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Numerical Modeling of the Viscoelastic Behavior of Potatoes

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Abstract
This paper presents a rheological study of agricultural product and its viscoelastic behavior, by EF through the objective numerical simulation tool based on parameters derived from experimental tests, mainly Young's modulus, Poisson's ratio and thermal conductivity, to study the behavior of raw potato (variety: spunta), to perform creep and conformance at constant load and each numerical model. The times imposed in the model and the strains recorded make it possible to determine the characteristic elastic part, the first and the second part of the creep curve and the determination of the quantitative parameters (dynamic viscosity η1, η2, E1, E2) of this biological material. These results which will be drawn present references to limit the maximum loads for the resistance of the potato against damage, and to increase the yield of the fresh product in the transports, storage and harvest also on the effect of temperature on the behavior of potatoes under the conditions encountered in its estimated cycles.
Keywords*: rheology, agricultural product, viscoelastic, EF, numerical simulation, experimental tests*

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I. Introduction

The damage, caused by static charges on agricultural products, is of great importance, as it affects fruits, vegetables [1].Some types of fruits and vegetables, such as apples, potatoes, tomatoes, are quickly damaged under such conditions given their mechanical behavior, it is important to know how these forces transmitted from fruit to each other and can cause permanent deformations at the contact points on the crop fruit or vegetable, and cause damage[2;3]it is very important to study this rheological phenomenon during storage, harvesting, transport and marketing[3; 4; 5], viscoelasticity is like a combination of recoverable elastic strain and permanent viscous strain (Figure 1). Viscous strain has been found to lead to time-dependent permanent strain (creep) under instantaneous constant stress[6, 7]almost all biomaterials exhibit viscoelasticity to varying degrees[8; 9].Many materials, mainly agricultural, exhibit a more complicated behavior[10; 11].Viscoelastic materials deform under a constant load or stress or strain, following the interpretation of the creep and relaxation curve, several researchers have shown that fruits and vegetables exhibit viscoelastic behavior of course potato[12].The deformation is measured as a function of time. The main advantage of creep compliance testing is that analysis can be facilitated using the Burgers model[13].

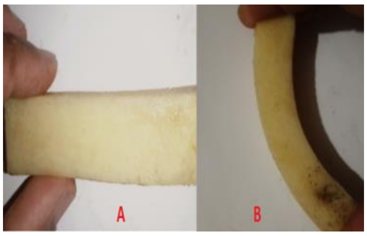

Figure 1. Response to loading and unloading potatoes

The development of the viscoelastic response of a material is modelled by a combination in several forms between spring and with a damper (figure 2), this complicated study makes it possible to highlight the two responses of the material at the microscopic, instantaneous and delayed, and both must be described in the same differential equation as a function of time. These relationships are a way to develop what happens in practice to understand molecular motions[14; 15].

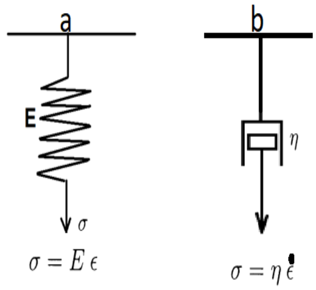

Figure 2. (a) The spring represents the elastic behavior and (b) the damper represents the behaviorof viscous material

II. Materials And Methods:

2-1.Theoretical Method and Formulation of the Problem

In the case of the Maxwell model, the spring and the damper undergo the same stress applied to the whole system (σ = σE = σEL), and the result the deformation e is the sum of the displacements of the spring (elastic) and damper (viscous) (Ɛ = ƐE + ƐEL)
[16; 17]
Behavior law

$$\text{Ɛ} = \frac{\sigma}{E} + \frac{\sigma}{\eta}.$$

While the De Kelvin - Voigt model (figure 3) the system undergoes the same strain (ε = εE = εEL), The total stress of the system is the sum of the stresses σt = σ E + σ EL(18)..

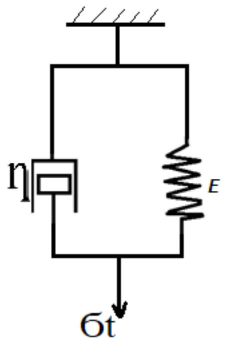

Figure 3. Kelvin- Voight Model

The stress of the spring resistance:

$$6_E = \mathcal{E}_E E_E$$

Likewise the constraint of the resistance of the dashpot (viscosity):

$$\sigma_{EL} = \eta\frac{d\varepsilon_{El}}{dt}$$

Therefore, we can write that the total load of the system can be explained by the following equation

$$6_t = 6_E + 6_{EL}$$

So we have;

$$6_t = \mathcal{E}_E E_E + \eta\frac{d\varepsilon_{El}}{dt} \quad \text{with} \quad (\varepsilon=\varepsilon_E=\varepsilon_{EL}),$$

Which give $\sigma_t = \varepsilon_t E_E + \eta\frac{d\varepsilon_t}{dt}$

The differential equation of the total strain is therefore written:

$$\frac{\sigma_t}{\eta} = \varepsilon_t\frac{E_E}{\eta} + \frac{d\varepsilon_t}{dt}$$

A solution like$\mathcal{E}_t = \frac{\sigma}{\eta}(1 - e^{\left(-\frac{-tE_E}{\eta}\right)})$

2-1_1. Study Model Selection Criteria

Burger's model indicates that the behavior of agricultural materials (potato, tomato) under stress or viscoelastic behaviors can be represented by Kelvin- Voight Model in series with the Maxwell model, which can also be modified [13;17;19;20]. As the complex behavior of these types produces, it is very important to fill in the maximum of data to identify it thanks to the creep test, that is to say that the analysis can be easy with this model

(Fig 4), larger number of rheological parameters can be estimated, the elastic, viscoelastic and viscous flow properties can be predicted separately[20; 21; 22]. The parameters of the model can thus be correlated with the discrete components of the tested product, in order to achieve a mechanism that reflects the changes in microstructure, in this case our approach is based, the first step an experimental study to collect and determine the properties ,mechanical, physical possible, we can then find the rheological properties from the finite element resolution by means of a numerical simulation which has been correctly traced as a function of the deformation / time [13 ;19].

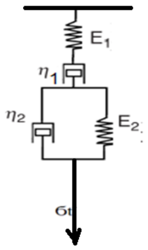

Figure 4. The Burger model consisted of the Maxwell and Kelvin - Voigt models in series.

2-1_2. Study OfThe Mechanism

Rheological models have been a useful tool for evaluating and predicting the mechanical response to the force imposed on food (or stress-strain). The rheological properties of many solid foods have been evaluated, in general, by creep tests, based on the behavior in compression and in tension [23].The rheological behavior of a material in addition to its sensory properties is governed by the physical structure and biochemical composition which determine its structural properties. In general, the combination of mechanical elements (usually springs and damper) can be used to model the viscoelastic response of agricultural materials[24 ;25]in order to better understand how the system reacts in the event of creep and recovery behavior we have several classical models, but the Burgers model has been widely used to represent the behavior of these types of materials, by connecting a Maxwell unit and a Kelvin unit in series, the Burgers model divides the creep stress of a polymer material into three types of strain[26]:

Instantaneous deformation:$\mathcal{E}_{E1} = \frac{\sigma}{E_{E1}}$

And plastic deformation (residual):

$$\mathcal{E}_1 = \frac{\sigma}{\eta_1}$$

The delayed elastic deformation of the Voigt model only:The delayed elastic deformation of the Voigt model only:

$$\mathcal{E}_2 = \frac{\sigma}{E_2}(1 - e^{\left(-\frac{tE_2}{\eta_2}\right)}) \quad \text{Or shear stress} \zeta = \frac{\eta_2}{E_2}$$

$$\frac{\sigma}{\eta_2} = \frac{d\varepsilon_2}{dt} + \frac{E_2}{\eta_2}\varepsilon_2$$

The overall strain of the system can be described by the following equation:

$$\mathcal{E}(t) = \mathcal{E}_{E1} + \mathcal{E}_1 + \mathcal{E}_2$$

Where the indices Ei, ηi correspond to the evolution of the response of materials as a function of time, elastic, viscoelastic and viscoplastic, this temporal function of Ɛ (t) thus, the creep behavior can be as follows:

$$\mathcal{E}(t) = \sigma[\frac{1}{E_1} + \frac{t}{\eta_1} + \frac{1}{E_2}\left(1 - e^{\left(-\frac{tE_2}{\eta_2}\right)}\right)]$$

Where E1 and E2 are the modulus of elasticity of elastic elements, η1 and η2 are viscous elements in dampers, σ and t are respectively the applied stress and the creep time.Creep is a slow, continuous deformation of a material under constant stress. Unlike ordinary metals, agricultural materials experience creep even at room temperature. An instantaneous strain (ε0) proportional to the applied stress is observed after the application of the stress and this is followed by a gradual increase in the strain as shown in Figure 5.

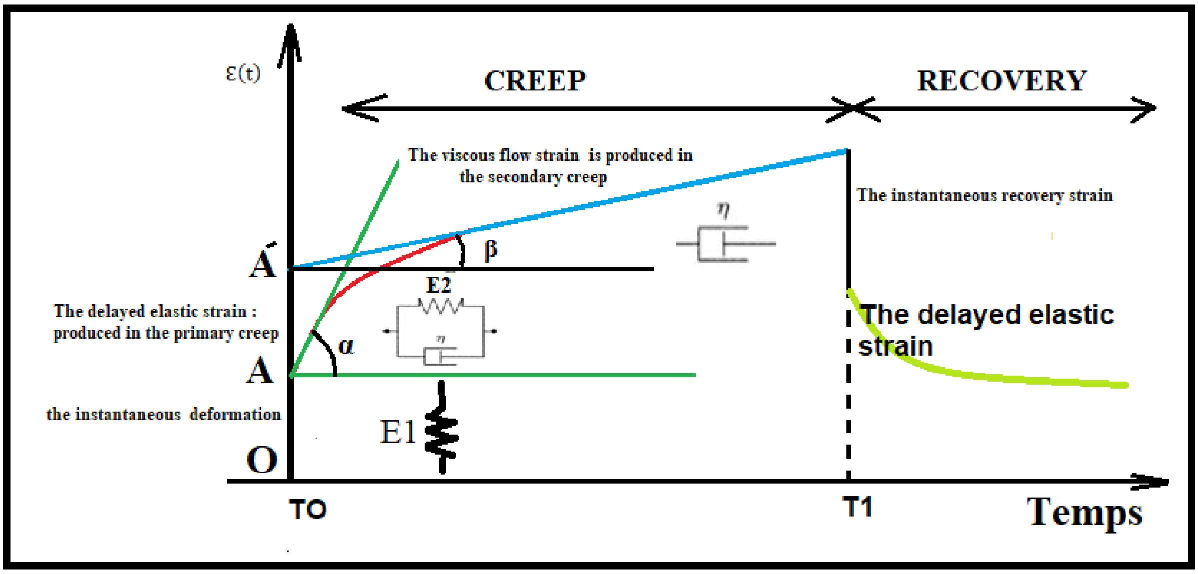

Figure 5.the behavior corresponding to the viscoelastic strain time of the four-element Burger model

The total strain at any time is represented by the sum of the instantaneous elastic strain and the creep strain. The process creep of viscoelastic materials can be divided into three typical creep stages (instantaneous strain, primary and secondary creep (Figure 5). For ideal linear viscoelastic materials, instantaneous strain represents the elastic property of the material. Instant recovery strain is usually equal to the instantaneous creep strain. The delayed elastic strain is produced in the primary creep, and it takes time for full recovery. Viscous flow stress is produced in the secondary creep, which is an irreversible component of the deformation [27;28;29].
The above equation has four unknowns which can be determined from the creep curve and the following initial conditions at t = 0:

$$\varepsilon(t=0) = \varepsilon_1 = \frac{\sigma 0}{E1}$$

$$\varepsilon_2 = \varepsilon_3 = 0$$

Whereσ0 / E1 is the starting phase of deformation which is caused by spring 1. The creep speed at the start t = 0 can be found by differentiating the deformation equation from the Burgers model:

$$\frac{d\varepsilon}{dt} = \frac{\sigma 0}{\eta 1} + \frac{\sigma 0}{\eta 2} \cdot e - t/\tau$$

Determination η1 ‹is the slope of the creep function at infinite time (t = t1) represented (tang B) ‹from the curve ‹the angle β measured to calculate η1 from:

$$\varepsilon(t=t1) = \varepsilon = \frac{\sigma 0}{\eta 1} = \mathrm{tg}\beta$$

After the passage the elastic creep begins at t = 0 with a strain as a function of time, where the explanatory parameters of this phase (curve) are found, the value of η2 can be evaluated from the following equation:

$$tg\alpha = 6\left(\frac{1}{\eta_1} + \frac{1}{\eta_2}\right)$$

It remains to determine E2 and E1 directly from the curve:

$$A\check{A} = \frac{6_0}{E_2}$$

According to the four-element burger model, it is necessary to calculate the constants (E1, E2, η1, η2), here by the graphic method to evaluate the creep, that is to say the behavior of the material studied [17; 19 ;30;31;32].

2-1-3. Numerical Method

from the experimental determination of the mechanical parameters for the numerical simulation, to arrive at the determination of significant and exploitable results of the mechanical and rheological properties of potatoes, we took tubers of the spunta varieties that we put between 7 and 46 ° C for 24 hours until a homogenization of the temperature gradients is observed as shown in the following figures (figure 6) then carry out experimental tensile tests under the same conditions for all the specimens (potato: figure 7) and with the same test bench, subsequently this problem will be simulated by finite elements

Figure 6: thermal homogenization of potato studied in an oven

Subsequently we determine the mechanical properties of Young's modulus, of moisture proportion which will be useful in determining the Poisson's ratio thereafter, all these values will be used as limiting conditions for numerical models, and of course thermal conductivity[33].

Figure 7: Fixation of the specimen and course of the tensile test

The results of the mechanical properties (tensile test) of the material are shown in Table 1, we try to minimize and simplify as much as possible the shapes and the geometrical stresses of the test specimen which was used (a rectangular parallelepiped).[34; 35, 36]

Table 1: Mechanical behavior of the test specimens studied

T Variety: spunta	T=7°C	T=25°C	T=46°C
	t=24 h		
μ: the Poisson's ratio	0,46	0,39	0,32
E(Mpa) :Young's modulus	3,2	3,8	4,2
L=100 mm			
K=°C+273,15 [°C=0 ↔ °F=32]			

2-2 Numerical Simulation

Solving finite element (FE) of problems using numerical simulation models is a very useful tool for predicting how materials respond to forces and other physical effects. In the case of the potato, FE models can be used to study the expected yields at creep loads at different temperatures.

2-2-1.Problem Analysis

This analysis must determine the parameters of calculation which will lead to determine the unknowns in each node, this stage depends on the method followed capable of making the problem correspond to the diagram of convergence. The main difficulty is to find a good compromise between the criteria of the problem, the analysis of these leads to release a certain number of hypotheses, and to make choices to condition the results. After the graphic representation, one introduces the parameters indicated in the table, then the choice of the numerical viscoelastic model and their necessary conditions, after the phase of assembly, one imposes the boundary conditions for the simulation of the stresses are indicated on figure 8, fixation on one side and a constant tensile force is applied each time on the left surface, the sample surface is blocked on the other side to perform the creep test.

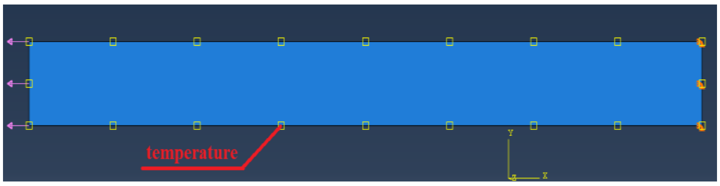

Figure 8. Boundary conditions of constant stress stress simulation

After the creation of stiff, and imposed the necessary loads each time, one modifies the force and the temperature according to the model of study, the discretization or the mesh (simple in this case: quadrilaterals with 4 nodes) as shown in the following figure.

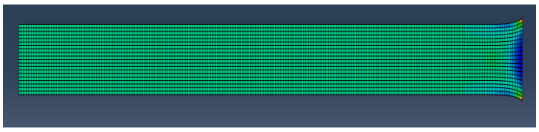

figure 9. eprovette mesh

The results of the simulation are visualized by figure 10 and the measurements represented in the following curves (figure: 11, 12, 13) whose values we take and introduce in Excel in order to be able to determine the creep parameters each time grouped in tables (2 -3-4) , the figure 10 also explains the transformation at each phase and gives the stress of each zone;

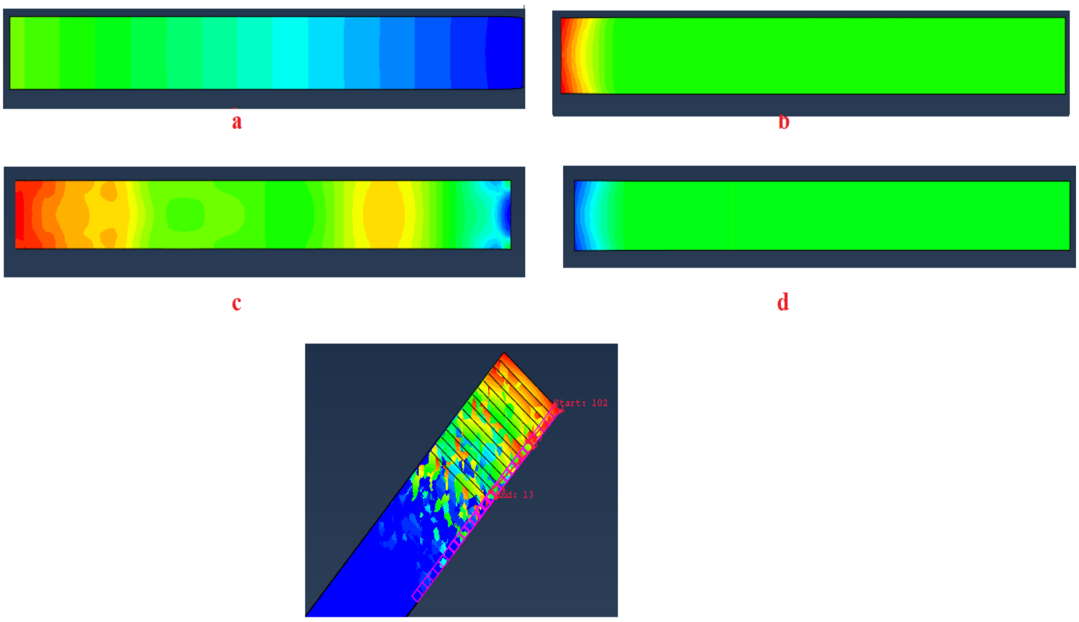

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Figure 10. visualization of the results as a function of time, (a) start of loading, (b) intermediate stage, (c) maximum phase of loading, (e) elimination of the free return force of the material

III. Result And Discussion

For constant stresses over time, and in imposed temperature (for each model) , in the absence of initial strain, the strain in the Burger element at any time is expressed as follows:

- ➢ The first term expresses the elastic strain which appears instantaneously after loading and is cancelled out after the removal of the load.
- ➢ The second term represents the irreversible creep strain in the element once it is subjected to constant stress. The third term expresses the delayed elastic strain which increases under the applied stress, then recovered once the stress has been lifted and the element maintained unloaded for an indefinite period.
- ➢ The results are used in the tables where one determines each time all the parameters of this model in four test steps and especially the dynamic viscosities of the first and secondary creep which will be the parameters to calculate each time the creep performance, which is represented by the creep conformity, J (t) which is defined as the ratio between the creep strain ε (t) and the applied stress (σ) as follows in each phase: J (t) = f (E1, E2, η1, η2, σ) = (Ɛ (t)) / σ.[37].

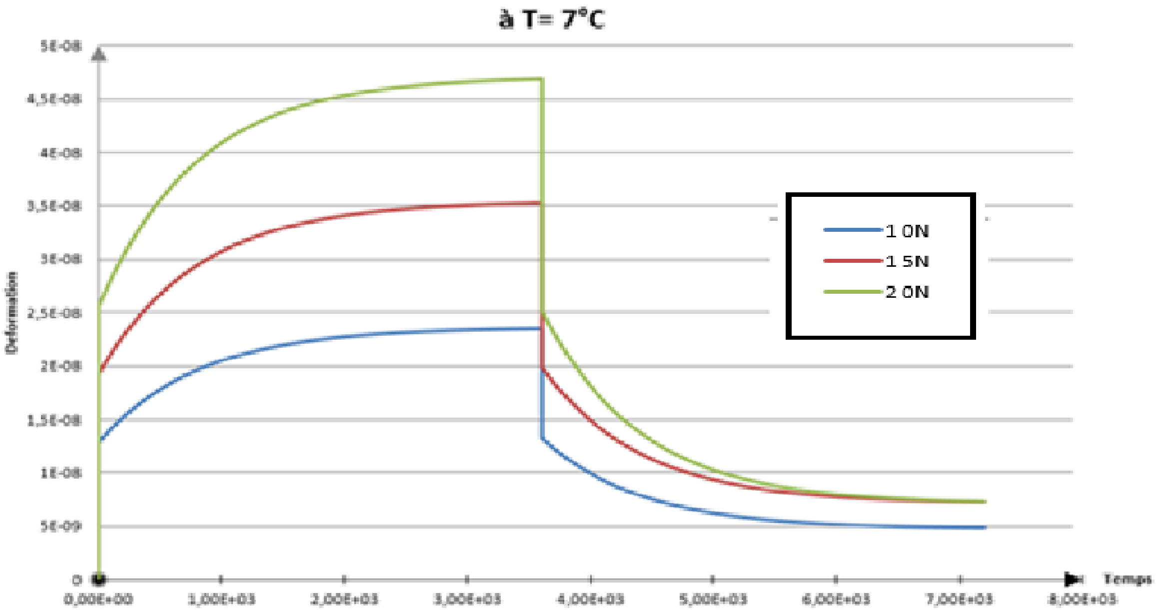

Figure 11. Creep and potato recovery for a Burgers model (T = 7 ° C)

Table 2: Material constant determined from the creep simulation test curve. (T = 7 ° C)

Equation	The test piece	Parameter	Result		
			10N	15N	20N
$\varepsilon(t) = \frac{6_0}{E_1} + \frac{6_0}{\eta_1} + \frac{6_0}{E_2}\,(1 - e^{-\frac{E_2\,t}{\eta_2}})$					
OA=(60 /E1)	T=7°C	E1 MPa	3,2		
AǍ=(60 /E2)					
tg β==(6 /η1)		η1 MPa s-1	2,64E+04	7,45E+03	6,80E+02
tgα=6 (1 /η1)+(1/η2)		η2 MPa s-1	8,80E+03	1,91 E+04	1,81 E+04
		E2 MPa	5,1	4,64	4,56

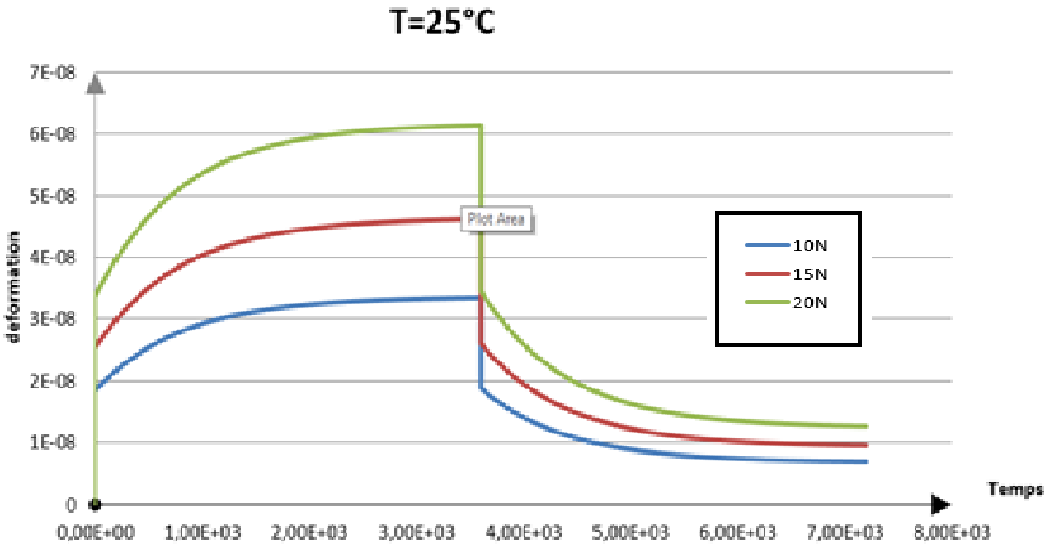

Figure 12. Creep and potato recovery for a Burgers model (T = 25° C)

Table 3: Material constant determined from the creep simulation test curve. (T = 25 ° C)

Equation	The test piece	Parameter	Result		
			10N	15N	20N
$\varepsilon(t) = \frac{6_0}{E_1} + \frac{6_0}{\eta_1} + \frac{6_0}{E_2}(1 - e^{-\frac{E_2 t}{\eta_2}})$					
OA=(60 /E1)	T=25°C	E1 MPa	3,8		
AĂ=(60 /E2)					
tg β= (6 /η1)		η1 MPa s-1	4,34E+04	5,67E+04	7,56E+04
tgα=6 * (1 /η1)+(1/η2)		η2 MPa s-1	5,93E+03	5,05E+03	4,37E+03
		E2 MPa	5,57	6,31	6, 38

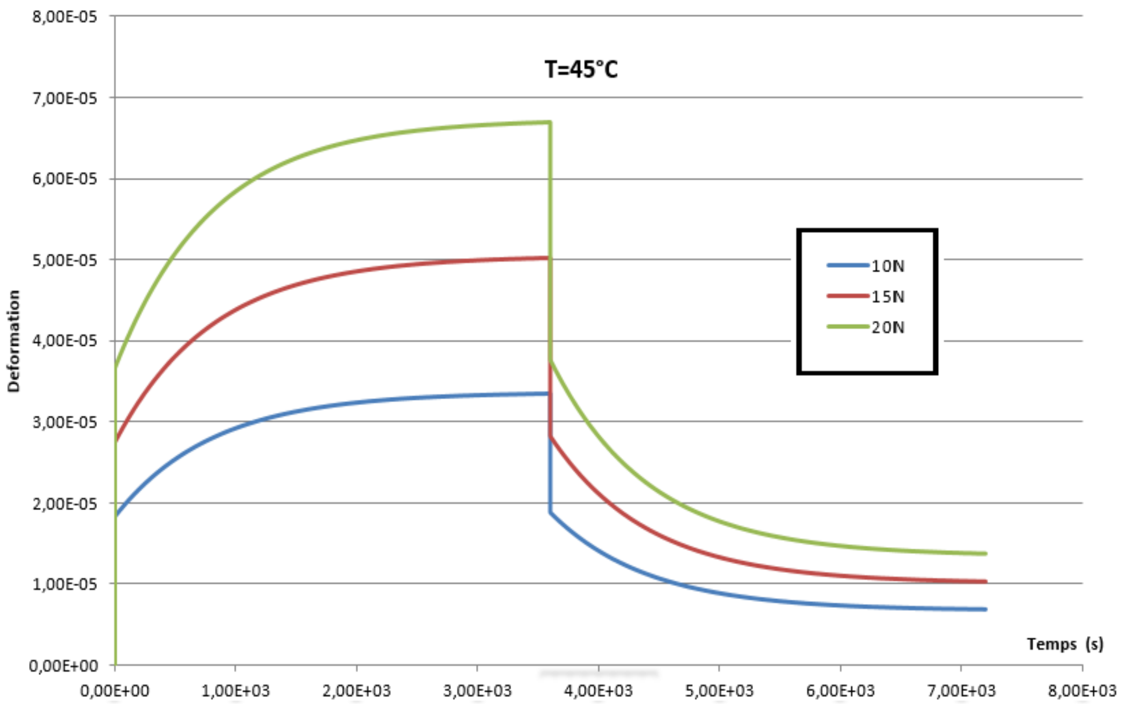

Figure 13. Creep and potato recovery for a Burgers model (T = 45 ° C)

Table 4: Material constant determined from the creep simulation test curve. (T = 45 ° C)

Equation	The test piece	Parameter	Result		
			10N	15N	20N
$\varepsilon(t) = \frac{6_0}{E_1} + \frac{6_0}{\eta_1} + \frac{6_0}{E_2}(1 - e^{-\frac{E_2 t}{\eta_2}})$					
OA=(60 /E1)	T=45°C				
AĂ=(60 /E2)		E1 MPa	4,2		
tg β==(6 /η1)		η1 MPa s-1	5,97E+04	7,59E+04	8,69E+04
tgα=6 (1 /η1)+(1/η2)		η2 MPa s-1	7,56E+03	5,26E+03	3,76E+03
		E2 MPa	7,44	6,14	6,03

The creep compliance equation is evaluated according to the four elements of the Burger model, with the equation:

$$(t) = \sigma[\frac{1}{E_1} + \frac{1}{E_2}\left(1 - e^{\left(-\frac{tE_2}{\eta_2}\right)}\right) + \frac{t}{\eta_3}]$$

The analysis of static forces has an important role in the study of the resistance of the potato to avoid the threshold of mechanical damage by permanent deformation, it is, therefore, necessary to manage the loads well and avoid creating waste. In this study, the required experiments and parameters of potato samples (Spunta) and simulation by the finite element method gave the dynamic properties of creep, pressure and viscosity at each step.

The simulation results showed that the stress increases when the load increases, but also from the curves one can clearly observe the effect of the temperature on the viscosity (η, 1η2) which is inversely proportional or two Young moduli (E1, E2) of this product which means that the material becomes more viscous (Fig. 15) It should therefore be kept away from high temperatures.

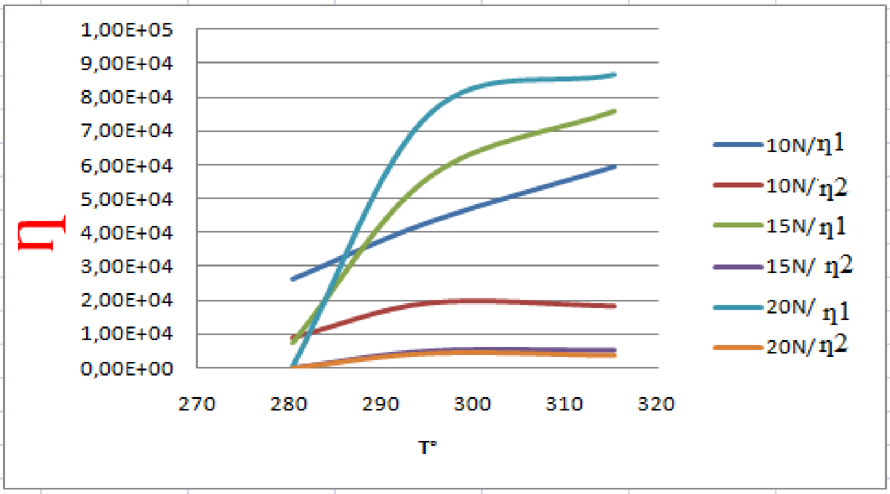

Figure15. Effect of temperature on the variation of viscosities

Effect of temperature on the delayed creep of the potato, we notice that the deformation and the viscosities increase significantly with the temperature (Fig. 15).

It is necessary to avoid stacking more tubers in uncontrolled climatic conditions for a long time, which can increase the indicated pressure beyond the valve that leads to the concentration of stresses, of course, these parameters must be taken into account in the storage cases, which have notable effects.

In general, knowledge of the behaviour of potatoes subjected to moderate heating is an important aspect of a large number of applications, and of particular interest. Indeed, the increase in temperature is accompanied by a decrease in mechanical properties (hardness, resistance, etc.) due to the physicochemical effect caused by the effects linked to stresses, temperature and pressure.

IV. Conclusion

The results indicated that the methods useful for studying the rheological behaviour of raw potato tissue by numerical simulation such as the effect of the strain imposed by the constant load.

It has been shown that by modifying the parameters of the mechanical creep model (Berger's model) it becomes possible to ensure good control of the properties sought by the results and by the calculations of the creep properties and the viscoelastic properties over a wide range of stresses, where the effect of temperature on the response of materials can be verified and this relationship is translated into a curve.

we can draw that under a constant load of 20N and temperature of 45 ° C η1 can go to 8.69 E + 04 MPa.s-1 and η2 same condition 3.76E + 03 MPa.s-1, also for all models the results of viscosity and young modulus is inversely proportional.

The instantaneous compliance values (j (t) = Ɛ (t) / б0) or (Jo) were greater than that of delayed compliance (Jr). Indeed, the Jo represents the elastic component, while the Jr is a combination of viscous and elastic components. As the creep and recovery behaviors are highly dependent on the molecular chain structure. At the end of the curve it is clear that there is a delayed elastic deformation which is conducive to the lengthening of the molecular chain and the remaining point is conducive to sliding explains that the material never regains its initial shape (remove the elasticity for the plastic field).

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