STRUCTURAL MATERIAL INVESTIGATION OF HORSE HOOF
DECLARATION

This thesis is submitted by Miguel García Cabrera to the University of Skövde for the Bachelor Degree in Mechanical Engineering, in the School of Technology and Society.

Date of Submission: 13th May 2013

I certify that all materials in this thesis which is not my own work has been identified and that no material is included for which a degree has been conferred on us previously.

Signature

Miguel García Cabrera
ACKNOWLEDGMENTS

I would like to express my sincere gratitude to my project supervisors PhD. Alexander Eklind, M.Sc. Björn Kastenman. Moreover, I would also like to thank Dr. Anders Biel and M.Sc. Stefan Zomborcsevics for their great help and valuable comments. Finally, I am very thankful for the support of my family and close friends, who have been patient during all this hard and long period of this project.
ABSTRACT

This research focuses on a study of the material parameters of horse hoof. The study of the problem with the factors that affect to the fastening of the shoe is not performed. Three different tests are carried out to obtain the behavior of the horn wall of the horse hoof in different ways, under physiological conditions and variation of hydration level. The first one is a tensile test to obtain both the force/displacement relation and the stress/strain relation and the parameters derived from it. The second is a hardness test to determine how the material resists to several kinds of permanent-shape changes when a force is applied. Finally, a microscopic study is performed to analyze the fracture surface after testing the specimens. A meticulous analysis of the results and a broad comparison with several researches are performed. The end of the thesis work suggests future works needed to solve the problem.
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1. INTRODUCTION

1.1 BACKGROUND

Since the year 1500 B.C. the use of horses became more usual and important either to farmers, ranchers or warriors. From these times, horses began to be protected by hooves. In fact, in the Far East people began to use a horseshoe composed by herbs, roots and made of wood. In the area of Egypt and Persia began to spread the use of metal horseshoes attached to the hoof by means of straps. The Mongol army used a type of protection made of leather for the hoof. Also sandals, boots and socks were used by the horses of the Greeks and the Romans until they added a metal plate.

The use of the horseshoes as they are known today, that is with nails, did not start until the year 400 A.D. The use of them changed the normal structure and function of the hoof, but it was used for the benefits it provided. The main reason to use them was to protect the hoof of damage and wear. Furthermore, it provided greater traction and it was used for correcting many problems of deformity, that is, the change of size or shape of the hooves due to internal stresses caused by forces applied to them. Because of this, it would be necessary to find out the material parameters of the horse hoof and to determine their limit values in order to know the behavior of it and to control all the changes it suffers.

For a better understanding of which parts of the horse hoof influence over this investigation, an external and an internal view of the horse hoof are shown in Fig. 1 and Fig. 2 respectively.
Throughout history, several researchers have carried out different investigations about the biomechanics of the horse hoof. The first investigation about the biomechanics parameters was carried out by Lungwitz and Adams (1913). They described that the tubule density varied in different locations around the equine hoof capsule. In the same way, a similar research was carried out by Nickel (1938, 1939), who supported the theory of Lungwitz and Adams. Wilkens (1964) and Schummer et al. (1981) suggested a relationship between tubule density and resistance to wear of the hoof horn capsule. However, no data were given to support this statement.
Bruhnke (1931) accomplished a research about a comparison of the horn wall structure of the end of the toes in equine hooves. He stated that the tensile/shear force of the horn of the different equines decreased from the dorsal aspect towards the palmar/plantar aspect. However, it does not exist any data about this investigation again. Kind (1961) performed a comparative study about the wear of the hooves in some equines due to the structure of the hoof capsule placed in the front of the hoof.

The Young’s modulus was studied in different ways. According to Zoerb and Leach (1983), inner wall samples were less rigid and had a lower yield point than outer wall samples. This investigation was performed by studying the Young’s modulus and proportional limit for samples compressed in 3 orthogonal directions. Douglas et al. (1996) stated that the difference in stiffness between the outer wall and the inner wall was inversely related to moisture content by examining the Young’s Modulus of equine hoof wall in tension and compression. Also they affirmed that, possibly due to micro-structural defects, the modulus of elasticity was marginally higher in compression than in tension. Hinterhofer et al. (1998) focused their research in determining the relationship between the moisture contents and the Young’s Modulus of the wall of the horn hoof. In order to get this relationship they carried out different tension and bending tests. They conclude that Young’s modulus and the moisture contents of the various segments studied were approximately identical, when tested after drying at 65% humidity over 6 days. However, under this percentage, the results varied openly.

In order to determine possible effects of hoof wall viscoelasticity on fracture toughness and tensile parameters, Kasapi and Gosline (1996) examined the mechanical properties of fully hydrated equine hoof wall at various loading rates in compact tension fracture, tensile and three-point bending dynamic tests. Their conclusions revealed that, through a scanning electron microscopic examination of fracture surfaces, with an increasing strain rate, tensile parameters are positively affected and the equine hoof wall viscoelasticity did not appear to compromise fracture toughness.
Douglas et al. (1998) examined the stress/strain behavior of the equine laminar junction in three different directions: radial tension and proximodistal and medilaterial shear. They asserted that the Young’s Modulus increased with increasing strain magnitude, suggesting that mechanical history of the horse can affect the material properties of the tissue studied.

Nevertheless, despite all the studies mentioned above, no pattern has been encountered that can be solve the problem of the fastening of the nails to the horse hoof.

1.2 PROBLEM

Nowadays, each horseshoe is fitted to each horse hoof. The change of the horseshoe should be done in a maximum of six to eight weeks period. The problem is that people who work with horses spend a lot of time and money each time they change the horseshoe. The horseshoes are attached to the hoof by means of nails. The way to fasten the nails consists of hammering slowly through the white line of the hoof. Once it reaches the wall of the hoof, it hammers stronger until penetrating it. There, the nails are bent downwards on the outside for secure fastening. The problem appears when the horse makes an effort with the horseshoe resting on the ground. At this moment, the hoof is displaced around 8 mm in each side due to the strengths it suffers. If the nails have been fastened and bent downwards without excessive effort, that is softly, the nails become to unfold gradually until they are thrown out. Nevertheless, if the nails are fastened and bent downwards in a strong way, once the hoof is displaced, they break and tear the hoof.

In general, people interested in solving this problem are those who work with horses, for instance, farmers, breeders and ranchers. However, the most interested people in the performance of this research are the people who compete with horses and all the enterprises related to them, considering that a competition is the moment in which the hoof suffers the maximum forces and loads. Hence, it is the moment in which the hoof is more deformed with the subsequent consequences explained above.
In order to solve this problem, different tests are carried out and the data obtained are presented along this thesis. Moreover, further conclusions from the performed analysis are presented at the end of the thesis and future works are suggested.

1.3 PURPOSE AND GOAL

The main goal of this research is to find out the most important material parameters of the horn wall of the horse hoof and to analyze and to determine their limit values by performing different kind of tests.

This investigation study the behavior of the different material parameters, so that it tries to look for a pattern that it may determine a line throughout the horn wall of the horse hoof, in which the nails can be fastened to the hoof in an easy and simple way and without danger of breakage. In addition, this pattern tries to avoid the loosening of the horseshoe when it displaces due to the strengths and the loads suffered.

1.4 METHODS

A literature study about different research studies is performed with the aim of studying the field of the horse hoof. The main purpose is to know and learn different ways of testing relevant parameters for this thesis as the Young’s modulus, the stress/strain relation, the toughness, the stiffness and their behavior under stress conditions and variation of moisture contents. For that, it was important to know what kinds of tests have been done before and how they have been carried out.

With the intention of achieving the goal and the purpose explained above, different methods are applied. Firstly, different parts of a hoof are chosen to be tested. The shape used for the samples is dog bone shape.

In order to determine the values of the different material parameters a tensile test, a hardness test and a microscopic analysis are done. Each experiment has been repeated several times for a better estimation of the values. Moreover, physical properties are studied so as to know the symmetry class, that is if the material is isotropic, which means that the material is uniform in all orientations,
or transversal isotropic, which means that the behavior of the material change with the orientation.

The first one is a tensile test experiment performed in a tensile test machine which is shown in Fig. 3. It determines the stress-strain relation.

Fig. 3. Instron 8872 tensile test machine (own source)

The second one is a hardness test experiment done in a hardness test machine which estimates the toughness of each sample. This machine is represented in Fig. 4.
Fig. 4. Sclerometer Hardness Machine A.B. Alpha (own source)

The last test is an analysis with a Zeiss Stemi 2000-C light microscopic of the samples, after the tensile tests, to obtain the relationship between the orientation of the tubules and the behavior of the parameters through an analysis of the fractured surface. The microscopic used is represented in Fig. 5.
The data obtained through the tests are compared in order to determine the standard way of fastening the horseshoes, so that the problem of the nails securing can be evaluated and solved.

1.5 DELIMITATIONS

The main goal of this project is to determine the material parameters of the horny wall of the horse hoof and its limits as it is explained above.

The proximal/distal dorsal, the medial quarter and the lateral quarter of the horse hoof are the parts selected from where the samples are taken in order to do the experiments. Each sample is from a black hoof. These parts are shown in Fig. 6.
Therefore, it is not possible to compare the values of the parameters and its behavior between the forelegs (front legs) and the hind legs (back legs), whose sizes and shapes are different, since all the specimens are from right forelegs of the horse.

Through the tensile test, the elongation and the force applied are obtained. Derived from these values, mechanical parameters are achieved such as:

- The elastic strain ($\varepsilon_e$), whose value determines the elastic behavior until plastic behavior.
- The plastic strain ($\varepsilon_p$), whose value determines plastic behavior until the point of breakage.
- The elastic limit, which defines the maximum stress that a material can bear without suffering permanent deformations.
- The point of breaking, which determines the last stress that the material suffers until breaking.
- The stiffness, that is, the ability of a material to withstand loads without acquiring big deformations and/or displacements.

Through the hardness test, the resistance which the material puts up against the deformation is calculated. The Rockwell B toughness of the wall is obtained.
The last test is a microscopic study after tensile and hardness test to study the fracture surfaces. From this test, it is known if the behavior of the material is ductile or brittle and some images are done to corroborate it.

In addition, all the problems related to the horseshoe and its influence in the horny wall, the toe, the heel and the quarters are not either included in this investigation.
2. IMPLEMENTATION

This chapter consists of a broad summary and documentation about the relevant information that has been taken into account in the thesis to reach the purpose. Furthermore, it is included a specific description of the details of the execution process that has been carried out.

2.1 MATERIALS

The hooves of the horses used throughout this thesis have been taken from three different horses (Swedish Halfblood), which have been chosen randomly. All the samples have been taken from deceased horses (for unknown reasons that are unrelated to this research) that belonged to the Biologiska Yrkeshögskolans Hovslagarskola i Skara and to the Dalsjöfors Slaughterhouse, Sweden. The specimens have been acquired from horses of variable age, unknown physical conditions and few hours later after dying. Also, the samples have been oriented to the tubule axes (Fig. 8) parallel to the tension load.

Once the hooves are picked up, the procedure followed, at first, consists of cutting the whole hoof off, separating them from the legs, in order to work with the material more easily. This process is carried out by a specialist on the field with a band saw as it is shown in Fig. 7.
Afterwards, the hooves are sawn manually for a better accuracy in order to obtain the fragment needed. The next step is to smoothen them with a file to get the size and the shape required and finally, the hoof wall tissue is separated from the third phalanx (coffin bone) using a scalpel.

As it is presented in Fig. 8, the hoof may be divided into three different layers: the perioplic stratum or the stratum externum, the coronary stratum or the stratum medium and the laminar stratum or the stratum internum.
The stratum externum is the most superficial part of the hoof. It is composed of a thin layer made of horny material, with whitish coloring and gleam, since it is not pigmented. It spreads recovering the wall and swelling it until reaching the bulbs. The thickness of the stratum diminishes in ancient animal, even it can disappear. Due to this, no samples have been taken from this layer.

The stratum internum is the innermost part of the wall and it is in contact with the third phalanx. It is organized into epidermal primary lamellaes and epidermal secondary lamellaes. These lamellaes are very important as they are entrusted to both the fastening of the hoof and the absorption of the shocks. That is, the impacts that the hoof suffers in the limb. However, it is composed of many nerves since it is the innermost tissue and consequently, the most fragile part of the hoof. Thus, the study of the stratum internum is not relevant in terms of mechanics parameters of the horn wall and it is not investigated in this thesis.
The stratum medium forms the hardest region with the biggest thickness of the epidermal hoof. It is originated in the coronary band and it grows distally until the ground contact surface is reached, for instance the grass. It consists of the dermis or the corion and the epidermis. Both of them are mixed, making up the tubular and intertubular material which is characteristic of this layer. The growth of the tubules is shown in Fig. 9, and it is parallel to the epidermis. It is very important either to know the direction of the growth of these tubules or their density considering that both variables affect directly to the materials parameters which are the objectives of this research.

Fig. 9. Sketch illustrating the formation of the horn tubules and intertubules from the growing areas (Van Nassau 2008)

Based on Reilly et al. (1998), the density has been supposed with a mean value of 16 tubules/mm². The majority of the hoof-wall is formed by stratum medium. The tissue inside of this stratum makes the externally visible wall up, with the exception of the stratum externum in the proximal border in case of existing. Due to all of this, the materials used in this study have been extracted from this stratum.
The samples have been manufactured and divided into two groups depending on the test for which they were used. That is, specimens for tensile tests and specimens for hardness tests.

2.2 MOISTURE CONTENTS

The moisture content is considered as the amount of water contained inside the material. It is expressed as a ratio that may vary from 0, that is when the material is completely dry, to the value of the porosity of the material in its point of saturation.

According to Butler and Hintz (1977), Bertram and Gosline (1987) and Küng et al. (1993), moisture content affects directly to the mechanical properties of the horny wall of the horse hoof. They stated the importance of studying the moisture content if it is intended that the results obtained through the materials tested are approximated to the situation in vivo. Conforming to Fraser and MacRae (1980), the stiffness is inversely related to hydration state in materials with keratin structures, where keratin is understood as a protein with fibrous structure which makes up the main component that forms the horn hoof. As reported by Douglas et al. (1996), the hydration level is a relevant factor to obtain the resistance of fracture, or toughness, since there is a close relation between the stiffness and the fracture behavior in keratinous materials.

Due to all of this, the moisture content has been measured in each sample. The procedure consists of weighting the mass of the sample just after the decease of the horse and then, weighting them after 4 days in an oven drying. In both cases the mass has been measured using a precision balance with a sensitive of 0.01 grams. Therefore, it can be obtained the percentage of hydration level through the application of the next equation:

\[
\%u = \frac{m_{wet} - m_{dry}}{m_{dry}} \cdot 100
\]

Where:
- \( m_{wet} \) is the mass of the sample before drying in the oven
- \( m_{dry} \) is the mass of the sample after drying in the oven
2.2.1 MOISTURE CONTENT RESULTS

In Table 1 are shown the values obtained about the hydration level.

<table>
<thead>
<tr>
<th>Nº</th>
<th>Sample</th>
<th>Mass Before Dying (gr.)</th>
<th>Mass After Dying (gr.)</th>
<th>% Moisture Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>2,23±0,01</td>
<td>2,23±0,01</td>
<td>0%</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>4,87±0,01</td>
<td>3,95±0,01</td>
<td>23,29%</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>1,99±0,01</td>
<td>1,59±0,01</td>
<td>25,16%</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>2,11±0,01</td>
<td>1,70±0,01</td>
<td>24,12%</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>2,11±0,01</td>
<td>1,66±0,01</td>
<td>27,11%</td>
</tr>
<tr>
<td>6</td>
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<td>0,96±0,01</td>
<td>22,92%</td>
</tr>
<tr>
<td>7</td>
<td>Proximal</td>
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<td>1,33±0,01</td>
<td>27,07%</td>
</tr>
<tr>
<td>9</td>
<td>Distal</td>
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<td>1,34±0,01</td>
<td>26,87%</td>
</tr>
<tr>
<td>11</td>
<td>Dorsal</td>
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<td>29,79%</td>
</tr>
<tr>
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</tr>
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<td>8</td>
<td>Medial</td>
<td>1,70±0,01</td>
<td>1,34±0,01</td>
<td>26,87%</td>
</tr>
<tr>
<td>9</td>
<td>Quarter</td>
<td>3,51±0,01</td>
<td>2,77±0,01</td>
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</tr>
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<td>10</td>
<td>Lateral</td>
<td>1,49±0,01</td>
<td>1,13±0,01</td>
<td>31,86%</td>
</tr>
<tr>
<td>14</td>
<td>Quarter</td>
<td>1,55±0,01</td>
<td>1,17±0,01</td>
<td>32,48%</td>
</tr>
</tbody>
</table>

Table 1. Results of the hydration level (own source)

2.3 TENSILE TESTS

As it is explained in point 1.4, the tensile tests were conducting using an Instron Model 8872 tensile testing machine with a maximum loading capacity of 25kN and an extension rate of 0.02 mm · s⁻¹. Dog bones shapes were the shapes chosen for the samples as it is represented in Fig 10.

![Dog bone shapes](image)

Fig. 10- Dog bone shapes samples (own source)
The mean values of them have been approximately \( L_0 = 11.4 \) mm (length) and \( b = 5.25 \) mm (width), with a thickness value of \( 6.5 \) mm in cross section. Six samples have been taken from the proximal/distal dorsal, four samples from the medial quarter and another 4 samples from the lateral quarter. Smooth pneumatic grips have been used to hold the samples to the tensile machine. The displacement and the elongation have been measured by a clip gauge, which has been directly connected to a computer that has obtained the data of each experiment. The distance required to use the clip gauge has been approximately \( 11.4 \) mm (the same as the initial length). Due to the danger of breakage of the extensometer, the tensile experiments have been divided into two parts, since the use of the clip gauge is limited only to the 10% of the elongation. It has been attached to the samples by means of two rubber-bands placed on the far left and on the far right respectively. This measure has been taken to avoid the creation of stress concentration areas that could cause the premature breakage of the specimens. All this process can be seen in Fig 11.

![Fig. 11. The procedure to attach the sample and the clip gauge to the tensile test machine (own source)](image)

The tensile test consists of subjecting the sample to a load with controlled displacement until breakage. This test measures the resistance that a material
opposes to a static force or to a force applied slowly. This stress is an axial
stress of traction. Derived from the tensile test, which is made with elongation
rate controlled, the progressive force applied and the displacement of the
samples are calculated for different values. The load cell, which is connected to
the grips, sends a signal to the computer with the value of the load applied. By
means of these values, the force-displacement relation can be represented in a
graph. An example of this graph is shown in Fig. 12.

\[ F = K \cdot (L - L_0) \]  

(1)

Where \( F \) is the force applied, \( K \) is the constant of the spring, \( L \) is the length
under load and \( L_0 \) is the initial length.

The elastic zone ends when the curve deviates from the initial straight. That is,
when the material reaches the yield point. From this moment, the material
begins to acquire a permanent deformation and it has reached the plastic zone.
Then, the equation (1) explained above is not valid in this area. Therefore, the

---

Fig. 12. Example of Force-Displacement curve (own source)
limit value that separates the elastic zone and the plastic zone is called yield point, and the force applied to achieve this point is called $F_{yp}$.

The next part of the diagram is unsteady and it depends on the material since $F_{max}$ varies depending on it. Between $F_{yp}$ and $F_{max}$ the specimen extends permanently and uniformly along its length. The deformation is concentrated on a zone which forms a neck causing the load drop slightly. Once the specimen is thinner in this region, the load is applied to a smaller area making the breakage of the sample.

Applying the values obtained through this graph, it can be determined the resistance to the fluency and the resistance to the traction, independently of the size of the samples, dividing the load applied between the initial cross section $A_0$, obtained through the multiplication of the initial thickness ($t_0$) by the initial width ($b_0$). That is:

Resistance to the fluency: $\sigma_{yp} = \frac{F_{yp}}{A_0} \, (MPa)$ \hspace{1cm} (2)

Resistance to the traction: $\sigma_{ult} = \frac{F_{max}}{A_0} \, (MPa)$ \hspace{1cm} (3)

Where $A_0 = t_0 \cdot b_0 \, (mm^2)$ \hspace{1cm} (4)

as it is a rectangular specimen.

Analyzing the specimens once they are broken, it is possible to calculate either the final thickness $t_f$ or the final width $b_f$. So that, the final area is defined as it follows: $A_f = t_f \cdot b_f \, (mm^2)$ \hspace{1cm} (5)

These values may be expressed both as a percentage of reduction of the area $\%R_A$ and a percentage of lengthening between notches $\%\Delta L$. These parameters can be calculated with the following equations (Askeland 2001):

$$\%R_A = \frac{A_0 - A_f}{A_0} \cdot 100$$ \hspace{1cm} (6)

$$\%\Delta L = \frac{L_f - L_0}{L_0} \cdot 100$$ \hspace{1cm} (7)
Both parameters are standardized measures that define the ductility of the material. However, due to the impossibility of an accurate measure of the final area, these results are approximated. The ductility is defined as the ability to undergo big deformations and to change form without breaking. Another parameter that can be determined is the brittleness. That is, the inverse of the ductility or the ease of the material to be broken. The last parameter derived from this graph is the tenacity. The tenacity represents the energy dissipated during the test, that is, the amount of energy. The more amount of energy, the more toughness the material becomes. The tenacity shows the resistance of the material to crack quickly. The value of the tenacity is bigger when a good relationship between the resistance and the ductility is achieved. A material may be ductile but not tough, or it may be resistant but not tough. It can be determined as the area under the curve Force-Displacement. An example of the relationship between brittleness, ductility and tenacity is shown in Fig. 12.

![Diagram showing the relationship between tenacity, ductility and brittleness](image)

**Fig. 13. Relation between tenacity, ductility and brittleness (own source)**

Through the values determined in the Force-Displacement curve, it can be obtained the stress-strain diagram. The stress equation, as it has been explained above, can be calculated with the following equation (KTH Department of Solid Mechanics, 2010):
\[ \sigma = \frac{F}{A_0} \text{ (MPa)} \quad (8) \]

And the one-dimensional strain (KTH Department of Solid Mechanics, 2010):

\[ \varepsilon = \frac{L - L_0}{L_0} \cdot 100 \quad (9) \]

In Fig. 14 is represented an example of a Stress-Strain curve.

![Stress-Strain curve](image)

**Fig. 14. Example of Stress-Strain curve (own source)**

The Stress-Strain curve can be divided into the same areas as the Force-Displacement graph. That is, an elastic zone and a plastic zone. Inside the elastic zone the Hooke’s Law may be applied since a linear-elastic material (KTH Department of Solid Mechanics, 2010) is supposed:

\[ \sigma = E \cdot \varepsilon \quad (10) \]

The parameter \( E \) that correlates stress and strain in Hooke’s Law is called Young’s Modulus. It corresponds to the slope of the strain/stress curve, or rather the tangent of the curve. It depicts an indicator of the material stiffness in such a way that if the Young’s Modulus increases, the stiffness increases as well. Furthermore, it measures the resistance of the inter-atomic bonds of the material.

So that, taking into account the equations (8) and (9) and replacing them, it can be stated that:
\[ \frac{F}{A_0} = E \cdot \frac{L_f - L_0}{L_0} \rightarrow F = E \cdot A_0 \cdot \frac{L_f - L_0}{L_0} \]  

(11)

The Stress-Strain diagrams of distinct materials vary thoroughly. Even different tensile tests from the same material may produce completely different results since they depend on the temperature of the sample and the loading speed. Because of that, these parameters have not been changed for a better accurately of the results, along this thesis.

2.3.1 TENSILE TESTS RESULTS

As it is explained in the subchapter 2.1, the tensile tests were divided into two parts because of the limit with the clip gauge. Thus, the diagrams and the results are separated below depending on the side of the horse hoof. One test of each part is shown. For further graphs, go to the Appendix 1.

PROXIMAL/DISTAL DORSAL RESULTS

![Test 2 - First Part](image)

Fig. 15. Force-Elongation Diagram second test, first part, with extensometer (own source)
Fig. 16. Engineering Stress-Strain curve, second test, first part, with extensometer (own source)

Fig. 17. Force-Elongation Diagram second test, second part, without extensometer (own source)
MEDIAL QUARTER RESULTS

**Fig. 18.** Force-Elongation Diagram ninth test, first part, with extensometer (own source)

**Fig. 19.** Engineering Stress-Strain Curve, ninth test, first part, with extensometer (own source)
Fig. 20. Force-Elongation Diagram, ninth test, second part, without extensometer (own source)

LATERAL QUARTER RESULTS

Fig. 21. Force-Elongation Diagram twelfth test, first part, with extensometer (own source)
Fig. 22. Engineering Stress-Strain Curve, twelfth test, first part, with extensometer (own source)

Fig. 23. Force-Elongation Diagram, twelfth test, second part, without extensometer (own source)
2.3.2 SUMMARY CHART OF TENSILE TEST RESULTS

Derived from the diagrams, several parameters can be calculated. A summary chart of this tensile test results is shown in Table 2. The equations (6), (7) and (10) showed in point 2.1, are used to calculate either the percentage of reduction of the area (%R<sub>A</sub>), or the percentage of lengthening between notches (%∆L), or the Young modulus (E), respectively.

<table>
<thead>
<tr>
<th>Nº Test</th>
<th>Initial Area (mm&lt;sup&gt;2&lt;/sup&gt;)</th>
<th>Initial Length (mm)</th>
<th>Final Area (mm&lt;sup&gt;2&lt;/sup&gt;)</th>
<th>Final Length (mm)</th>
<th>%R&lt;sub&gt;A&lt;/sub&gt;</th>
<th>%∆L</th>
<th>E (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>29,44</td>
<td>11,90</td>
<td>22,80</td>
<td>13,2</td>
<td>22,55%</td>
<td>10,92%</td>
<td>247</td>
</tr>
<tr>
<td>2</td>
<td>35,84</td>
<td>10,70</td>
<td>24</td>
<td>17,97</td>
<td>21,32%</td>
<td>67,94%</td>
<td>650</td>
</tr>
<tr>
<td>3</td>
<td>31,36</td>
<td>10,6</td>
<td>22,04</td>
<td>17,88</td>
<td>29,72%</td>
<td>68,68%</td>
<td>943</td>
</tr>
<tr>
<td>4</td>
<td>28,80</td>
<td>11,75</td>
<td>21,24</td>
<td>18,25</td>
<td>26,25%</td>
<td>55,32%</td>
<td>796</td>
</tr>
<tr>
<td>5</td>
<td>24,32</td>
<td>11</td>
<td>17,40</td>
<td>18,29</td>
<td>28,45%</td>
<td>66,27%</td>
<td>297</td>
</tr>
<tr>
<td>6</td>
<td>25,20</td>
<td>12,10</td>
<td>19,84</td>
<td>13,94</td>
<td>21,27%</td>
<td>15,21%</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Standard deviation</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0,04</td>
<td>0,27</td>
<td>261,78</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Nº Test</th>
<th>Initial Area (mm&lt;sup&gt;2&lt;/sup&gt;)</th>
<th>Initial Length (mm)</th>
<th>Final Area (mm&lt;sup&gt;2&lt;/sup&gt;)</th>
<th>Final Length (mm)</th>
<th>%R&lt;sub&gt;A&lt;/sub&gt;</th>
<th>%∆L</th>
<th>E (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>24,57</td>
<td>11,25</td>
<td>18,56</td>
<td>17,03</td>
<td>24,46%</td>
<td>51,38%</td>
<td>229</td>
</tr>
<tr>
<td>9</td>
<td>27,30</td>
<td>11,20</td>
<td>20,88</td>
<td>18,67</td>
<td>23,52%</td>
<td>66,70%</td>
<td>1044</td>
</tr>
<tr>
<td>11</td>
<td>30,36</td>
<td>11,70</td>
<td>23,40</td>
<td>20</td>
<td>22,92%</td>
<td>70,94%</td>
<td>14</td>
</tr>
<tr>
<td>13</td>
<td>28,60</td>
<td>10,10</td>
<td>22,80</td>
<td>15,47</td>
<td>20,28%</td>
<td>53,17%</td>
<td>67</td>
</tr>
<tr>
<td></td>
<td>Standard deviation</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0,02</td>
<td>0,09</td>
<td>479,14</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Nº Test</th>
<th>Initial Area (mm&lt;sup&gt;2&lt;/sup&gt;)</th>
<th>Initial Length (mm)</th>
<th>Final Area (mm&lt;sup&gt;2&lt;/sup&gt;)</th>
<th>Final Length (mm)</th>
<th>%R&lt;sub&gt;A&lt;/sub&gt;</th>
<th>%∆L</th>
<th>E (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>24,57</td>
<td>11,25</td>
<td>18,56</td>
<td>16,74</td>
<td>24,46%</td>
<td>48,80%</td>
<td>1297</td>
</tr>
<tr>
<td>10</td>
<td>32,33</td>
<td>11,15</td>
<td>25,3</td>
<td>18,13</td>
<td>21,74%</td>
<td>62,60%</td>
<td>305</td>
</tr>
<tr>
<td>12</td>
<td>34,20</td>
<td>12</td>
<td>25,44</td>
<td>21,06</td>
<td>25,61%</td>
<td>75,50%</td>
<td>213</td>
</tr>
<tr>
<td>14</td>
<td>39,53</td>
<td>12,45</td>
<td>31,62</td>
<td>22,33</td>
<td>22,33%</td>
<td>79,36%</td>
<td>56</td>
</tr>
<tr>
<td></td>
<td>Standard deviation</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0,02</td>
<td>0,14</td>
<td>562,31</td>
</tr>
</tbody>
</table>

Table 2. Summary chart of tensile test results (own source)
2.4 HARDNESS TESTS

The hardness tests (Fig. 4) is conducted using a sclerometer hardness machine A.B. Alpha with a maximum loading capacity of 250 Kgf. It consists of a glass tube of 300mm of height. Inside the tube, there is a hammer with a rounded diamond tip of 2.4g, which falls on the sample once the load is applied. The height of the fall is approximately 254 mm and the measured scale is divided into 140 divisions.

Rectangular shapes have been chosen to do the experiments as it is shown in Fig. 24

![Fig. 24. Hardness test samples (own source)](image)

The mean dimensions of the samples have been approximately L=7 mm (length), b=6.5 mm (width) and h=4.5 mm (thickness). Before the experiments, it has been necessary to prepare the evaluated surface of the specimen, filing it until it is completely smooth and entirely perpendicular to the ball that goes right through the sample.

Through this experiment, hardness may be estimated. Hardness or toughness is defined as the property of the surface layer of a material to resist both elastic and plastic deformations as well as its destruction. That occurs in the presence of local contact stresses inflicted by another harder body (indenter) with defined shape and size, which suffers no residual deformations.

There are three different sorts of hardness tests. The first one is called Brinell Hardness Test and it consists of a toughness measured of the material by means of an indentation method, measuring the penetration of an object within the material that it is studied. This method is used in brittle materials (low hardness) and thin samples. It utilizes a tempered steel ball with different diameters as indenter for low values and a tungsten carbide ball for high values. The measured value is the diameter of the cap on the material surface. The
measurements of this method are very sensitive to the state of preparation of the surface and it is not very accurate due to the difficulty of measuring the notch. Nevertheless, it is a very cheap technique and it is very advantageous if the material used is heterogeneous. It measures only until 600 HB, otherwise, over this value, the steel ball is deformed and the results are not valid. It would be necessary to use another hardness test for higher values. To determine the Brinell Hardness the following equation is utilized (Askeland 2001):

\[
BHN = \frac{2 \cdot P}{\pi \cdot D \cdot (D - \sqrt{D^2 - d^2})}
\]  

(12)

Where:
- \( P \) is the applied load (kgf)
- \( D \) is the diameter of the indenter (mm)
- \( d \) is the diameter of the indentation mark (mm)

A Brinell Harness Test sketch is exposed in Fig. 25.

![Brinell Hardness Test](image)

**Fig. 25. Brinell Hardness Test (Askeland 2001)**

The second toughness experiment is called Vickers Hardness Test or Universal Test. It is an improvement of the Brinell test since either the required calculations are independent of the size of the indenter or the indenter can be used for all materials irrespective of the hardness, due to its high resistance to
self-deformation. Its indenter is a diamond pyramid with a base angle of 136º. The indenter is pressed against the test specimen under lighter loads different to those used in the Brinell test. Then, the diagonals of the square notch are measured and the length average of both is calculated in order to apply the next equation (Askeland 2001):

\[
HV = \frac{F}{A} \approx \frac{1.8544F}{d^2}
\]  

(13)

Where:
- \( F \) is the load applied to the diamond (kgf)
- \( A \) is the surface area of the resulting indentation (mm\(^2\)) and it is calculated as:

\[
A = \frac{d^2}{2 \cdot \sin(136^\circ/2)} \approx \frac{1.8544F}{d^2}
\]  

(14)

- \( d \) is the average length of the diagonal left by the indenter (mm)

This method is recommended for hardness values superior to 500HB and it can be used even with non-planar surfaces. A scheme of Vickers test is introduced in Fig. 26.

![Fig. 26. Vickers Hardness Test (Askeland 2001)](image)
The third hardness method is called Rockwell Hardness Test. Despite it is an indentation method, this experiment does not try to measure the toughness in a straightforward way through the direct determination of the magnitude of the contact stress, otherwise it is calculated by means of an arbitrary number which is inversely proportional to the indenter penetration. Because of this, while Brinell and Vickers methods possess the principal insufficiency that the measurement of the marks take time and the results are not very accurate due to the accumulation of material dislodged near the edges, the Rockwell test is much more agile, accurate and objective. Thus, this one is the method chosen to measure the hardness.

The Rockwell Hardness Test is defined as an indentation testing method by which, through the use of a calibrated machine, a diamond spheroid-conical indenter or a steel hardened ball is forced against the surface of the material to be tested, in two steps, measuring the permanent depth of the mark under specifics conditions of loading.

The procedure consist of, at the beginning, penetrating the indenter superficially on the surface of the sample under the action of the preload $P_0$, remaining it until the end of the test. This ensures a greater accuracy of the values since the vibrations and the irregularities of the thin surface layer are excluded. Then, the specimen is exposed to the action of the total load $P_f$, whose value is $P_f = P_0 + P_1$, and the depth penetration increases. After, the principal load $P_1$ is removed, suffering the specimen-indenter system an elastic recovery as the only load applied is $P_0$. At this moment is possible to measure the depth $h$, which will determine the value of the Rockwell Hardness (HR). Analytically, depending on the indenter used, the equation to measure the Rockwell Hardness varies:

- For the diamond cone:

$$HR = 100 - \frac{h}{0.002}$$ (15)

- For the steel balls:

$$HR = 130 - \frac{h}{0.002}$$ (16)

It is deduced from these equations that each Hardness Rockwell unity corresponds to a penetration of 0.002mm. In order to take a good coherence,
this value is subtracted to certain limit value in such a way that, the smaller depth penetration value the bigger Rockwell value will be and vice versa.

However, nowadays, the development of the Rockwell Hardness machine has allowed their indicators to measure the values automatically by reason of its dials.

A sketch of the procedure to obtain the Rockwell Hardness is shown in Fig. 27.

As it is explained above, the Rockwell value depends on the indenter used and the load applied. Based on the possible combinations of both parameters, the ASTM E18 Standard has defined fifteen different hardness scales. These scales and its applications are shown in Table 3.

<table>
<thead>
<tr>
<th>Scale</th>
<th>Indenter</th>
<th>Total Load</th>
<th>Scale Color</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Diamond cone</td>
<td>60</td>
<td>Black</td>
<td>Hard metals, tempered surfaces, thin sheet (&lt;0.4mm)</td>
</tr>
<tr>
<td>D</td>
<td>Diamond cone</td>
<td>100</td>
<td>Black</td>
<td>Pieces with tempered surfaces of medium-hardness, sheets</td>
</tr>
<tr>
<td>C</td>
<td>Diamond cone</td>
<td>150</td>
<td>Black</td>
<td>Tempered steels</td>
</tr>
<tr>
<td>F</td>
<td>Steel ball Ø 1/16&quot;</td>
<td>60</td>
<td>Red</td>
<td>Annealed copper alloys. Metallic thin sheet (&gt;0.6mm)</td>
</tr>
<tr>
<td>B</td>
<td>Steel ball Ø 1/16&quot;</td>
<td>100</td>
<td>Red</td>
<td>Brittle steels of construction, non-ferrous metal</td>
</tr>
<tr>
<td>G</td>
<td>Steel ball Ø 1/16&quot;</td>
<td>150</td>
<td>Red</td>
<td>Bronze, Beryllium-copper, Nickel-copper, malleable smelting</td>
</tr>
<tr>
<td>H</td>
<td>Steel ball Ø 1/8&quot;</td>
<td>60</td>
<td>Red</td>
<td>Aluminium, lead, zinc</td>
</tr>
<tr>
<td>E</td>
<td>Steel ball Ø 1/8&quot;</td>
<td>100</td>
<td>Red</td>
<td>Smelting, Al-Mg alloys, antifriction metals,</td>
</tr>
</tbody>
</table>
2.4.1 ROCKWELL HARDNESS TEST RESULTS

The method used to measure the hardness test is the Rockwell B scale. Therefore, a steel ball with a diameter of 1/16 inches (1.5875mm) is used as an indenter and a load applied of 100 kgf. Furthermore, three repetitions of each sample are carried out for a better accuracy. The results obtained through this method are summarized in Table 4.

<table>
<thead>
<tr>
<th>Nº Sample</th>
<th>Test 1</th>
<th>Test 2</th>
<th>Test 3</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>PROXIMAL/</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DISTAL</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DORSAL</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>20 HRB</td>
<td>19 HRB</td>
<td>20 HRB</td>
<td>20 HRB</td>
</tr>
<tr>
<td>2</td>
<td>19 HRB</td>
<td>22 HRB</td>
<td>21 HRB</td>
<td>20 HRB</td>
</tr>
<tr>
<td>3</td>
<td>19 HRB</td>
<td>19 HRB</td>
<td>19 HRB</td>
<td>19 HRB</td>
</tr>
<tr>
<td>4</td>
<td>22 HRB</td>
<td>20 HRB</td>
<td>19 HRB</td>
<td>20 HRB</td>
</tr>
<tr>
<td>5</td>
<td>20 HRB</td>
<td>25 HRB</td>
<td>19 HRB</td>
<td>21 HRB</td>
</tr>
<tr>
<td>6</td>
<td>19 HRB</td>
<td>23 HRB</td>
<td>21 HRB</td>
<td>21 HRB</td>
</tr>
<tr>
<td>MEDIAL</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>QUARTER</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>15 HRB</td>
<td>14 HRB</td>
<td>15 HRB</td>
<td>15 HRB</td>
</tr>
<tr>
<td>9</td>
<td>14 HRB</td>
<td>18 HRB</td>
<td>15 HRB</td>
<td>16 HRB</td>
</tr>
<tr>
<td>11</td>
<td>16 HRB</td>
<td>14 HRB</td>
<td>14 HRB</td>
<td>15 HRB</td>
</tr>
<tr>
<td>13</td>
<td>14 HRB</td>
<td>12 HRB</td>
<td>17 HRB</td>
<td>14 HRB</td>
</tr>
<tr>
<td>LATERAL</td>
<td></td>
<td></td>
<td></td>
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<td>13 HRB</td>
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<td>11 HRB</td>
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<td>18 HRB</td>
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Table 4. Summary chart of Rockwell B Hardness test results (own source)
2.5 MICROSCOPIC ANALYSIS

In addition to the tensile and hardness test, a microscopic analysis of the fractured surface, after testing the samples, is carried out in order to corroborate the results obtained in the other tests. A Zeiss Stemi 2000-C light microscopy was used to perform the study as it is shown in Fig. 5. This microscopy allowed a magnification of the image of 50 times (x50).

Certain materials are identified by their fractures. An examination of the fracture can throw a possible clue to the low values of the resistance and the ductility of the material. The fracture, in mechanical terms, is defined as the separation of a solid under tension in two or more pieces. In general, the fracture can be classified into ductile and brittle.

The ductile fracture occurs after a strong plastic deformation and, it is characterized by slow crack propagation. It begins with the formation of a neck and small cavities inside the strangulation zone. Then, the cavities fuse into a crack in the center of the sample and it propagates towards the surface perpendicularly to the stress applied. When approaching the surface, the crack changes the direction 45° with respect to the stress axis, achieving the complete fracture. An example of a ductile fracture and a moderately ductile fracture are shown in Fig. 28 (a) and Fig. 28 (b).

![Fig. 28. (a) Ductile Fracture. (b) Moderately Ductile Fracture (Askeland 2001)](image)
However, the brittle fracture has fast crack propagation without an appreciable deformation. Usually, it occurs along specific crystallographic planes called fracture planes, which are perpendicular to the applied stress. Most of brittle fractures are trans-granular, that is that they propagate through the grains. Nevertheless, if the grain boundaries are a weakness area, it is possible that the fracture propagates inside of the granules. An example of brittle fracture can be seen in Fig. 29.

Another sort of classification is in terms of shape. They can be:
- Symmetrical Fractures: These kinds of fractures are called cone fracture or crown fracture. Derived from the tri-axial stress caused by the constriction, it is reached a situation in which the small inclusions that the material contains in the burdened area become to break or separate. All of this causes micro hollows which grow gradually at the same time that the plastic deformation, until
they coalesce. Thereby, it is generated an internal flat fissure with disc shape, which is oriented usually to the direction of the applied stress. Finally, the breaking is completed by cutting along a conical surface oriented approximately 45° to the stress axes. The origin of the breakage along the conical surface is the fact that the tri-axial stress is lost progressively since the normal stress is zero on the free surface. All this progression is caused at the same time that the apex of the fissure approaches to the surface of the bar. Therefore, plastic constriction decreases and consequently the shear stress axis at 45° become predominant, taking to plastic rupture along these planes. A sample of this fracture is represented in Fig. 30.

![Fig. 30. Conic and crown fracture (Askeland 2001)](image)

- Flat fractures: if the material is brittle, a tri-axial superficial state is induced, tending to suppress the conical area. Hence, it is obtained a flat fracture (Fig. 31).

![Fig. 31, Flat fracture (Askeland 2001)](image)
- Irregular fractures: the non-axial load causes asymmetric fractures. Also, they can be caused by the heterogeneity of the material, any defect or any failure such as segregation, bubbles or inclusions of strange materials. There are more classifications of the fracture such as texture and color, but they are not relevant to this thesis due to the characteristics of the material.

2.5.1 MICROSCOPIC ANALYSIS RESULTS
In the same way as in point 2.4, only one microscopic analysis image of each side of the hoof is shown in this subchapter. The most representative images were chosen. For further images, go to Appendix 2.

IMAGES PROXIMAL/DISTAL DORSAL
The sample number 3 was chosen because of the clarity of the image. This analysis is shown in Fig. 31.

Fig. 32. Microscopic image of fracture surface of sample 3 (own source)
IMAGES MEDIAL QUARTER
For the same reasons as before, the sample 7 was chosen to show the fracture surface belonging to the medial quarter (Fig. 33).

![Fig. 33. Microscopic image of fracture surface of sample 7 (own source)](image)

IMAGES LATERAL QUARTER
From the lateral quarter sample 14 was selected. Its image is represented in Fig. 34.

![Fig. 34. Microscopic image of fracture surface of sample 14 (own source)](image)
3. CONCLUSIONS

The main purpose of this research is to find a pattern throughout the wall of the horny hoof that is able to solve the problem with the fastening of the nails of the horseshoe. However, no pattern has been founded due to both the insufficient amount of samples and the insufficient amount of hooves, which impeded the possibility of comparing several specimens. These problems were caused by the difficulties to take hooves (it was needed a special permission) and the deficiency of time. Nevertheless, it has been possible to find the principal material parameters of the horse hoof.

Derived from the moisture content study, it has been demonstrated that the parameters vary concurrently to the water content. It can be stated that for a lower level of hydration, the material increases its stiffness, reducing their mechanical resistance and hence, its ductility, turning it into a much more brittle material. This causes the material being less tough, giving advantage to faster crack propagation that might appear. Additionally, the plastic behavior of the completely dehydrated sample is nonexistent, implying that, once the elastic zone has finished, the material cannot bear deformations, becoming to break. In contrast to this, for higher water content values, the stiffness of the material diminishes, increasing its mechanical resistance, its ductility and its tenacity. All these statements have been corroborated both in the tensile test, through the equations of percentage of reduced area and the percentage of lengthening between notches, and the microscopic study. The study of the mechanics fracture resulted in a flat fracture for the sample dehydrated (brittle fracture), as well as for a moderately ductile fracture regarding to hydrated samples. With regard to the shape, the fracture may be considered as irregular due to the existence of heterogeneity and failures in the material although, it can be appreciated a fracture angle approximately of 45° on the surface. This induces to suppose a ductile behavior in the material.

In relation to the Young´s Modulus, it can be appreciated the divergence between the sides of the hoof. It increases in the proximal/distal dorsal, and it diminishes both in the medial quarter and in the lateral quarter, caused by the variation of the stiffness. Anyway, it can be appreciated big differences in values...
of the sample from the same side, perhaps due to both the small variation of sizes between samples and the degradation caused by the environmental conditions that the hoof suffers.

Also, it can be concluded that the material is very brittle according to the results obtained from the hardness test. The value in the proximal/distal dorsal is slightly higher than in the quarters, due to both the capsule that recovers this part and the bigger thickness commented before. It is noteworthy that, due to the low values of the hardness and the non-completely flat surface of the specimens, the results of the toughness test are not completely accurate, obtaining estimated values.
4. DISCUSSIONS

Throughout this research, the material parameters and how the moisture content affects them has been studied, as discussed above. Comparison of the results of this research with those of Douglas et al. (1996), Hinterhofer et al. (1998) and Bertram and Gosline (1987), regarding to the relationship between the moisture content and the stiffness derived from the tensile test, shows several similarities. The moisture content of the sample was slightly higher in these researches than in the current study, excepting in the research of Douglas et al. (1996) that it was slightly lower. Douglas et al. (1996) distinguished between inner and outer samples in the toe of the horse, obtaining a mean value of the Young´s Modulus of 728 MPa, with an hydration level of 31,7%. The Young´s Modulus value is very similar to this determined by Hinterhofer et al. (1998) which was 761.8 MPa with a moisture content value of 22,7%. The average value obtained along this thesis for elasticity modulus in proximal/distal dorsal is 587 MPa with an average of hydration level of 24,52% (excluding the first sample that was completely dehydrated). The change of this value may be caused by the variation of strain rate, according to Kasapi and Gosline (1996), which state the influence of this parameter over the estimation of the Young´s Modulus. However, according to Bertram and Gosline (1987), the Young´s Modulus resulted in 410 MPa for inner and fully hydrated samples (40.2%). Adding to this, the value of the first sample evaluated in this research (sample fully dehydrated) that was 247 MPa. Hence, it can be stated that whether the moisture content increases or decreases in comparison with the situation in vivo of the horses (approximately 25%), the stiffness of the material decreases and consequently, the material has lower work of fracture. That is, the rate of crack propagation increases. This statement is similar to the findings of Leach (1980) and Leach and Zoerb (1983), who tried to demonstrate the relationship between the stiffness and the water content.

With respect to the results of the quarters, it can be deduced that the behavior of the hoof is not the same in each side due to the difference in anatomical position and in mechanical function. Effectively, in the current research, both the Young´s Modulus and the moisture content vary openly between the quarters and the toe. The Young´s modulus in the medial quarter was 339 MPa with an
hydration level of 27.77%, while in the lateral quarter it was 467.75 MPa and had a moisture content of 29.48%. Therefore, presumably, given the difference in thickness between the quarters and the toe, the stiffness value will be lower in the lateral and medial quarter, as it is explained above. Moreover, this difference can also be noticed in the moisture content, as it is logical to think that if the thickness is lower, the sample is closer to the dermal and the epidermal and thus, the softest tissue, which is the most hydrated part. All this would explain the greater flexibility of the quarters with respect to the displacement caused by the stride in the hoof. Similar statements were reported by Douglas et al. (1996), ensuring that “a gradient of stiffness between the relatively rigid outer horn and the soft tissues of the dermis will help to reduce stress values at the interface between epidermis and dermis and will reduce the magnitude of the peak stress experienced by the soft tissues during locomotion”. No more parameters such as the hardness, the tenacity and the ductility, have been compared due to the non-existence of similar researches.
5. FUTURE RESEARCH

While conducting this study there are some areas that might be worth investigating. Since the final purpose of this research has not been able to achieve, certain researchers are suggested for future investigations. Regarding to the hardness, it is recommended to do a thorough study of the hardness of the nails. That is, considering that the hardness of the horse hoof has been calculated, once the toughness of the nails is known, it is possible to find the relationship of both parameters. The tearing of the hoof due to the nails will be able to be under control and thus, it will be feasible the fastening of the horseshoe. In addition, to get this objective, it is necessary to do a research of the strength, stresses and loads that the horse undergo when it is doing the effort with the limb. It is important to connect the values of the strengths, obtained through this investigation, with the material parameters shown in the current thesis. A simulation of the shoe in a 3D strength perspective should be done to appreciate the functioning of the horse hoof. The lack of time has not allowed doing all the necessary tests. So that, it would be required either to increase the rate of specimen tested in order to get an accurate result, or to compare the behavior of the parameters with more hooves belonging to different equines. Finally, based on several research studies shown in the references, it has been supposed the isotropy of the material. It would be interesting to check this characteristic, so as to corroborate no differences between both tension and compression, and the material parameters in all the directions.
APPENDIX 1

Along this appendix, the rest of the tensile tests which are not shown in subchapter 2.3 are represented from Fig. 35 until Fig.66. It is important to clarify that the first test, which corresponds to the sample completely dehydrated consists of two parts only, unlike to the rest of the tests. Furthermore, in the fourth test, the sample broke out of the stress area. Accordingly, the results from this test are not precise.

**Fig. 35. Force-Elongation Diagram, first test, first part, with extensometer (own source)**

**Fig. 36. Engineering Stress-Strain Curve, first test, first part, with extensometer (own source)**
Fig. 37. Force-Elongation Diagram, third test, first part, with extensometer (own source)

Fig. 38. Engineering Stress-Strain Curve, third test, first part, with extensometer (own source)
Fig. 39. Force-Elongation Diagram third test, second part, without extensometer (own source)

Fig. 40. Force-Elongation Diagram fourth test, first part, with extensometer (own source)
Fig. 41. Engineering Stress-Strain Curve, fourth test, first part, with extensometer (own source)

Fig. 42. Force-Elongation Diagram fourth test, second part, without extensometer (own source)
Fig. 43. Force-Elongation Diagram fifth test, first part, with extensometer (own source)

Fig. 44. Engineering Stress-Strain Curve, fifth test, first part, with extensometer (own source)
Fig. 45. Force-Elongation Diagram fifth test, second part, without extensometer (own source)

Fig. 46. Force-Elongation Diagram sixth test, first part, with extensometer (own source)
Fig. 47. Engineering Stress-Strain Curve, sixth test, first part, with extensometer (own source)

Fig. 48. Force-Elongation Diagram sixth test, second part, without extensometer (own source)
Fig. 49. Force-Elongation Diagram seventh test, first part, with extensometer (own source)

Fig. 50. Engineering Stress-Strain Curve, seventh test, first part, with extensometer (own source)
Fig. 51. Force-Elongation Diagram seventh test, second part, without extensometer (own source)

Fig. 52. Force-Elongation Diagram eighth test, first part, with extensometer (own source)
Fig. 53. Engineering Stress-Strain Curve, eighth test, first part, with extensometer (own source)

Fig. 54. Force-Elongation Diagram eighth test, second part, without extensometer (own source)
Fig. 55. Force-Elongation Diagram tenth test, first part, with extensometer (own source)

Fig. 56. Engineering Stress-Strain Curve, tenth test, first part, with extensometer (own source)
Fig. 57. Force-Elongation Diagram tenth test, second part, without extensometer (own source)

Fig. 58. Force-Elongation Diagram eleventh test, first part, with extensometer (own source)
Fig. 59. Engineering Stress-Strain Curve, eleventh test, first part, with extensometer (own source)

Fig. 60. Force-Elongation Diagram eleventh test, second part, without extensometer (own source)
Fig. 61. Force-Elongation Diagram thirteenth test, first part, with extensometer (own source)

Fig. 62. Engineering Stress-Strain Curve, thirteenth test, first part, with extensometer (own source)
Fig. 63. Force-Elongation Diagram, thirteenth test, second part, without extensometer (own source)

Fig. 64. Force-Elongation Diagram fourteenth test, first part, with extensometer (own source)
Fig. 65. Engineering Stress-Strain Curve, fourteenth test, first part, with extensometer (own source)

Fig. 66. Force-Elongation Diagram, fourteenth test, second part, without extensometer (own source)
APPENDIX 2

A broad set of images derived from the rest of the test is shown in this appendix from Fig. 67 until Fig. 74. No images were obtained from samples 2, 10 and 13 since after finish the test, the specimen did not break.

Fig. 67. Image of fracture surface of Sample 1 (own source)

Fig. 68. Image of fracture surface of Sample 4 (own source)
Fig. 69. Image of fracture surface of sample 5 (own source)

Fig. 70. Image of fracture surface of sample 6 (own source)
Fig. 71. Image of fracture surface of sample 7 (own source)

Fig. 72. Image of fracture surface of sample 8 (own source)
Fig. 73. Image of fracture surface of sample 11 (own source)

Fig. 74. Image of fracture surface of sample 12 (own source)
LIST OF REFERENCES


• Pollitt, C., 2006. The horse´s foot-The inside story. *Australian Equine Laminitis Research Unit.*


