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Journal of Agroalimentary Processes and Technologies 2017, *23* (4), 236-244

*Journal of Agroalimentary Processes and Technologies*

# Mathematical model for compression strength of pork meat tenderized by using mechanical processing

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**Received: 13 July 2017; Accepted: 12 November 2017**

***Abstract***

The paper presents a mathematical model for compression strength for pork meat tenderized by using mechanical process. The mathematical model is based on compression characteristic diagrams that are experimentally determined after pork meat tenderization by using statically pressing. In order to decrease the wet curing / marinating period of the pork meat, a new tenderizing process consists in one statically pressing followed by certain steps of cyclic vacuum processing. The paper presents characteristic shear force amount obtained by using Werner - Bratzler testing method for a cured - hot smoked final product tenderized by pressing and cyclic vacuum processing, in comparison with no tenderized cured - hot smoked final product.

***Keywords***: compression strength, mathematical model, Warner - Bratzler method

## 1. Introduction

Tenderization is the mechanical action of producing multiple cuts in the meat muscle in order to increase the surface area and thereby facilitate extraction and solubilization during the mas-saging phase. Softening of the muscle is also obtained, making the meat more adaptable to the cooking moulds. Tenderization, pre-massage and massage are closely interrelated, and not all products require the same mechanical action. Thus the mechanical action must be intensified and adapted in order to compensate for some of the negative consequences that may result in the product's quality. This will depend on the rest of the process and, above all, on the presentation and final quality of the product itself [2, 4, 11].

Tenderizing process breaks down collagens in meat to make it more palatable for consumption. There are several ways to tenderize meat: mechanical tenderization, such as piercing; the ten-derization that occurs through cooking, such as braising; tenderizers in the form of naturally occurring enzymes, which can be added into food before cooking (examples of enzymes used for tenderizing: marinating the meat with vinegar, wine, lemon juice, butter-milk or yogurt; brining the meat in a salt solution (brine) [2, 9].

Cohesion of the muscles takes place thanks to the myofibrillar proteins which have been extracted during the manufacturing process and which are found on the surface of the muscle. These proteins form the exudates and, due to their gelling capacity, act as glue between the muscles. It has been widely demonstrated in the pertinent literature that the greater number of proteins extracted, the greater the stability between muscles and therefore the better the slice-ability and mastication. Extraction of myofibrillar proteins is achieved through both mechanical and chemical actions [2, 9].

The degree to which the muscle structure is opened will determine the final quantity of proteins present in the exudates. This opening of the structure is

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done by means of tenderization, pre-massage and massage. Chemical action - in brine composition, the presence of salt and phos-phates increases the pH and the ionic strength of the medium, giving rise to the opening of the protein chains and facilitating their extraction [2, 9].

By means of certain additives, aside from the above-mentioned salt and phosphates, such as carra-geenan and vegetable gums, muscle texture can be slightly hardened and / or "plastified", however this alone will not be sufficient to compensate for the meat's lack of firmness. It has been observed that the mechanical action of tenderization does have a positive effect on this type of meat, because the texture is less fragile due to an increased surface of contact between muscles.

Using commercial meat without muscle selection, in order to standardize the tenderizing processes, previous research studied the effect that tenderization has on consumer' mastication in whole muscle cooked products [2, 9, 11, 12].

Raw meat material used for cured-cooked meat products is mainly derived from neck, hind leg, shoulder or loin. In some regions, lean muscle meat may also be processed to local cured - cooked specialties.

There are slight differences in the processing technology of cured - cooked products, mainly depending on the size of the meat parts used for product manufacture. Curing brine is adminis-tered in all products, usually done by brine injection. Even distribution of the injected brine is achieved by treating the injected meat pieces in a meat tumbler, and when no tumbler is available, "resting periods" for the meat pieces are needed [2, 3, 9].

For some raw - cured products smaller amounts of curing brine are injected directly into the muscle tissue to accelerate the curing process. This fast curing technique significantly shortens curing periods, as curing substances migrate in both directions, from outside to inside and from central to less central parts.

But because of this accelerated process, the curing flavor remains less intensive and texture of these products remains softer then in products applying dry or wet curing. The shelf life is also reduced significantly and most products are kept refrigerated.

Typical products of this fast-cured type are cured - smoked pork, beef, sheep and goat meat. Fast curing with injection of curing brine will therefore remain the method of choice for rapid turn-over cured-cooked meat products only [2, 3, 9].

During wet-salting process, the curing salt solution infiltrates the meat tissue and at the same time liquid from the meat tissue is extracted by the salt surrounding the meat. Depending on the size of the meat cuts, the curing process alone can last up to several weeks for equal penetration of the meat cuts with curing salt (at temperatures of about +4°C, a pork shoulder takes about two weeks, a leg of pork about four weeks).

As exception to the common technology of using curing salt (containing nitrite or nitrate, or a mixture of both), some well - known traditional cured - raw ham products (e.g.*"Parma Ham"* and *"San Daniele Ham"* in Italy; *"Jinhua Ham"* in China; *"Jamon Serrano"* in Spain; *"Jambon Savoie"* in France; Romanian traditional products *"Cotlet Perpelit"*, *"Pulpa Perpelita"* and *"Ceafa Perperlita"*), are made without nitrite, using common salt only. For these products carefully selected pork meat with bone, and boneless respectively, are used. Although *no nitrite is used*, a stable red color is achieved in these cured - raw ham products. This red color derives from the natural meat color intensified by the drying and ripening process [2, 7, 9].

In principle, three different types of tenderization are used by food processors [3, 9]:

- Dual - roller tenderizer consists of two counter cutting rollers through which the meat is forced, producing cuts on both sides of the muscle, while simultaneously applying pressure on the entire piece.
- Rollers with prongs: alternative to the blade head because deep cuts are produced with - out tearing the muscle, but with a sharper blade and making cuts on both sides. Used for low in-jection products in which the muscle should be kept as whole as possible.
- Rollers with knives: sharp serrated knives that produce quickly multiple cuts and a certain degree of muscle tearing, depending on the separation between rollers. This type of tenderization is the one that results in greater protein extraction, but is also the one that may have greater impact on the appearance of the product.

## 2. Materials and Methods

### 2.1. Material, processing method and equipment

This paper presents experimental and theoretical research concerning a new method to obtain a cured - hot smoked boneless back leg "*Pulpa Hituita*"product similar with traditional Romanian assortment "*Pulpa Perpelita*" made by SC AVI-GIIS SRL Mihaesti, Valcea County.

In principle, the processing technology of this traditional cured - hot smoked - cooked product type consists in: wet curing phase of entire pieces of muscle meat in 12 - 15 % curing salt concen-tration, during 2 - 3 weeks; drying / ripening phase in cold ventilation for 6 - 8 hours; cold smoke phase (20 - 25°C) for 2 - 3 days, followed by a short sequence of hot smoke phase (80 - 85°C), for 4 - 6 hours [7].

According to Romanian legislation, sodium nitrite ($NaNO_2$), sodium or potassium nitrate ($NaNO_3$ / $KNO_3$), or any alternative curing substances are not permitted in traditional cured - cooked types products usual processing, and no brine injection is allowed [8].

In order to produce traditional cured - hot smoked - cooked product "*Pulpa Hituita*", 2 large pieces (one piece from each leg, from symmetrical both sides) of pork boneless back leg were used (according Animal Slaughter Certificate: 12 months, 75…80 kg in carcass; large farm).

Each of this large piece of pork boneless back leg was cut in 3 equal small pieces (aprox. dimensions: length x width x height = 180 x 90 x 40 mm).

In order to determine the efficiency of the new tenderizing and curing method proposed in this paper, 2 of these small pieces were used to make "*Pulpa Hituita*" in similar technological con-dition alike "*Pulpa Perpelita*" is made at SC AVI-GIIS SRL Mihaesti.

The other 4 small pieces were used to obtain "*Pulpa Hituita*" made by using the proposed method.

In order to improve the final product tenderness, and in the same time to reduce as much is possible the wet curing phase, this paper propose a tenderizing method based on meat *simul-taneous compression and piercing processing*, followed by *intensive cyclic vacuum process.*

The tenderizing process performed to improve the final product tenderness and to decrease the wet curing period's, consists in meat's *simultaneous compression and piercing processing* by using the experimental *Multi - needle compression and piercing device* (Figure 1).

This experimental equipment consists in two parallel plates: the down fixed plate with 120 holes (ø5,5); the upper mobile plate with 120 needles (ø5, $20^0$ conical sharp) disposed in the same shape and reciprocity distance as into the industrial brine injection equipment.

The meat compression is realized between the two plates of the *Multi - needle compression and piercing device* that is actuated by the crosshead of universal testing machines *LBG 10* (within Environmental Engineering Laboratory into Faculty of Electrical Engineering).

The experimental research presented in this paper consists in *simultaneous compression and piercing* of the four small meat pieces at 2500 N, and at 3000 N respectively, from meat's initial height to 25...30 mm meat's final height. The testing machine's specialized software plotted compression force - deformation (extension) diagrams.

For these experiments, 200 mm/min compression crosshead speed was used.

In preliminary experiments it was observed that when a larger compression force is applied, the meat's tissues are too much damaged, and the smaller meat's final height of the product could be often not accepted by the consumer.

In actual massaging vacuum processing equipment (thumbler) the vacuum level do not exceed - 0,7 bar. Recent American and West - European meat tenderizing research papers recommend increasing the vacuum level up to - 0,95 bar [3, 9, 11].

This paper proposes the simultaneous curing and massaging of the tenderized meat by using *intensive cyclic vacuum processing*. In principle, the *experimental equipment for Cyclic Vacuum Processing* (*CVP*) consists in *vacuum pump*, *vacuum processing vessel*, and *condensed gases dryer module* (Figure 2). The main characteristics of the *vacuum pump* (HYVAC type): maximum flow rate up to 40 l/min; absolute pressure up to 50 mbar.

The *condensed gases dryer module*, in main, consists in a stainless steel vessel, containing 13X type molecular sieve [4].

***Figure 1***. Multi - needle compression and piercing device

***Figure 2.*** Experimental equipment for CVP

The *vacuum processing vessel* (designed and made according Romanian ISCIR norms: stainless steel W1.4571; welding coef. 1) permits vacuum experiments for absolute pressure up to 0,5 mtorr. A rotative mixing device (mounted into the vacuum; stainless steel W1.4571) can be put in ope-ration for rotational motion (1 - 60 rot / min) by a special electromechanical transmission speed variator. To observe the inlet vessel during vacuum process, one of the flanges is made in trans-parent visor (high resistance polycarbonate) [4].

The experimental equipment for *CVP* and *Multi - needle compression and piercing device*, too, were designed and made by Unconventional Technologies and Equipment for Agro-Food Industry Laboratory within Faculty of Agriculture and Horticulture, in collaboration with Environmental Protection in Industry within Faculty of Electrical Engineering, within the University of Craiova [4].

The *intensive cyclic vacuum process* consists in the following processing steps:

- The compressed and pierced meat (4 pieces tenderized after simultaneous compression and piercing as above was presented) is introduce into the rotative mixing device of the vacuum pro-cessing vessel that contain only 3% salted concentration brine (proportion 1:1 for meat, and brine, respectively). During this experiment 10 rot / min rotational speed was set.
- Each intensive vacuum cycle lasts 20 min consists in 10 consecutive steps, each lasting 2 min: slow vacuuming up to - 0,85 bar (during 1 min), followed by maintaining for 1 min at this vacuum level, followed by fast de-vacuuming up to the ambient atmosphere (Figure 3).
- After finishing each 20 min intensive cyclic vacuum process, the used brine was replaced by a fresh cold one. The used brine replaces last 3…4 min, and during this period the meat is relaxed after it was squeezed by the vacuuming process.
- For this paper were performed 6 vacuum cycles, thus all the vacuuming process last in total 140 min.

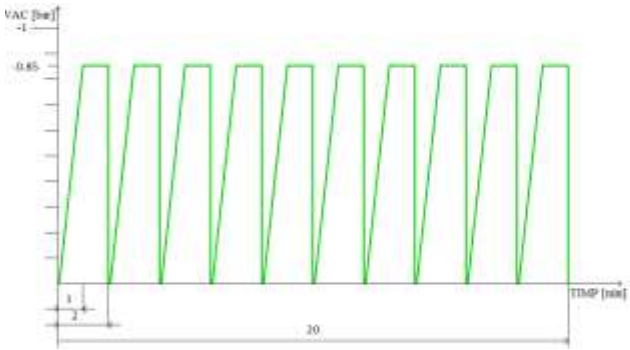



***Figure 3.*** Intensive cyclic vacuum process diagram

All the six meat pieces (2 pieces no tenderization, brined in 12 % salt concentration, during 2 weeks: *TRAD*; each 2 pieces tenderized by simultaneous compressed and pierced at 2500 N, and 3000 N respectively, followed by intensive cyclic vacuum process: *CP 2500.CVP*, *CP 3000.CVP* respectively) were ripened in cold ventilation for 6 - 8 hours, then cold smoked (20 - 25°C) for 2 days an hot smoked (80 - 85°C), for 4 hours.

### 2.2. Tenderness evaluation by using Warner - Bratzler method

The most relevant and utilized methods to estimate meat's tenderness are compression test, and Warner - Bratzler shear test. During Warner - Bratzler test the shear blade acts simultaneously compression and slicing / shearing of the product [4, 10].

To perform inter-disciplinary researches concerning tenderness analysis, universal testing machine *Lloyd Instruments LRXPlus 5* (Unconventional Technologies and Equipment for Agro - Food Industry Laboratory - UTEFIL, within Faculty of Horticulture in Craiova) was used.

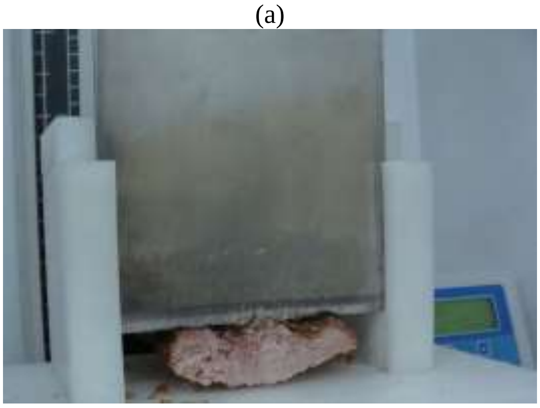
Due to collaboration between UTEFIL and Environmental Engineering Laboratory within Faculty of Electrical Engineering, a *Warner - Bratzler experimental equipment* was made.

In principle, this equipment consists in a special rigid frame that permits fast fitting and sliding of interchangeable Warner - Bratzler shear blades [4].

The experimental research performed for this paper, 100 mm/min cutting speed was set.

Warner - Bratzler test during share force performing for "*Pulpa Hituita*" obtained by using *CP 2500.CVP* method, and *CP 3000.CVP* method respectively, is presented in Figure 4.

(a)



(b)

***Figure 4.*** *"Pulpa Hituita"* during Warner - Bratzler shear force test (a. *CP 2500.CVP*; b. *CP 3000.CVP*)

**2.3. Mathematical model to determine the compression strength of the tenderized meat**

The compression strength behavior is represented by the internal stress within the meat when certain compression force determines the decrease of the sample height's amount (deformation during compression force acts).

In this paper, a mathematical method based on MathCAD software was proposed to study the compression strength' behavior [1, 5, 6, 8].

Therefore, to determine the deformation's variation diagrams when a certain force is applied, experimental data were used to describe the compression force matrix:

$$M := \begin{pmatrix} F_1^5 & F_1^4 & F_1^3 & F_1^2 & F_1 \\ F_2^5 & F_2^4 & F_2^3 & F_2^2 & F_2 \\ F_3^5 & F_3^4 & F_3^3 & F_3^2 & F_3 \\ F_4^5 & F_4^4 & F_4^3 & F_4^2 & F_4 \\ F_5^5 & F_5^4 & F_5^3 & F_5^2 & F_5 \end{pmatrix}, \quad (1)$$

and the vectors that define the each deformation determined by each compression force.

$$v := \begin{pmatrix} d_1 \\ d_2 \\ d_3 \\ d_4 \\ d_5 \end{pmatrix}, \quad (2)$$

where each $d := k, k + m...l$ , ($k$ :=0; $m$ := 0,5; $l$ := 10) [6].

After several preliminary analytical calculi, it was observed that the nearest function which approximates the experimental force - deformation diagram, is the fifth degree polynomial function defined by the relation [6].

$$F(d) = \alpha \cdot d^5 + \beta \cdot d^4 + \gamma \cdot d^3 + \delta \cdot d^2 + \varepsilon \cdot d \quad (3)$$

Where

$\alpha, ..., \varepsilon$ represent influence coefficients that have to be determined solving the relation [6].

*soln:=lsolve(M,v)* (4)

The mechanical work when compression force is applied, has to be determined by solving the equation [6].

$$W_{mec} = \int_{d_1}^{d_2} F(d) \cdot d(d) \quad (5)$$

## 3. Results and discussions

In order to determine the influence of compression and piecing process on meat's compression strength and the final product tenderness' too, the meat was stressed with 2500 N and 3000 N, respectively, compression force. The experimental diagrams are presented in Figure 5*a*, for 2500 N, and in Figure 6*a* for 3000 N.

Using rel. (1), rel. (2) and rel. (4), for 2500N compression force, were determined:

$$M := \begin{pmatrix} 0{,}145^5 & 0{,}145^4 & 0{,}145^3 & 0{,}145^2 & 0{,}145 \\ 2{,}765^5 & 2{,}765^4 & 2{,}765^3 & 2{,}765^2 & 2{,}765 \\ 4{,}338^5 & 4{,}338^4 & 4{,}338^3 & 4{,}338^2 & 4{,}338 \\ 7{,}109^5 & 7{,}109^4 & 7{,}109^3 & 7{,}109^2 & 7{,}109 \\ 9{,}523^5 & 9{,}523^4 & 9{,}523^3 & 9{,}523^2 & 9{,}523 \end{pmatrix} \; ; \; v := \begin{pmatrix} 4{,}173 \\ 191{,}850 \\ 562{,}170 \\ 1207{,}610 \\ 1975{,}750 \end{pmatrix} \; ; \; soln = \begin{pmatrix} -0{,}017 \\ 0{,}609 \\ -7{,}535 \\ 43{,}628 \\ 11{,}624 \end{pmatrix}$$

and after solving rel. (3), it was obtained the particular polynomial function that best describes the diagram's evolution of meat's deformation when compression force is applied:

$$F(d) = -0{,}017 \cdot d^5 + 0{,}609 \cdot d^4 - 7{,}535 \cdot d^3 + 43{,}638 \cdot d^2 + 11{,}624 \cdot d \quad (6)$$

After similar calculi, the particular polynomial function that best describes diagram's evolution of meat's deformation when 3000 N compression force is applied:

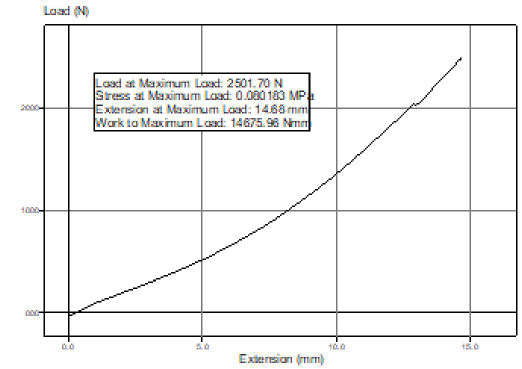
$$F(d) = -0{,}042 \cdot d^5 + 0{,}653 \cdot d^4 - 3{,}271 \cdot d^3 + 38{,}236 \cdot d^2 - 0{,}038 \cdot d \quad (7)$$

The force - deformation diagrams plotted by using rel. (6) for 2500 N, respectively rel. (7) for 3000 N, are presented in Figure 5b (for 2500 N), and in Figure 6b (for 3000 N), respectively.

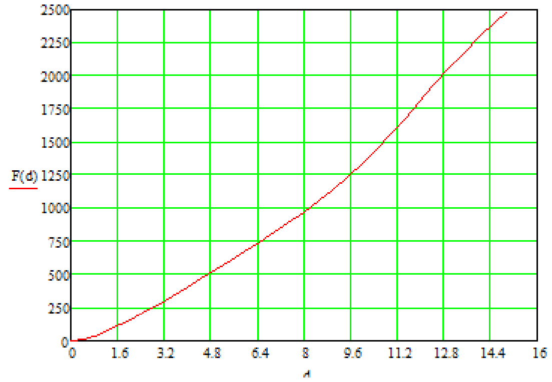
The comparisons between diagrams both in Figure 5*a* and Figure 5*b* when 2500 N compression force is applied, and in Figures 6*a* and Figure 6*b* when 3000 N compression force is applied, confirm the correctness of the proposed mathematical model.

In Table 1 there are presented the experimental mechanical work and the mechanical work determined by using the mathematical model, when compression forces 2500 N and 3000 N, respectively, are applied.

The differences between the mechanical work determined by using experimental method and the mathematical model are smaller than 3,07 % for 2500 N, and 2,76 % for 3000 N, that confirm the correctness of the proposed mathematical model.

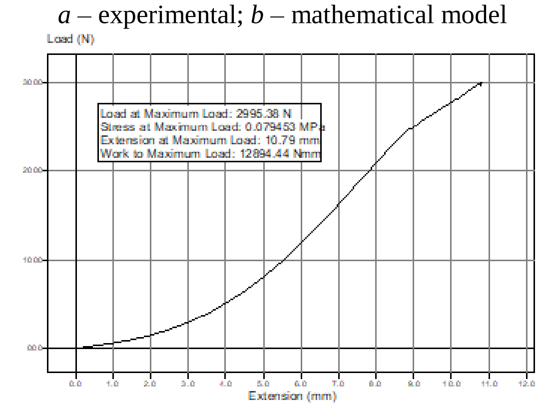



(a)

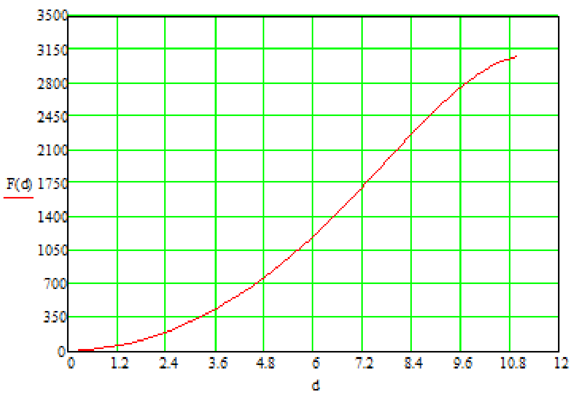



(b)

***Figure 5.*** Compression diagram for 2500 N
*a* – experimental; *b* – mathematical model




(a)




(b)

***Figure 6.*** Compression diagram for 3000 N
*a* – experimental; *b* – mathematical model

These small differences could be explained by viscoelastical deformation of the tissues' structure when meat is stressed during compression force test.

***Table 1.*** Mechanical work when compression force is applied

| Method | Mechanical work, N·mm | |
|---|---|---|
| | Compression force | |
| | 2500 N | 3000 N |
| Experimental | 13382 | 14676 |
| Mathematical Model | 12973 | 14271 |

To evaluate the efficiency of *simultaneous compression and piercing* followed by *intensive cyclic vacuum process* on the tenderness of cured - hot smoked *CP 2500.CVP* and *CP 3000.CVP* "*Pulpa Hituita*" final product, the Warner - Bratzler shear force experimentally determined for this pro-cessing method was compared with the shear force amounts obtained for "*Pulpa Hituita*" made using traditional method (*TRAD*).

Representative Warner - Bratzler shear force diagrams for *CP 2500.CVP* pieces, and for *TRAD* pieces, respectively, are presented in Figure 7 and Figure 8, respectively.

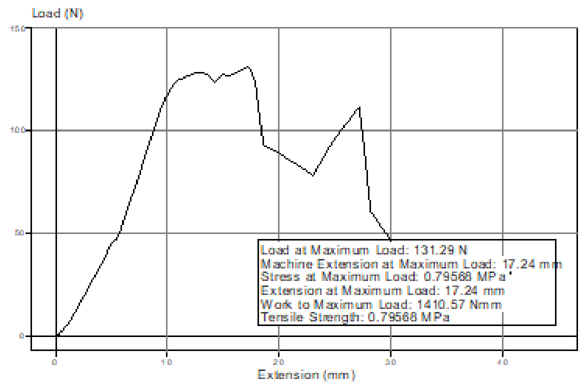



***Figure 7.*** Warner - Bratzler shear force test diagram for "*Pulpa Hituita*"made by using 2500 N compression force (*CP 2500.CVP*)

In Table 2 are presented the maximum shear force amount and the shear force average for each "*Pulpa Hituita*" type. Table 2 presents too, the decrease of percentage average shear force (in comparison with traditional homemade "*Pulpa Hituita*"'s tenderness) by using each pro-cessing method, that demonstrate the final product tenderness' increasing.

Table 2 represents a synthesis of the influence of *simultaneous compression and piercing* followed by *intensive cyclic vacuum process* on the tenderness of cured - hot smoked on "*Pulpa Hituita*" final tenderness':

- in comparison with traditional homemade *TRAD* "*Pulpa Hituita*" tenderness', *CP 2500.CVP* method determines 19,25 % improving of the final product tenderness';
- instead, in comparison with traditional homemade *TRAD* "*Pulpa Hituita*", *CP 3000.CVP* method determines an important improving up to 40,39% of the final product tenderness';
- in comparison with the method *CP 2500.CVP*, by using *CP 3000.CVP* method "*Pulpa Hituita*" could be obtained up to 39,29% tenderness' improving.

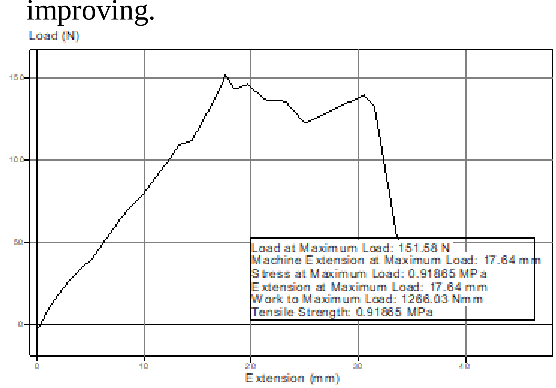



***Figure 8.*** Warner - Bratzler shear force test diagram for "*Pulpa Hituita*", made by using traditional method (*TRAD*)

***Table 2.*** Warner - Bratzler shear force for "*Pulpa Hituita*"

| Sample code | Maximum shear force min…max amount, N | Shear force average, N | Decrease of shear force average, % |
|---|---|---|---|
| *TRAD* | 140,72...189,38 | 164,51 | - |
| *CP 2500.CVP* | 118,16...152,31 | 132,84 | 19,25 |
| *CP 3000.CVP* | 103,45...127,19 | 112,35 | 31,71 |

## 4. Conclusions

In order to improve the cured - hot smoked "*Pulpa Hituita*" tenderness', the tenderizing method consisting in simultaneous compression and piercing followed by intensive cyclic vacuum process could be used.

Simultaneous compression and piercing causes pressing and relaxation of the muscle structure and breaking up of the cells, making the membranes more permeable and increasing mobi-lization of the proteins up toward the surface of the muscle when the intensive cyclic vacuum process is applied. The degree to which the muscle structure is opened will determine the final quantity of proteins present in the exudates.

Due to much intensive osmosis phenomena when simultaneous compression and piercing followed by cyclic vacuum process is applied, meat's compression strength decreasing deter-mines faster brine's infusion into the meat' tissues.

As one of the most recommended analyze method, the Warner - Bratzler shear force test offered objective results concerning the influence when simultaneous compression and piercing followed by cyclic vacuum process is used, on final products tenderness'.

In main, the when simultaneous compression and piercing followed by cyclic vacuum process method has two important advantages:

- reducing the *wet curing phase* from 2 weeks to only 140 min;

- improving the tenderness of Romanian traditional cured - hot smoked product "*Pulpa Hituita*" (19,25...31,71 %), in comparaison with the traditional product made with no tenderized meat.

- low salt content (3 %) and uniform distribution into the product volume.

Considering physically issues, mechanical tenderizing is a process that has to reduce the meat's mechanical characteristics amounts of the final product. Each tenderizing method produces signi-ficant changes of specific strain within the meat's tissues, which determines the tenderness' improvement.

The main conclusion drawn in this paper refers the correctness of the mathematical model, proved both by the diagrams' configuration and by the intermediary or maximum amounts simila-rities' between the numerical tenderizing diagrams, and the experimentally diagrams, respectively.

Further general and specific conclusions could be draw after this mathematical model will be applied for other types of meat, before and after the same or other mechanical tenderizing methods. The data presented in this paper can be important for all the specialists interested in decreasing the wet curring period and in tenderness improvement, too of the traditional meat products.

**Compliance with Ethics Requirements.** Authors declare that they respect the journal's ethics requirements. Authors declare that they have no conflict of interest and all procedures involving human / or animal subjects (if exist) respect the specific regulation and standards.

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