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Evaluation of hoof horn quality by tensile test and hardness test using acoustic emission

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Hodnocení kvality rohoviny pomocí tahové zkoušky a zkoušky tvrdosti pomocí akustické emise

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ABSTRACT

The research aimed to explore the use of tensile tests and hardness tests in combination with acoustic emission to evaluate the physical properties of hoof horn quality in dairy cows. Lameness is a significant issue in dairy farms worldwide, with a prevalence ranging from 14-31%. Reducing its occurrence is essential to minimize economic losses in farms. Lameness can cause production, reproduction, and welfare problems, leading to high costs of hoof treatment, lower milk production, and premature culling of animals from breeding. Even small changes in breeding management, nutrition, or technology can disrupt the formation of keratin and lead to changes in the horn. Evaluating the mechanical properties of the horn could be one of the tools to control the quality of the horn and prevent animal lameness. The goal of the experiment was to record the acoustic emission when the material broke and investigate the differences in the physical properties of the biological material. Both tests found high variability in sample resistance and acoustic signals depending on the sampling location. Samples taken from the hoof wall showed greater hardness, while samples taken from the heel were more elastic. These parameters and possible differences could be used to evaluate horn quality, which plays a fundamental role in the development of hoof disease and lameness.

Keywords: dairy cow, hoof horn, acoustic emission, tensile test, hardness test

ABSTRAKT

Cílem práce bylo prozkoumat využití tahových zkoušek a zkoušek tvrdosti v kombinaci s akustickou emisí pro hodnocení fyzikálních vlastností kvality rohoviny paznehtu u dojnic. Kulhání je významný problém na mléčných farmách po celém světě, s prevalencí v rozmezí 14–31 %. Snížení jeho výskytu je nezbytné pro minimalizaci ekonomických ztrát v zemědělských podnicích. Kulhání může způsobit problémy v produkci, reprodukci a welfare, což vede k vysokým nákladům na ošetření paznehtů, nižší produkci mléka a předčasnému vyřazování zvířat z chovu. I malé změny v chovu, výživě nebo technologii mohou narušit tvorbu keratinu a vést ke změnám rohoviny. Hodnocení mechanických vlastností rohoviny by mohlo být jedním z nástrojů kontroly kvality rohoviny a předcházení kulhání zvířat. Cílem experimentu bylo zaznamenat akustickou emisi při rozbití materiálu a prozkoumat rozdíly ve fyzikálních vlastnostech biologického materiálu. Oba testy zjistily vysokou variabilitu odporu vzorku a akustických signálů v závislosti na místě odběru vzorků. Vzorky odebrané ze stěny paznehtu vykazovaly větší tvrdost, zatímco vzorky odebrané z patkové části byly elastičtější. Tyto parametry a případné rozdíly by mohly být využity pro hodnocení kvality rohoviny, která hraje zásadní roli při vzniku onemocnění a kulhání paznehtů.

Klíčová slova: dojnice, rohovina paznehtu, akustická emise, zkouška tahem, zkouška tvrdosti

INTRODUCTION

The quality of hoof horn is crucial in preventing hoof diseases and lameness in cattle. These issues not only significantly affect the health and welfare of animals but also result in high economic losses for breeders (Ranjbar et al., 2016). Farm management, including animal nutrition (Van Marle-Köster et al., 2019) and housing technology (Franck et al., 2006), has a significant impact on the quality of hoof horn. Poor horn quality, disorders of tissue composition, and hygroscopic properties are typically associated with most hoof diseases. The physical properties of the hoof, including hardness, resistance, and viscoelasticity, mainly determine its ability to resist pathogens (Barbosa et al., 2016). These properties are determined by the hoof's chemical composition, which mainly includes minerals such as calcium, phosphorus, zinc, and magnesium (Barbosa et al., 2020), as well as selenium, vitamins, amino acids, and fatty acids (Van Marle-Köster et al., 2019). The quality of the horn is significantly reduced by processes such as desiccation or fluid oversaturation. Optimal moisture of the horn is ensured by glycoproteins and lipids (Lean et al., 2013). Higher environmental humidity reduces hardness, while low humidity causes brittleness (Clark and Petrie, 2007).

The hoof is covered by a keratinized epidermis that protects it from damage. This epidermis is created by the process of keratinization (Khomyn et al., 2018), which is a complex phenomenon that is sensitive to hormonal control, nutrient influx, and environment (Osorio et al., 2016). Cattle hooves consist of α-keratin (Tombolato et al., 2010), which is an insoluble material that is resistant to the influence of adverse environmental factors (Khomyn et al., 2018). The structure of the horn capsule and the arrangement of tubules, intertubular matrix, and laminar cells mainly determine the hoof resistance (Franck et al., 2006). The tubules are oriented parallel to the limb and are surrounded by keratin in circular lamellae, which prevents any cracks from propagating proximally (Clark and Petrie, 2007). Elasticity and shock absorption are ensured by a greater proportion of intermediate filaments (McKittrick et al., 2012). Physical characteristics such as hardness or tensile strength tests can be used to assess the strength and biomechanical behavior of hooves (Van Marle-Köster et al., 2019). The physical properties of hoof horns are not typically the focus of scientific research, despite their critical role in assessing the health status of the limbs. To date, there has been no comprehensive description of the methods available for evaluating the physical indicators of hoof horn quality in dairy cows. The objective of the present experiment was to record the acoustic emission (AE) during material crack and to ascertain the underlying factors that generate the acoustic effect.

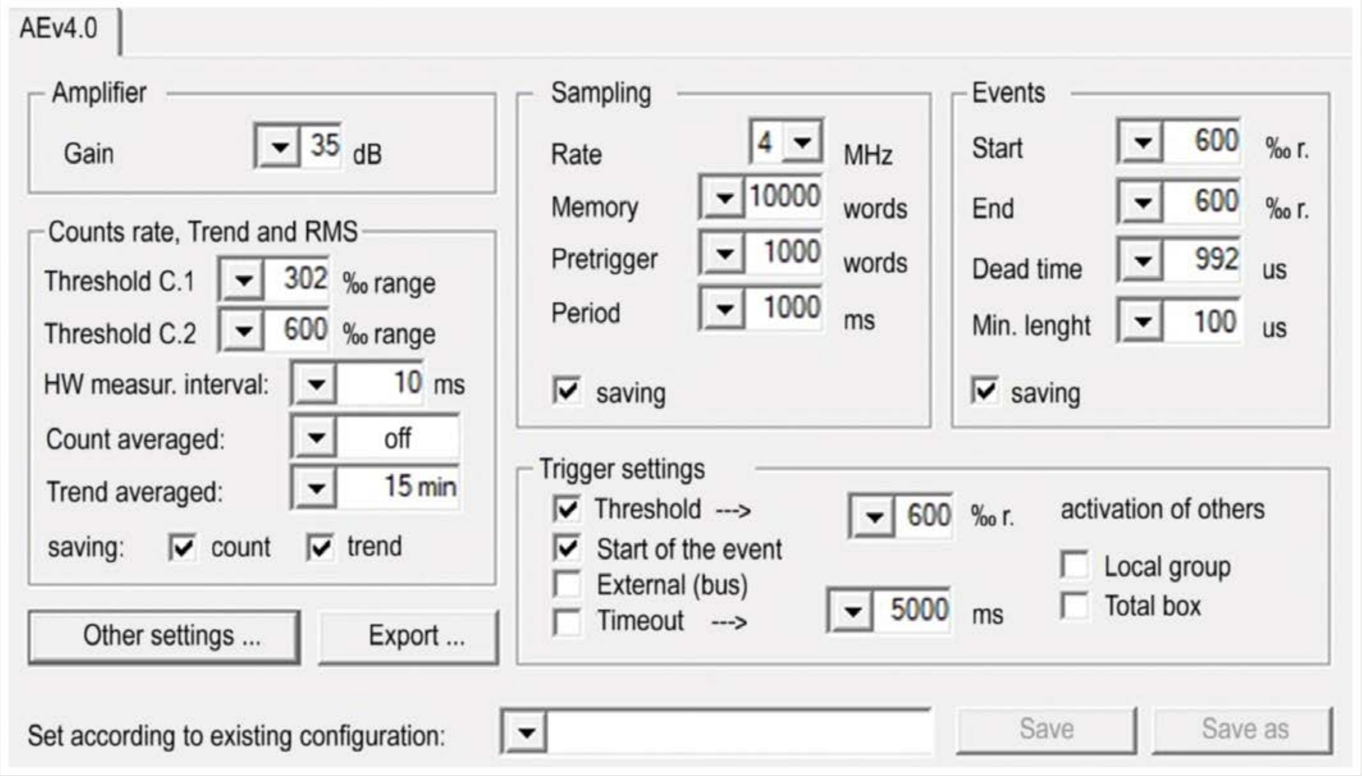
MATERIAL AND METHODS

Hoof horn samples were collected from 12 Holstein cows at the end of the first lactation period. The dairy cows were kept in free box housing. The lying boxes were lined with straw, and the manure corridor was pumped up six times daily. The measurement focused on the variation in the physical properties of pelvic limb hoof horn in dairy cows. The material observed was the hoof horn of dairy cows, which was cleaned and cut to size 50 × 10 × 10 mm for the tensile test and samples of size 10 × 10 × 10 mm for the hardness test. Hoof horn quality was monitored using destructive tests in combination with measuring the intensity of internal structure disruption using AE. A tensile test was carried out at the Mendel University in Brno Faculty of Agrisciences, Department of Food Technology, and a modified Brinell hardness test was carried out at the Department of Technology and Automobile Transport. Horn samples were prepared from different parts of the hooves of slaughtered dairy cows.

In both tests, an Xedo device and an IDK 9 piezoelectric sensor from the Dakel company were used to record the acoustic signal. The sensor was fixed to the surface of the samples using a special epoxy-based gel adhesive to achieve a better transfer of AE from the sample to the sensor. This yielded the maximum recording of AE signals when dislocations appeared in the loaded sample. Acoustic emission signals were recorded using the Dakel software Daemon. This software's configuration, shown in Figure 1, was 35 dB in the tensile test for amplifiers. A Count 2 threshold signal with a recording interval of 10 ms was used for signal evaluation. For the pressure test (hardness test), the software settings were identical, but the amplifier was set to 40 dB (see Figure 2).

Tensile test

For the tensile test, 9 samples of size 50 × 10 × 10 mm were cut from the hooves. The tensile test was carried out on an experimental device with a tearing machine and the maximum force achieved to destroy the sample was 1500 N. This tearing device, TIRATESTU 27025 from the Institute of Food Technology, is designed for a maximum load of up to 3 KN. Nine samples were used for the tensile test. Figure 3 shows the method of clamping the sample on the tearing machine. The machine feed is constant, and the force or voltage that changes with time or sample stretching is recorded. Stretching the sample causes changes (destruction) of the internal structure. This produces acoustic waves that can be detected by acoustic emission.


AEv4.0

Amplifier
Gain 35 dB

Counts rate, Trend and RMS
Threshold C.1 302 ‰ range
Threshold C.2 600 ‰ range
HW measur. interval: 10 ms
Count averaged: off
Trend averaged: 15 min
saving: ☑ count ☑ trend

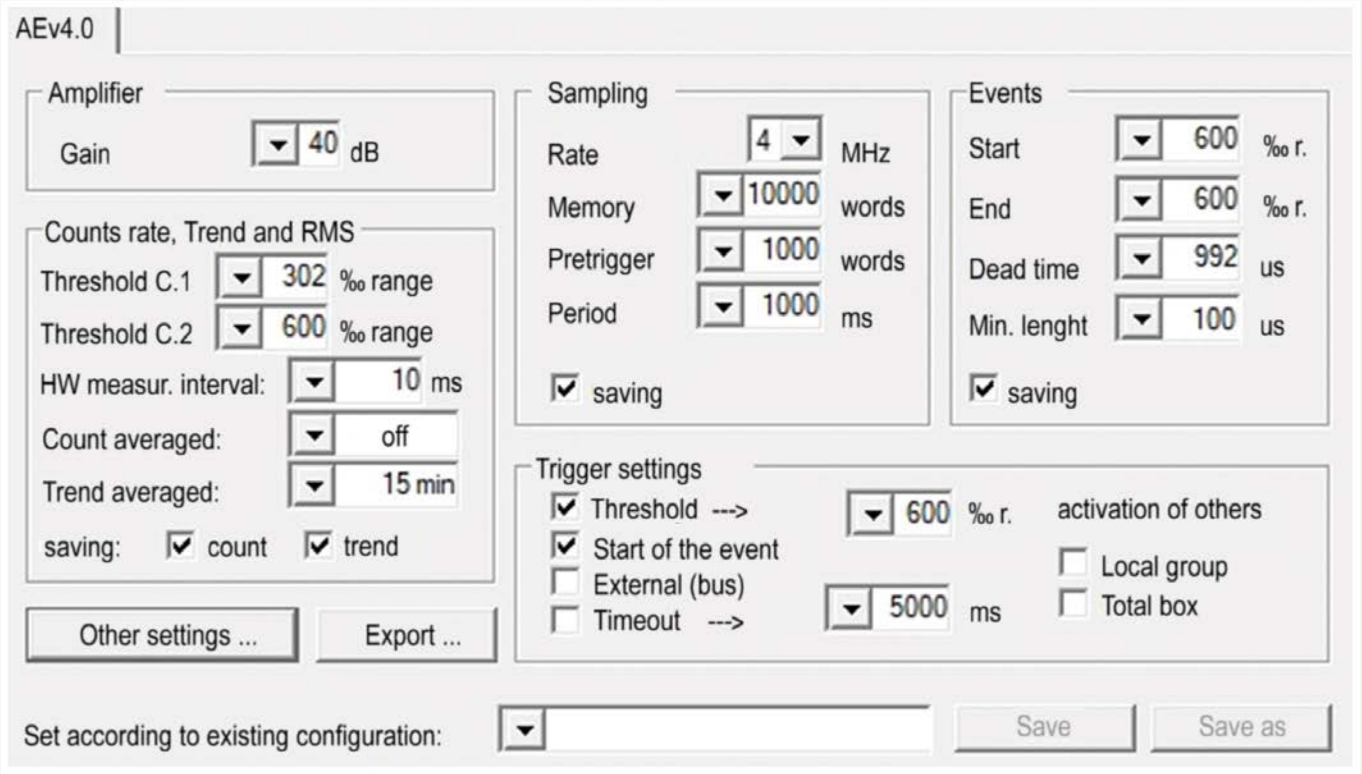
Sampling
Rate 4 MHz
Memory 10000 words
Pretrigger 1000 words
Period 1000 ms
☑ saving

Events
Start 600 ‰ r.
End 600 ‰ r.
Dead time 992 us
Min. lenght 100 us
☑ saving

Trigger settings
☑ Threshold ---> 600 ‰ r.
☑ Start of the event
☐ External (bus)
☐ Timeout ---> 5000 ms
activation of others
☐ Local group
☐ Total box

Set according to existing configuration:

Figure 1. AE settings used in tensile tests



Amplifier
Gain 40 dB

Counts rate, Trend and RMS
Threshold C.1 302 ‰ range
Threshold C.2 600 ‰ range
HW measur. interval: 10 ms
Count averaged: off
Trend averaged: 15 min
saving: ☑ count ☑ trend

Sampling
Rate 4 MHz
Memory 10000 words
Pretrigger 1000 words
Period 1000 ms
☑ saving

Events
Start 600 ‰ r.
End 600 ‰ r.
Dead time 992 us
Min. lenght 100 us
☑ saving

Trigger settings
☑ Threshold ---> 600 ‰ r.
☑ Start of the event
☐ External (bus)
☐ Timeout ---> 5000 ms
activation of others
☐ Local group
☐ Total box

Set according to existing configuration:

Figure 2. AE settings used in hardness tests

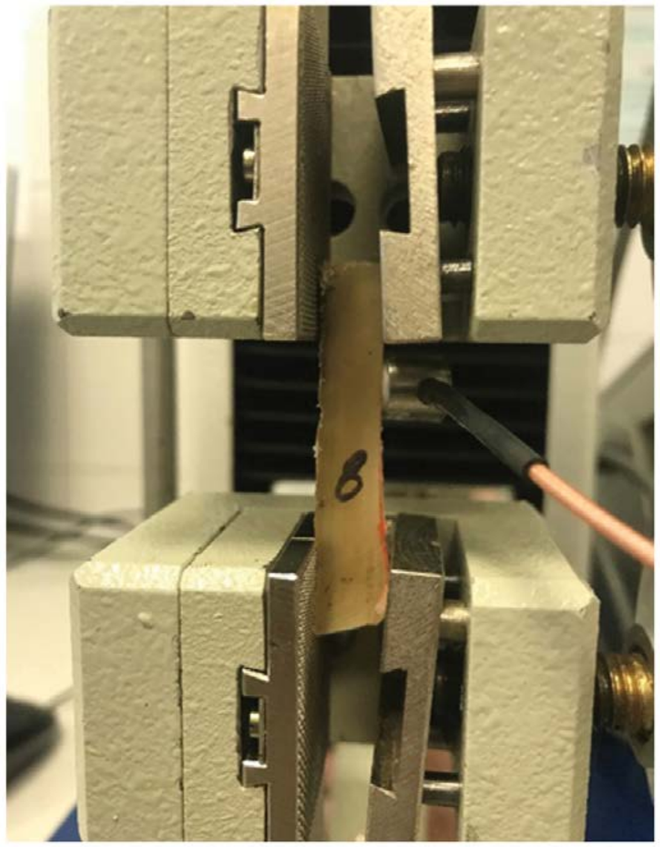


Figure 3. Tensile test progress

Hardness test (pressure test)

A pressure test was performed on an experimental device a table Brinell CHB-3000 hardness tester for 11 samples of horn. To measure the hardness, a special mandrel was designed and constructed (Figure 4).

It ensured penetration into the material in such a way as to cause the desired destruction and induce acoustic activity, which was defined by acoustic emission. This test was only used to induce dislocations when a specially designed mandrel in such a way as to cause the desired destruction and induce acoustic activity, which was defined by acoustic emission. This test was only used to induce dislocations when a specially designed mandrel disturbed the material. Therefore, the material's hardness was not recorded. With this test, the AE signal excited by cone indentation was recorded. The cone was pressed into the material with a force of 1500 N. The course of the hardness test using the developed tool (mandrel) is shown in Figure 5.

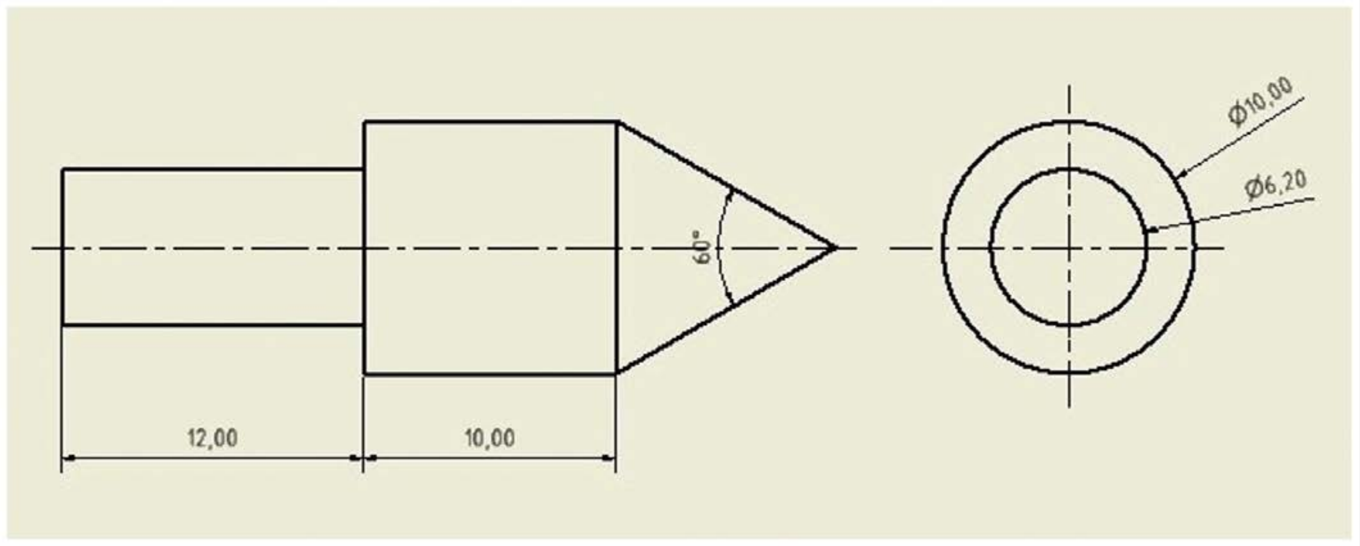


Figure 4. Diagram of the mandrel used in the Brinell test

Figure 5. AE sensing during metal indenter penetration

The location of the IDK-09 sensor is also obvious here. During the test, the mandrel was pressed into the material with a normalized force. This disturbed the structure and emitted acoustic waves, which were recorded using AE.

RESULTS AND DISCUSSION

Tensile test

The preparation of hoof horn samples from the pelvic limb of cows was a challenging process. A total of twelve samples were prepared. However, only four successful measurements could be obtained due to the non-standard and mutually different shapes of the experimental samples. Figure 6 shows the sampling locations of the successfully measured samples. The rest of the samples deteriorated before the actual measurement was carried out due to being clamped in the jaws or due to lateral forces (tension).

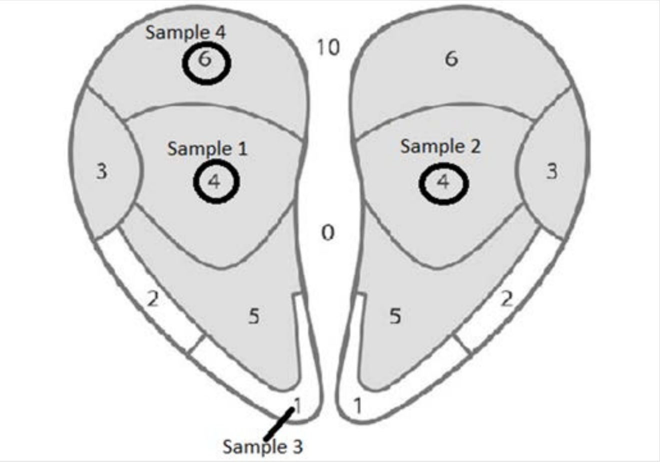


Figure 6. Sampling locations for the tensile test (Bicalho et al., 2009 – figure was subsequently modified)

Figure 7 shows the course of the tensile test. Sample 3 had the highest tensile strength, indicating greater hardness of the examined sample. This sample was taken from the tip of the hoof, where the horn is very hard and durable. On the other hand, to induce an acoustic response in Sample 4, it was not necessary to exert great force, indicating higher elasticity of the sample. This sample was taken from the heel of the hoof, where the horn is softer and more flexible. According to Van Marle-Kösler et al. (2019), who used tensile tests in their experiment, these differences could be used to predict problems where the softer horn is less resistant to external factors. The same authors observed that the front claws were harder compared to the hind claws, which they attribute to a greater load on the front limbs. In the study by Dostál et al. (2018), who investigated the possibility of using acoustic emission to test their tensile strength, the horn samples showed high variability, highlighting the need for further research and understanding in this area. Risk factors that considerably impact limb disease include management (Ebling et al., 2019), which plays a significant role in the prevention of lameness, especially nutrition management, and the environment (Dendani-chadi et al., 2020), genetics (Novotna et al., 2019), and various breeding conditions and technologies (Moreira et al., 2019). The ideal quality of the hoof is defined as normal horn growth that provides sufficient structural strength. This is the result of the relationship between nutrition, health, and stable conditions (Van Marle-Kösler et al., 2019). The health of the hooves is most affected by nutrition and housing technology (Langová et al., 2020). As demonstrated in the research by Blowey and Chesterton (2012), zinc, sulphur, and certain trace elements (zinc, copper and manganese) have been shown to have a positive effect on the hardness of hoof horns. The high proportion of silage in the diet has been demonstrated to significantly reduce the hardness of the hoof wall and foot (Manson, 1986). This, in turn, has been shown to increase the incidence of lameness. Decreased hoof hardness has also been reported in cases of high concentrate feed intake (Burger, 2017).

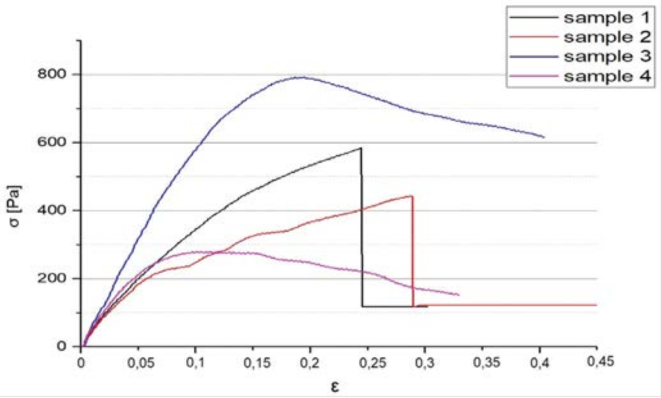


Figure 7. Dependence of normal stress on relative elongation

Figure 8 shows the progress of the AE signal measurement for the samples and the number of counts that exceeded the selected signal threshold. A rupture occurred in Sample 1, resulting in many times higher measured values of the acoustic signal than in the other samples.

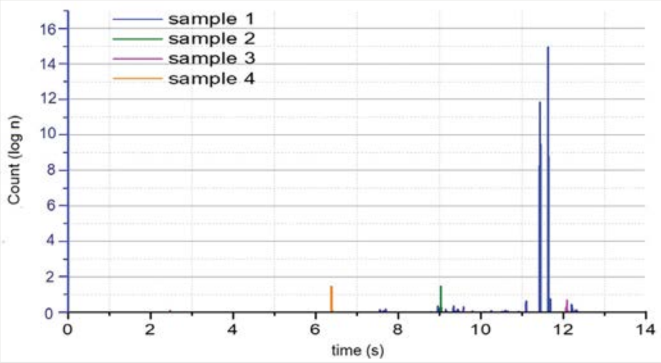


Figure 8. Progress of AE signal measurement

Despite the unfeasibility of preparing a sufficient number of data from the pilot study results for variance analysis, owing to the destruction of the samples before attachment to the measuring device or the possibility of repeating the measurement due to the destruction of the samples, the differences in the evaluated quantities are nevertheless discernible. Consequently, it is recommended that a measurement technique be developed to provide the data currently absent for an objective assessment of hoof horn quality. This will require the miniaturisation of the samples. This will enable a sample of hoof horn to be taken during regular hoof trimming. Furthermore, it will be possible to measure a higher number of samples, sufficient for variance analysis and characterization of the strength parameters of cow hoof horns.

Hardness test (pressure test)

During the experiment, the acoustic response in the material was recorded when a special mandrel was pressed into the horn sample. The 11 samples were divided into two groups: pigmented (6 samples) and non-pigmented (5 samples), before the actual measurement. Large differences in both hardness values and AE recording were observed among the samples. The signals showed that their amplitude exceeded the set threshold value (count).

Figure 9 displays the measurement results of the first group of non-pigmented samples, and it is evident that a low number of acoustic signals were produced. This indicates greater elasticity of the examined sample. The signal created as a result of dislocations and microcracks in the structure of the samples was absorbed by the sample itself due to the high elasticity when the fibers are arranged in all directions.

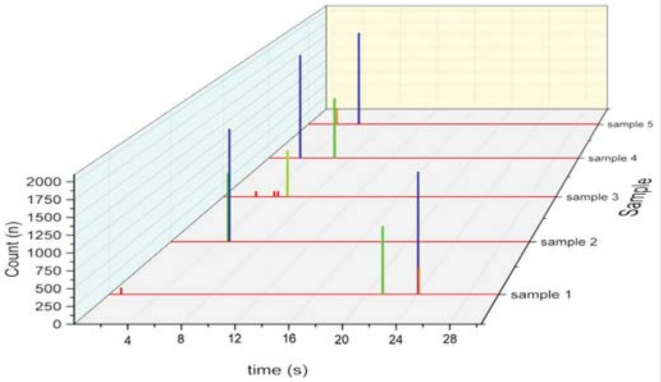


Figure 9. Record of AE during hardness test (5 samples)

Figure 10 shows that more acoustic signals were recorded for the second group of pigmented samples. This indicates that the material experienced faster destruction. This was particularly evident in Sample 3, Sample 5, and Sample 6, which displayed greater hardness and an increase in the acoustic signal when their fibers were disturbed by the formation, and subsequent propagation of dislocations. In contrast to our study, Van Marle-Köster et al. (2019) did not note significant differences in tensile strength attributable to colour. Each sample shows different values, as can be seen from the graphs. This is due to the diversity of biological material, where it is not possible to ensure identical samples and their mechanical properties (strength, flexibility).

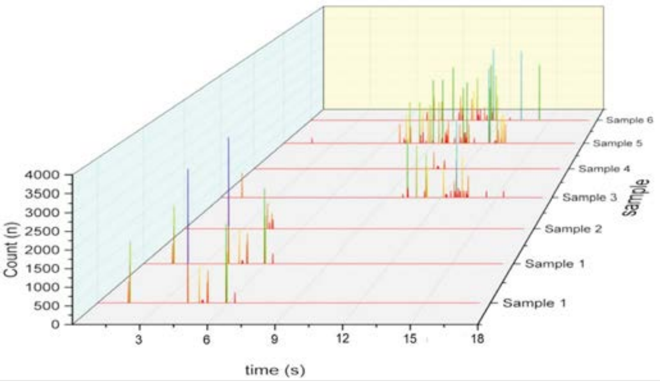


Figure 10. Record of AE during hardness test (6 samples)

Hoof treatment plays a crucial role in maintaining hoof health. Franck et al. (2006) investigated the differences between the horns in different parts of the hoof using Young's model (elasticity model). They found differences in hardness and elasticity between the horn on the dorsal and abaxial walls of the hoof and between the horn on the wall and the horn on the heel, which they attributed to the lower density and larger diameter of the tubules in the horn of the heels. Hinterhofer et al. (2007) also reached these conclusions using a tensile test. They also noted a decrease in resistance in the cornea of dairy cows with laminitis, with the greatest differences on the axial and abaxial sides. Khomyn et al. (2018) observed changes in the physical and mechanical properties of the horn in hooves with a lesion, focusing on a decrease in density and hardness. Inadequate heel height, elongated hoof walls, and imbalanced distribution of weight between the thoracic and pelvic limbs have been identified as contributing factors to impaired hoof characteristics and an increased need for preventive or medical treatment of the hoof (Sadiq et al., 2020; Sogstad et al., 2006; Nuss and Paulus, 2006). As posited by Lean et al. (2013) and

Alvergnas et al. (2019), there is a possibility that the nutritional status of an individual may be associated with the presence of a thicker layer of fat on the foot. This assertion is supported by the notion that dietary precursors of fat, such as formed lipids from feed and those derived from short-chain fats, have the potential to influence lameness (Lean et al., 2013). A lower fat layer on feet was observed in laminitic cows fed high concentrates (Tavares et al., 2019).

Only one study was found that dealt with the use of AE in the evaluation of the mechanical properties of the hoof horn, and it was only devoted to the tensile test (Dostál et al., 2018). The tensile test itself is an important method in determining the physical properties of the material, but in the case of assessing the properties of the horn, it is not of great importance since the cattle's hooves are mainly affected by compressive forces. Nevertheless, according to Clark and Petrie (2007), its use in the detection of microscopic defects and cracks in the cornea is possible.

Defined sample sizes were needed for both tests; therefore, they were prepared from slaughtered animals, which could cause desiccation of the hoof horn and bias the results. Additional measurements would be needed to define the standard properties of the horn in given areas of the horn capsule. According to Hinterhofer et al. (2009), in animals, there is a concentration of pressure not only in the hoof but also in the bones and tendons. For use in evaluating the physical properties of the horn, a hardness test using acoustic emission seems to be more suitable. The advantage of this test over a separate hardness test is that it reveals changes within the monitored material. This could be used when assessing the effects of disinfection on hoof horn quality.

CONCLUSIONS

The objective of the pilot study was to characterise the physical parameters of the hoof horn, which are influenced by various external environmental factors as well as internal parameters of the animal itself. This characterisation is intended for use in the management of dairy cow care. Adequate knowledge of these parameters would facilitate the assessment of the influence of individual factors on the quality of cow hoof horn, and consequently on the health of the hoof and the associated welfare of the cow. The assessment of hoof horn quality using acoustic emission revealed significant variation. The tensile test revealed that the most durable samples were taken from the tip of the hoof, where the horn is the hardest. Conversely, the most flexible samples were obtained from the hoof's foot. The hardness tests demonstrated a substantial variation in resistance and the strength of acoustic signals among the samples. The presence of acoustic signals was found to be positively correlated with the hardness of the samples, with the harder samples exhibiting a greater number of acoustic signals. Further measurements are required to establish standard values for the various hoof horn parts. The observed variations in the mechanical properties of the samples were attributed to the heterogeneity of the biological material, which precluded the possibility of obtaining samples with identical properties. It is also noteworthy that the samples were obtained from slaughtered animals, which may have influenced the physical properties of the hoof horn. The challenges encountered during the sampling process, coupled with the substantial variability in the outcomes, underscore the necessity for further research to comprehensively assess the quality of the hoof horn. Given the destruction of most of the cow hoof horn samples prior to measurement and the inability to obtain the required sample size during corrective hoof trimming, the focus should be on the miniaturization of samples for measurement and the actual methodology for measuring samples.

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