an elastic state. Seeds in a plastic state can penetrate and break into each other. In solving mechanical problems, generally we have to distinguish dry seed surfaces, hydrodynamically lubricated surfaces, and limiting friction. The friction or contact bond is given by the normal stress  $\sigma_n$  on the geometric contact area  $a_g$  (**Figure 12**). The normal stress of the contact points  $\sigma_n^c$  on the surface area  $a_s$  is then given by Eq. (16). Similarly, sliding friction  $\tau_n$  can be described by Eq. (17). where  $\tau_n^c$  is the shear strength of contact point (assumed to be the same everywhere). From Eqs. (16) and (17) is Eq. (18):

$$\tau_n = \frac{\tau_n^c}{\sigma_n^c} \sigma_n = \nu \sigma_n \quad (16)$$

$$\sigma_n^c = \sigma_n \frac{a_g}{\sum a_s} \quad (17)$$

$$\tau_n = \tau_n^c \frac{\sum a_s}{a_g} \quad (18)$$

According to Eq. (18), we obtain the friction response between the seed surfaces. It follows that shear friction in the case of seeds also does not depend on the size of the surface and is directly proportional to the normal stress. The area of contact point plasticity allows a more accurate description of the plastic state of the stresses in it as well as for the emerging strain. The surface area  $a_k$  is inversely proportional to the stress  $\sigma_n^c$  according to Eq. (16) and at the same time increases the shear stress of the contact point [23]. This effect is particularly evident in elastic materials such as steel, in which case their friction coefficient  $\nu$  increases considerably. In the case of structures such as seeds, this problem is limited by their skeletal fragility. In general, according to the friction adhesion theory, the intergranular friction coefficient is equal to the



**Figure 12.** Contact area  $a_s$  of the seeds on their outer boundary.

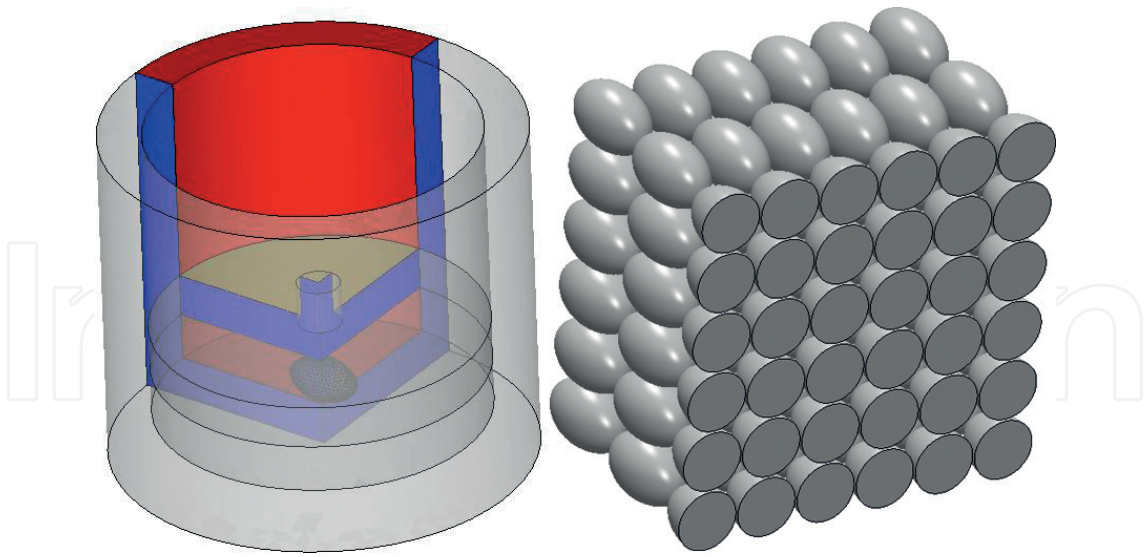
shear and normal strength of the contact point. Through this theory, we gain a function dependent on the amount of stress concentration at the boundaries between the seeds.

Therefore, the description of the mechanical behavior of the seeds as granular or particulate material must, for various reasons, be based on:

- initial seed configuration (seeds geometry, seeds orientation, shape regularity, and ripeness);
- the volume ratio of the individual phases in the press  $V_{Si} | V_A \neq V_{Si} \neq V_{oi}$  ( $V_A$  the volume of air,  $V_{Si}$  the volume of individual seeds,  $V_{oi}$  the volume of the oil fraction of each seed);
- the ratio of the initial elastic modules  $E_{Si} | E_{ripe} \neq E_{unripe} \neq E_{overripe}$  ( $E_{ripe}$  the ripe seed module,  $E_{unripe}$  the unripe seed module,  $E_{overripe}$  the overripe seed module);
- initial volumetric modules  $G_{Si} | G_{ripe} \neq G_{unripe} \neq G_{overripe}$ ; and
- initial shear modules  $K_{Si} | K_{ripe} \neq K_{unripe} \neq K_{overripe}$ .

As an example, we can consider a seed-system that will be compressed in an experimental container. Such a system will be loaded with axial stress  $\sigma_a$  and all-sided pressure  $\sigma_r$ . We will not consider a homogeneous system where the stress  $\sigma_a, \sigma_r$  would be totally consistent with the continuum, but we will consider a particle system where each part of the filled container (seeds, air, walls, and piston) contributes to  $\sigma_a, \sigma_r$ . Terzaghi [24] introduced in 1923 the construct of effective stress, which is a function of the total stress and the particle stress. The study states that the change in chamber pressure does not affect the dependency of  $(\sigma_a - \sigma_r)$  on axial strain of the system  $\epsilon_a$ . Terzaghi also introduced the boundary condition that we can simplify the particular systems in the individual planes of symmetry (**Figure 13**). The greater the seed filling in the container, the more accurate the calculation will be, not only as a continuous system but also as a particle system. This claim can be demonstrated by the example of compressing a system of regularly arranged ellipsoidal shaped seeds (such as *J. curcas* L.). If we make a simple axial section of the seeds, we obtain a 2D arrangement of identical circles with a radius  $r$ , where adjacent circles touch each other (**Figure 13**).





**Figure 13.** Symmetry planes for modeling (left) and axial section for 2D model (right).

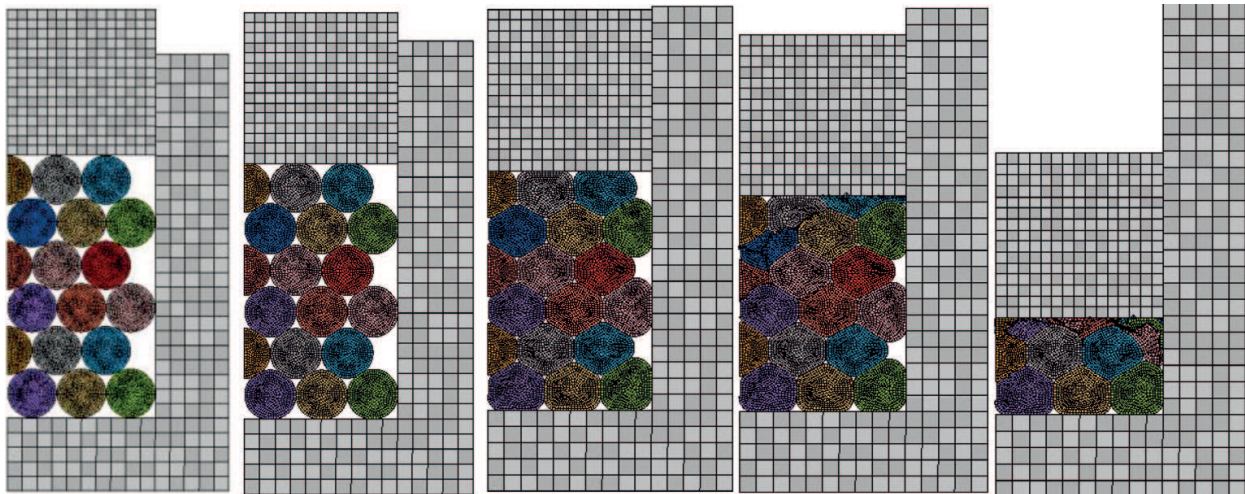
During compression, the radius  $\Delta r$  will change. Radius  $\Delta r$  will be a function of contact forces that can be derived from the Hertz or Mindlin relationship. Basically, if the contact forces are known, deformation of the circles for axial strain and lateral strain can be calculated according to Eqs. (19) and (20).

$$\varepsilon_S^a = \left( \frac{3(1-\nu_S)\sqrt{2}}{G_S} \right)^{2/3} \cdot \left[ 2 \left( \frac{1}{1+\nu_S} \frac{\sigma_a}{\sigma_r} \right)^{2/3} - \left( 2 \frac{1-\nu_S}{1+\nu_S} \frac{\sigma_a}{\sigma_r} \right)^{2/3} - 1 \right] \cdot \sigma_r^{2/3} \quad (19)$$

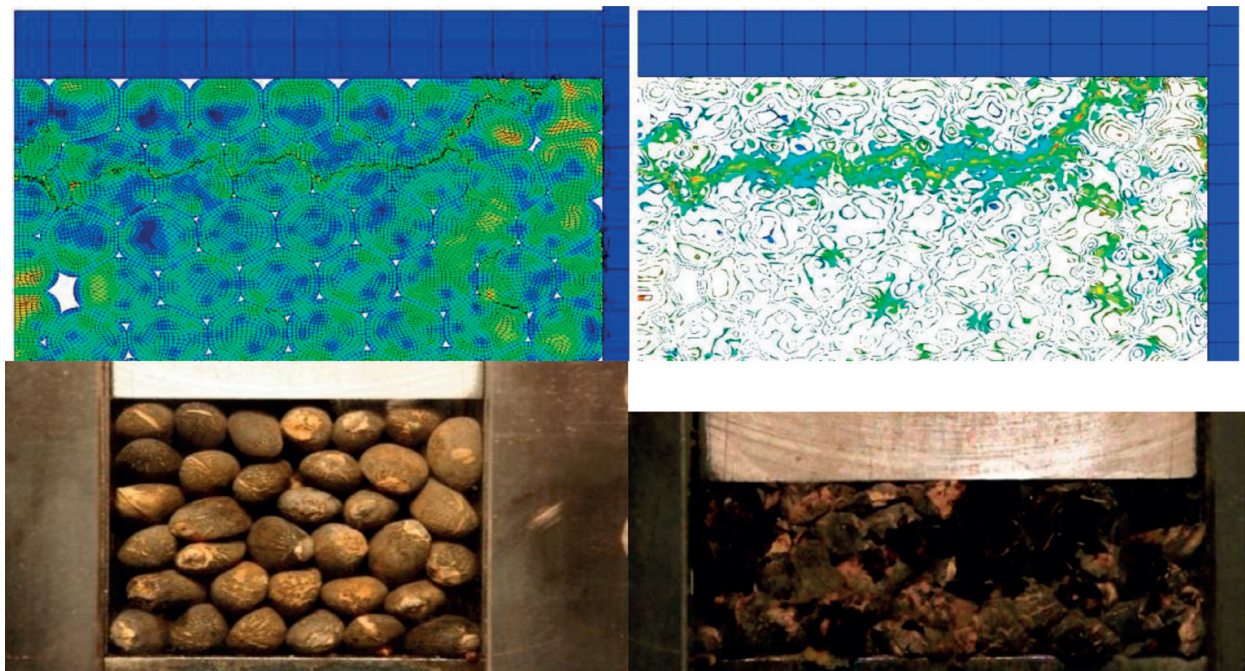
$$\varepsilon_S^r = \left( \frac{3(1-\nu_S)\sqrt{2}}{G_S} \right)^{2/3} \cdot \left[ \left( 2 - \frac{1-\nu_S}{1+\nu_S} \frac{\sigma_a}{\sigma_r} \right)^{2/3} - 1 \right] \cdot \sigma_r^{2/3} \quad (20)$$

It can be seen from Eqs. (19) and (20) that the size of the strain depends on the ratio of the main stresses  $\sigma_1/\sigma_3 \equiv \sigma_a/\sigma_r$ . There is a special case, where the contact forces of the ideal circular arrangement are statically determined (in case of hydrostatic tension, respectively, when  $\sigma_a = \sigma_r$ ). These mathematical derivations of stress and deformation give us insights about mechanical changes of the compressed seed system. The Terzaghi's principle is well described in [23], where a symmetrical numerical model was created to study the strain of the seed system during compression.

**Figure 14** shows the transformation of seeds stored in a regular hexagonal arrangement where the initial seed filling  $\alpha_S$  will gradually increase during compression as it  $\alpha_S < \alpha_{S1} < \alpha_{Sn} | t_0 < t1 < tn$ . **Figure 14** also shows the reorganization of the seeds and their subsequent clustering and joining in the case of a plastic failure. **Figure 15** is a comparison of the modeled individual seeds crack propagation with a real experiment. This gives us insight into the compressive behavior of individual seeds and thus the knowledge about the efficiency of the pressing process. By increasing the crack in the individual seeds, we also provide information on the movement and direction of the extruded oil.



**Figure 14.** Seed-system deformation in time.



**Figure 15.** Growth of the cracks in seeds during pressing (FEM model—above, experiment—bottom).

Consequently, the energy behavior of the seed system during compression can be evaluated, as shown in **Figures 16** and **17**. Figures compare numerical models and the experimental data (compressive forces and compressibility) for the different cylinder diameters. The results show a very good match that can be attributed to the simplified 2D symmetric model, which approximates empirically established relationships (19) and (20). A 2D seed-system modeling not only simplifies calculation and reduces time for computations but also allows for more accurate results compared to 3D modeling of single seed behavior (**Figure 10**). Appropriate simplification of mathematical models describing the mechanical



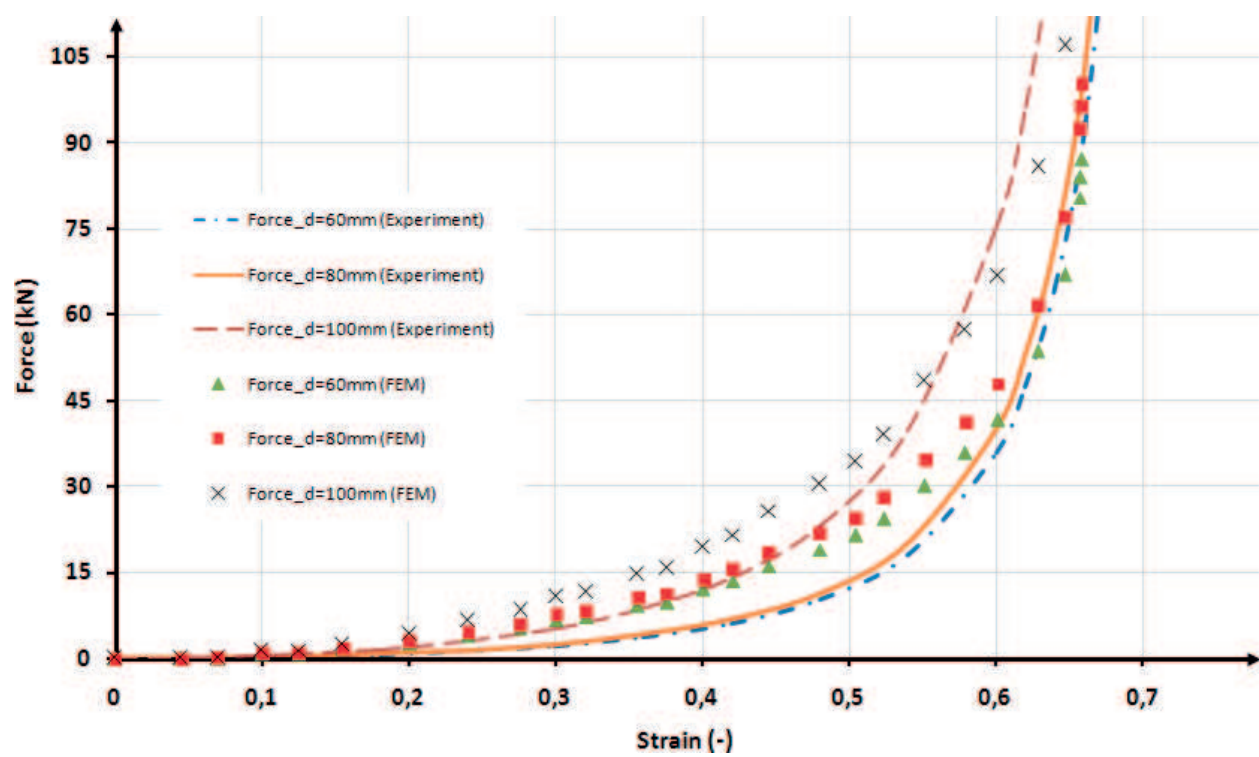


Figure 16. Comparison of experiment and FEM model for compressive force.

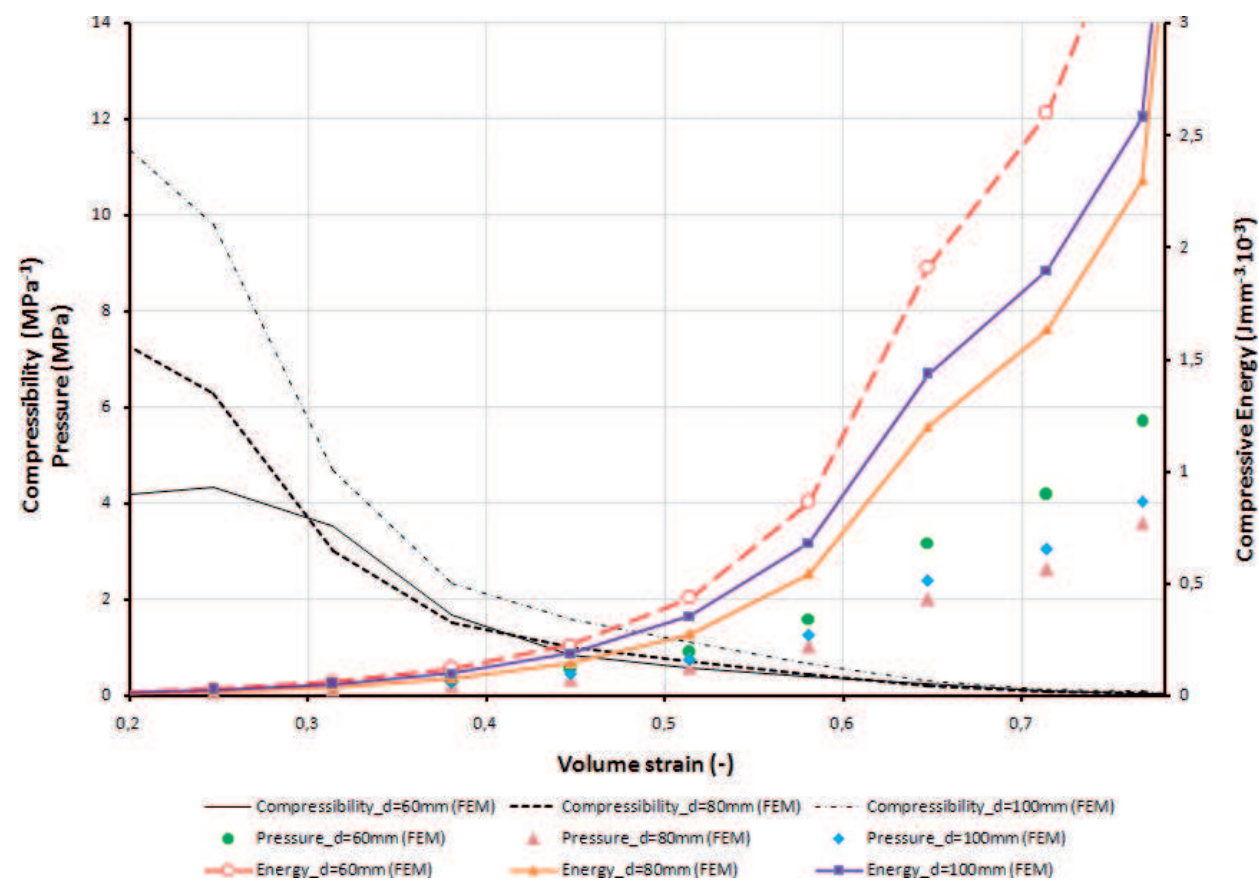


Figure 17. Strain response: compressive stress, compressive energy, compressibility (system of seeds).

behavior of seeds-system (edge conditions, symmetry, etc.) can provide us with results that are sufficient to comprehend complex processes and to optimize seed treatment technologies, compared to sophisticated models with disproportionate time-consuming calculation and interpretation. Mathematical models of seeds mechanical behavior are very important for different agricultural and engineering tasks (e.g., tillage mode, processing technology design, treatment control and optimization, procedures effectiveness increasing, seeds behavior prediction, etc.).

As this topic goes beyond the scope of this publication, we refer readers to various works focused on various aspects of mechanic behavior of seeds, using different theories, models, and modeling methods:

- modeling of seeds compression [21, 22, 23, 25, 31];
- modeling of stress or force relaxation of seeds [30];
- modeling of seeds movement and orientation [26];
- various contact and friction models utilization [1, 29];
- FEM application for seeds behavior modeling [21, 23]; and
- DEM application for seeds behavior modeling [27, 28].

## 5. Conclusion

A detailed understanding of the mechanical behavior of plant seeds is currently an important science and technology challenge. Post-harvest geometrical and mechanical properties of the seeds or seeds mechanical behavior are important from the point of view of treatment process optimization and machines design. Basic dimensions and geometrical properties (length, width, thickness, mean diameters, seed surface area, sphericity, etc.) were described in this overview type of paper. Selected mechanical properties (e.g., compression energy, stress in the structure, coefficient of friction, rupture force, etc.) were also described. Mechanical behavior of seeds has been described and discussed in terms of both single seed and seeds-system. Selected experimental results from the research of mechanical behavior of *J. curcas* L. seeds were used to bring seeds behavior as a granular and particulate material closer to readers.

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