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EXPRESS METHOD TO ESTIMATE STRUCTURAL IMPERFECTION AND BONE TISSUE STATUS

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Abstract. A new method for evaluating the bone status using the scattering parameter of hardness indexes (Weibull homogeneity coefficient m) is proposed. A comparative analysis of the condition of the bone tissue of birds, depending on age, breed and calcium content, is conducted. It is established that the scattering degree of mechanical properties, in particular, hardness, is a very structure-sensitive parameter.

KEYWORDS: Hardness, Scatter of Hardness Indexes, Homogeneity Coefficient, Bone Status

1. Introduction

The structure of the bone tissue has a sufficiently high hardness and mechanical strength, in addition, it is sufficiently sensitive to the influence of the internal and external environment [1,2]. Strength of the bone tissue increases with age and is related to hardness and osteometric characteristics of the limb skeleton [3-5]. Mechanical parameters can serve as a parameter for assessing the qualitative composition of the bone tissue in humans and all kinds of animals [6]. Tubular bone is a kind of "sensor", which is sensitive to changes in the internal environment of the organism. In case of hens during the period of bearing, this parameter can be represented by a varying amount of trace elements necessary for the formation of an egg in the bone tissue. Human bones become brittle with age, and their resistance to dynamic loads decreases.

Unfortunately, due to the specific structure of the bones (in fact, they are structural elements with a variable area and a significant gradient of mechanical properties in the cross section), there are practically no express methods at present that would allow for a reliable assessment of the bone tissue status during its formation and throughout the entire period of life. This is because the methods most commonly used for the express control of the material condition are based on hardness measurement. In addition, these methods are readily available, simple and practically fully automated. However, the use of absolute values of hardness for assessing the quality of biological material is not always justified and may lead to major errors. This is due to the fact that this physical quantity is a characteristic of the mechanical properties of the material, but does not characterize the structural heterogeneity of the material.

The purpose of this work is to develop an express method for assessing the current status of the bone material of hens, depending on age, breed and calcium content.

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2. Research technique

The quality control of the biological material taking into account changes that occur with age was performed using the LM method for measuring hardness of то at the G.S. Pisarenko Institute for Problems of Strength of Materials the National Academy of Sciences of Ukraine [7,8]. According to this method, the scattering parameters of hardness indexes during mass measurements are considered to be the informative signs of the material condition, rather than the absolute values of the mechanical characteristics, including hardness. A physical substantiation of this method is as follows: the scatter of mechanical properties is inherent in all materials, and the magnitude of their distribution depends, primarily, on their structural condition. Therefore, a change in the structural condition of the bone tissue, depending on the age and breed, can be assessed by the parameters of the distribution law, which describes this scattering, that is, the degree of scattering of mechanical properties.

As the scatter parameter, we adopted the Weibull coefficient of homogeneity, calculated from the Gumbel formula:

$$m = 0{,}4343\, d_n \left[\frac{l}{n-l} \sum_{i=1}^{n} \left(\lg H_i - \overline{\lg H} \right)^2 \right]^{\frac{1}{2}},$$

where parameter d_n is determined based on a number of measurements, H_i is the value of hardness determined from the i^{th} measurement; $\overline{\lg H}$ is the mean value of hardness determined by the results of n measurements ($n = 20 - 30$). The stability of hardness characteristics obtained in the mass measurements depends to a large extent on the homogeneity of the bone tissue structure.

Therefore, the greater the heterogeneity of the structure of the biological material, the greater the scatter of the measured values. The high value of the homogeneity coefficient corresponds to a lower scatter level of the characteristics of physical and mechanical properties and, accordingly, a better structural organisation.

The values of the homogeneity coefficient *m*, calculated according to the hardness characteristics in different sections of the bone depending on age, were compared. By the actual characteristics of the bone strength, one can predict the condition of the bone tissue throughout the entire period of life.

Hardness measurements in the transverse section of the mid-diaphyseal bone were made on the hardness tester HPO-10 by the Vickers method. To this end, a specimen was drawn in the form of a column from the mid-diaphysis tubular bone with a height not less than 15 mm (for fixation of the specimen). The mid-diaphyseal bone was chosen because the relative thickness of the diaphysis wall, despite its high variability, retains its specificity, both among the small (breed) and large (row) groups [9]. The workload was 237 g in the selected 12 points in a circle around the mid-diaphysis. Consequently, each of 12 impressions was obtained in a 30° field of the tubular bone section based on a 360° circle. Each indentation with a diamond (diamond pyramid) lasted 30 seconds. Five specimens of each bone were used for a certain age.

For comparing and determining the strength of bones during compression, the test machine FM-1000 with FastRed computerized measuring system was used.

We studied bones of the Cobb-500 laying hens aged 51, 114, 175, 228, 410 days and bones of chicken broilers aged 28, 42, 49 days. The birds were kept on the floor according to the generally accepted technology, fed with mixed fodders balanced by basic nutrients and macro- and microelements in accordance with age standards. After slaughter, the birds were weighed on the electronic scales Casio HL-4, the tubular bones were removed by preparation and kept in a cold place in a wet condition during the study.

3. Results and discussion

3.1. Laying hens.

As an example, Fig. 1 shows the absolute values of the femur hardness of the laying hens aged 51, 114, 175 and 410 days, and Fig. 2 shows the corresponding values of the homogeneity coefficient m *depending on the age of the bird.*

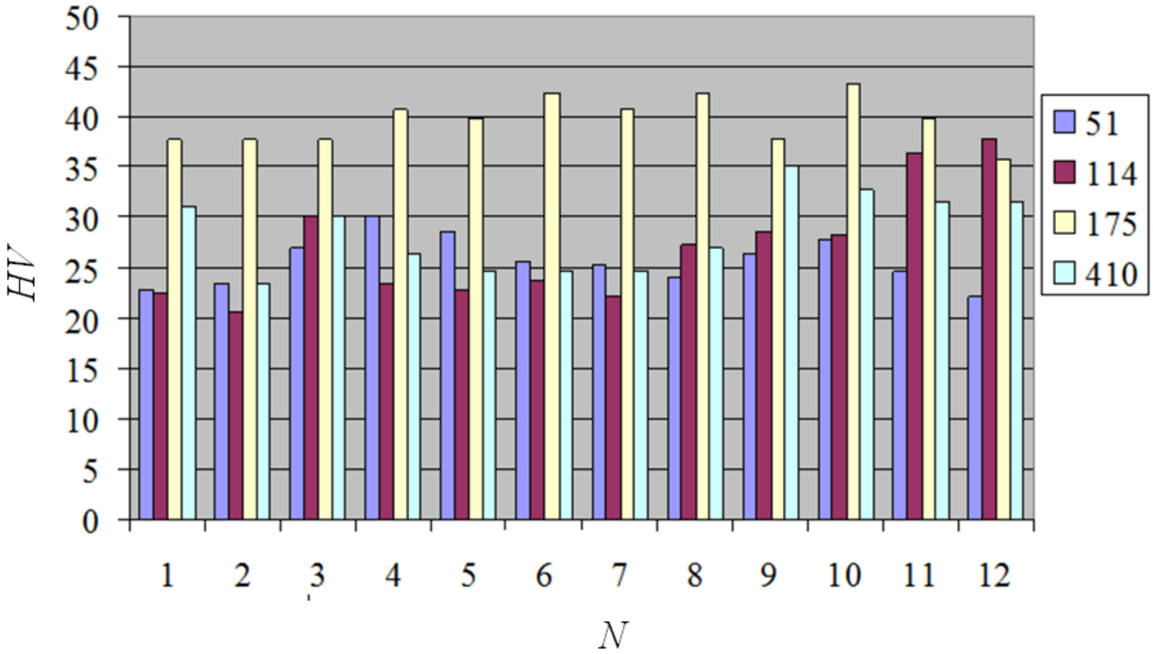

Fig. 1. Mean values of femur hardness of the laying hen aged 51, 114, 175, and 410 days in the selected 12 points in a circle around mid-diaphysis.

It is known that there is a periodicity and heterochronism in the growth of the limb skeleton [10]. For birds of different species, there are five main post-embryonic developmental periods, in which the growth and development of the organs essential to the body at a particular time is of paramount importance [11].

During the bearing period of the laying hens, a specific medullary bone tissue is formed in the bone marrow cavities of the tubular bone and some flat bones. Its mass is up to 10-12% of the total mass of the skeleton. This tissue is a moving source of calcium, which is directly used to form the egg shell. It has been established that this kind of calcium depot exists in all species and breeds of high-yielding animals. Calcium is excreted from these depots continuously, regardless of its feed. However, with a sharp fecundity deficit, the loss of calcium from the depot of the skeleton can be 30-35% of its amount in the body.

In our research, the depot of calcium is presented in Fig. 3,4. On the 114th day of hen’s life, all the bones studied (femur, tibia, etc.) have a well-defined medullary bone tissue, this period of life corresponds to the egg laying capacity of 40%. In the femur and tibia, this depot of calcium remains as long as to the 175th day (this period corresponds to the egg laying capacity of 79%).

The resistance of the bones, for instance, to compression, was correlated with a change in the homogeneity coefficient of hardness m for the above mentioned bones, and with the calcium depot during the age-related changes in the laying hens. Examples of typical stress-strain diagrams for the bones in compression are shown in Fig. 5. The analysis of these diagrams shows how the strength of each of the four bones changes with age. Note that the maximum strength of the femur, tibia and shoulder bones corresponds to 410 days of life, and that of the elbow bone – to 114 days of life. The comparison of the homogeneity coefficient of hardness and compressive strength of the bone material in the course of age-related changes in the laying hens is shown in Fig. 6. It has been found that for the femoral, elbow and shoulder bones, the best structural organization corresponds to 114 days of life. After some time, the organization of the bone structure deteriorates, but the integral strength of the bones increases due to the formation of local areas of strength. For the tibia, the best structural organization corresponds to 175 days. This period is characterized by a decreased egg laying capacity and the completion of the ossification processes. Microstructure of the bone tissue in the mid-diaphysis acquires a definitive state from 175 days after the onset period of ontogenesis. Analysis of the data shown in Fig. 2 and 6 suggests that the homogeneity coefficient of hardness *m* is very sensitive to the status of the bone tissue of birds depending on age, and at the same time it also reacts sensitively to the depot of calcium, depending on the periods of laying.

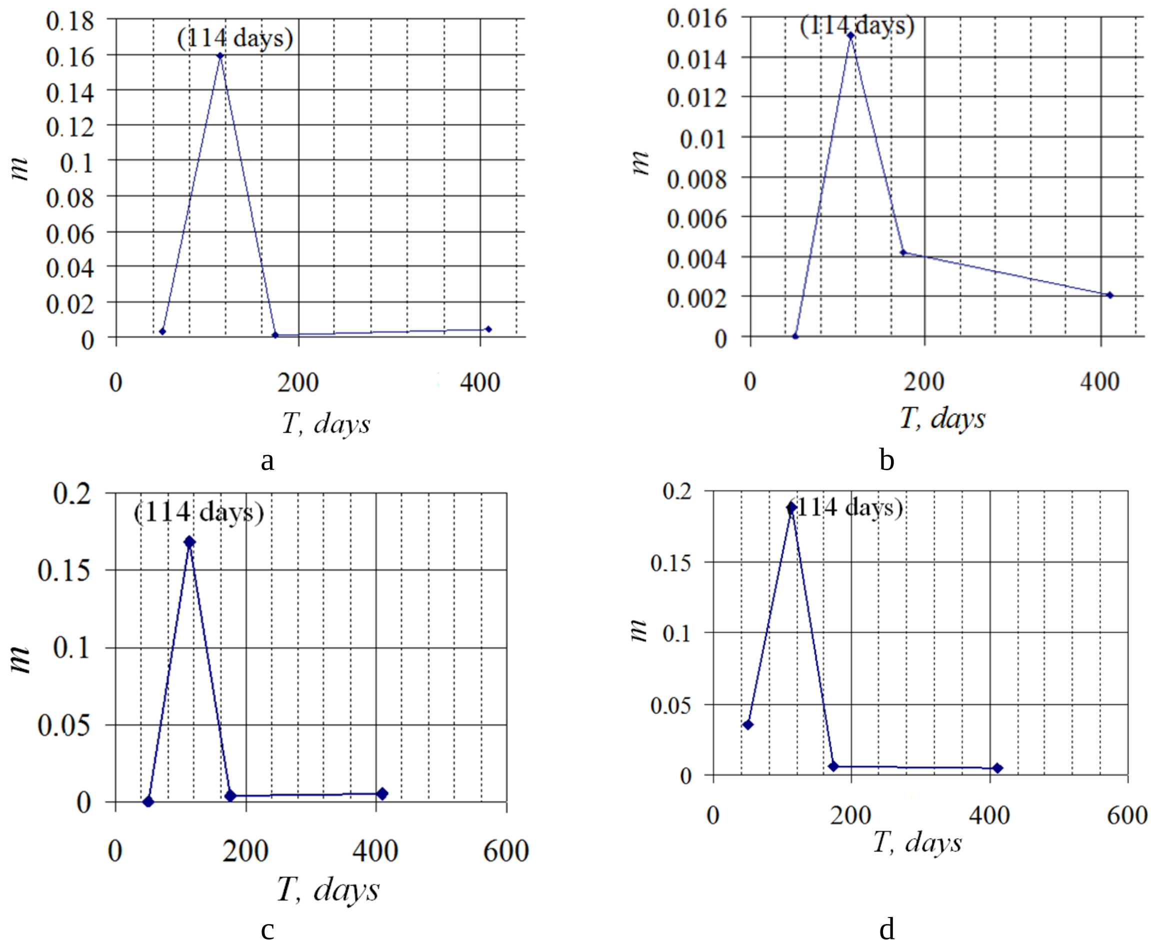

Fig. 2. Variation of the homogeneity coefficient of the bone hardness of the laying hens depending on age: a - femoral bone; b - tibia, c - elbow bone; d - shoulder bone

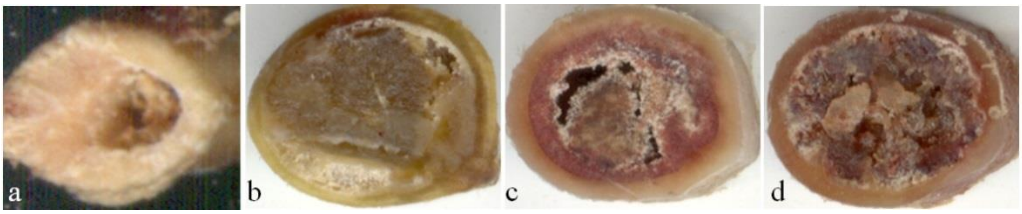

Fig. 3. Cross section of the mid-diaphysis femur of the laying hen at different ages: a – 10 days; b – 51 days; c – 114 days, d – 175 days.

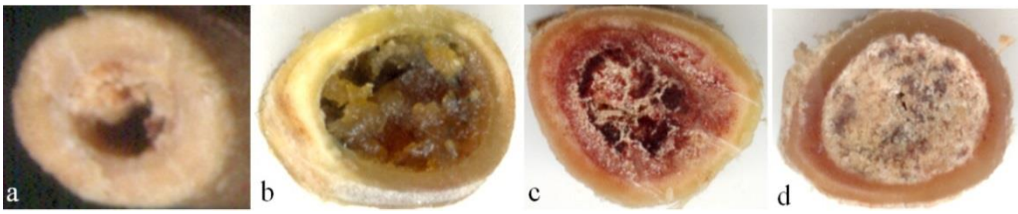

Fig. 4. Cross section of the mid-diaphysis tibia of the laying hen at different ages: a – 10 days; b – 51 days; c – 114 days, d – 175 days

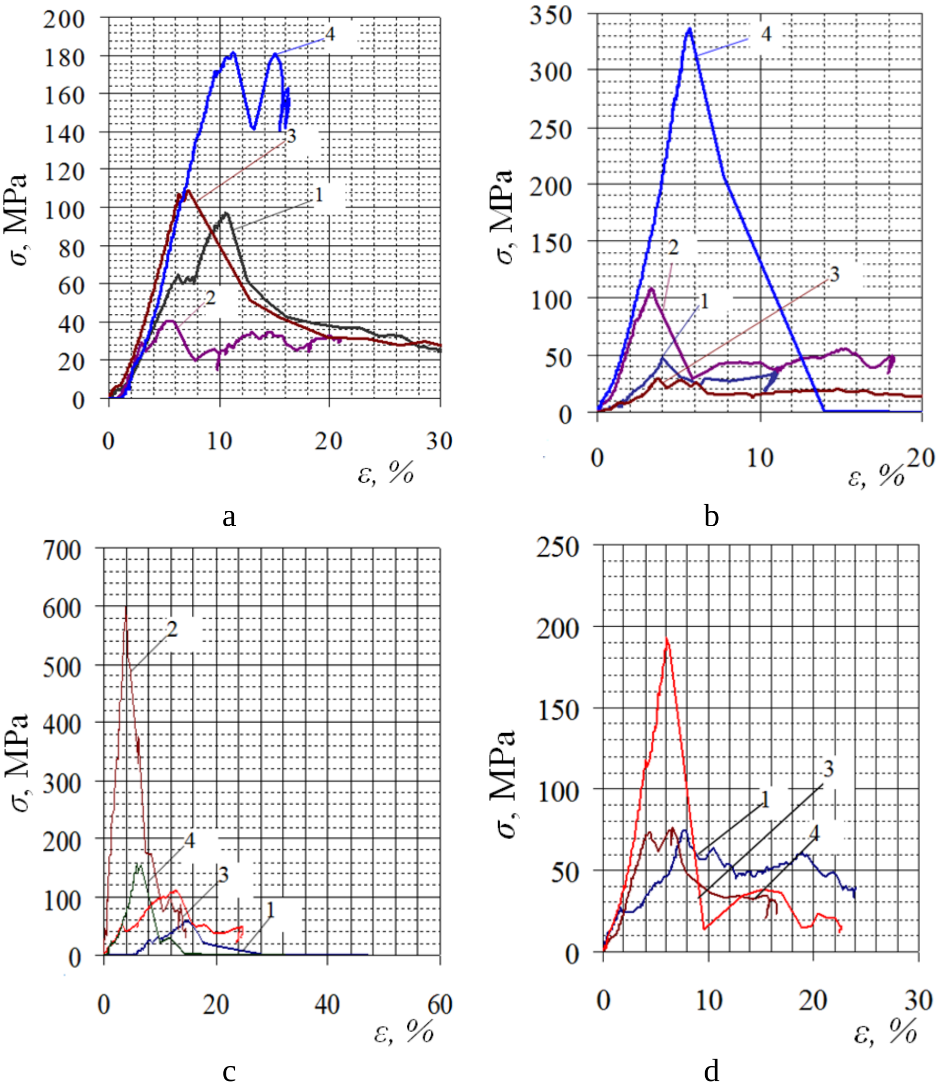

Fig. 5: Stress-strain curves of bone material of chickens of different ages: a - femoral bone; b - tibia; c - elbow bone; d - shoulder bone; 1 to 51 days, 2 to 114 days, 3 to 175 days, 4 to 410 days

3.2. Chicken broilers

The condition of the bone material of chicken broilers was evaluated using the same technique. Of the pelvic limb bones, the femoral bone has the highest hardness with certainty ($P \leq 0.05$). The fact that the femur has the greatest resistance to fracture is explained by the location of the bone in the pelvic limb skeleton. The proximal position of the femoral bone is the first to perceive static and dynamic loads. As an example, Fig. 7 shows the absolute values of hardness of the femur of chicken broilers depending on age.

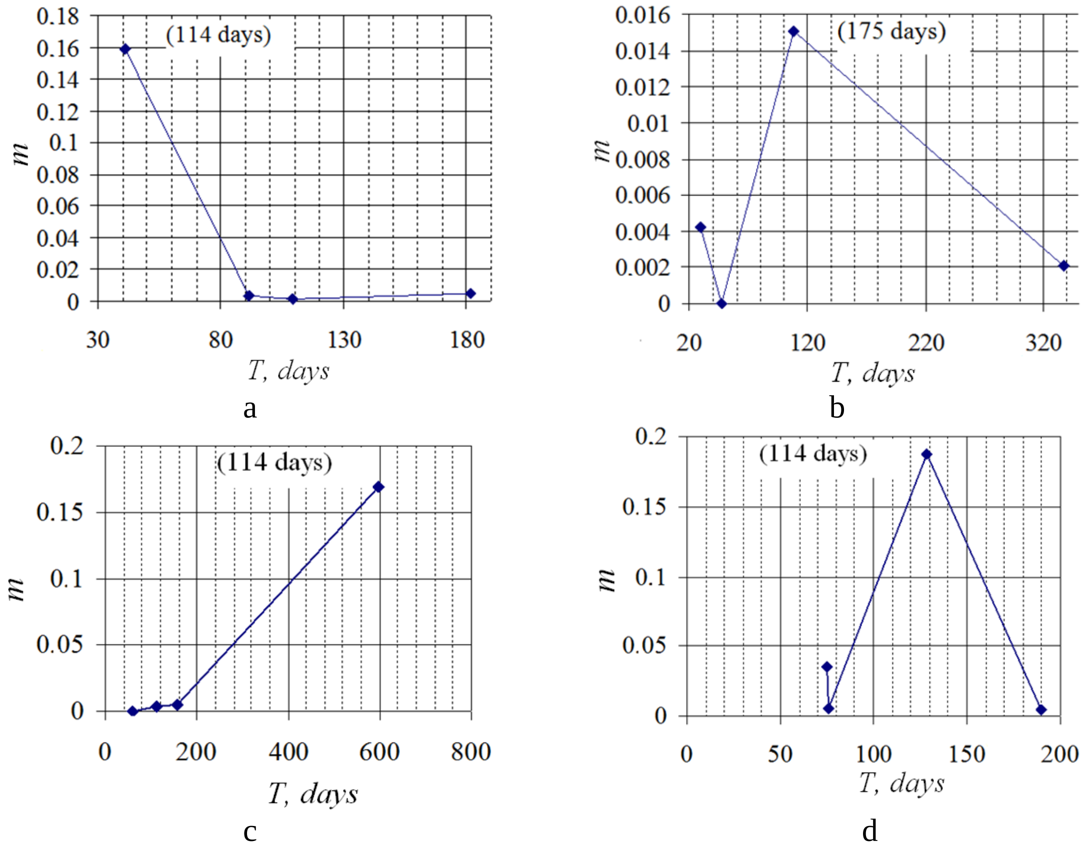

Fig. 6. Comparison of the homogeneity coefficient of hardness and compressive strength of bone material in the course of age-related changes in the laying hens: a - femoral bone; b - tibia; c - elbow bone; d - shoulder bone

Figure 8 shows the results of changes in the homogeneity coefficient of hardness for chicken broilers depending on age, and Fig. 9 shows corresponding stress-strain curves obtained when testing bones for compression. It is noteworthy that the maximum strength of the femur is reached on the 42nd day of life, and that of the tibia and shoulder bones – on the 49th day of life.

The results of the research of chicken broilers (Figs.7-9) show that within up to 49 days of postnatal period of ontogenesis, the intensive growth of the limbs proceeds. Accordingly, the low values of the homogeneity coefficient and compression strength parameters are recorded in comparison with the similar data obtained on the bones of the laying hens (see Fig. 1, 2, 5, 6).

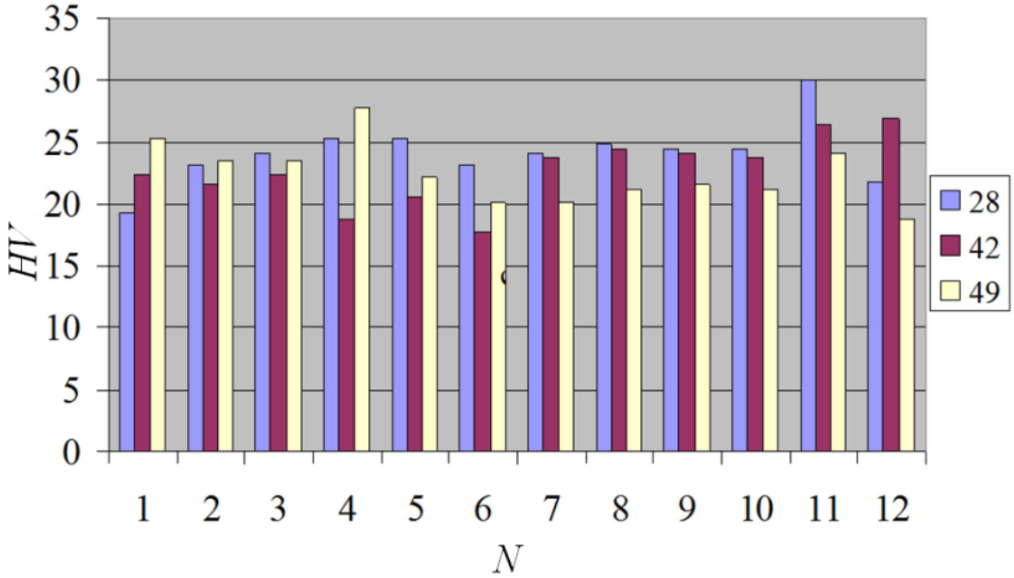

Fig. 7: The value of femur hardness of broiler chickens at the age of 28, 42 and 49 days in the selected 12 points in a circle around mid-diaphysis.

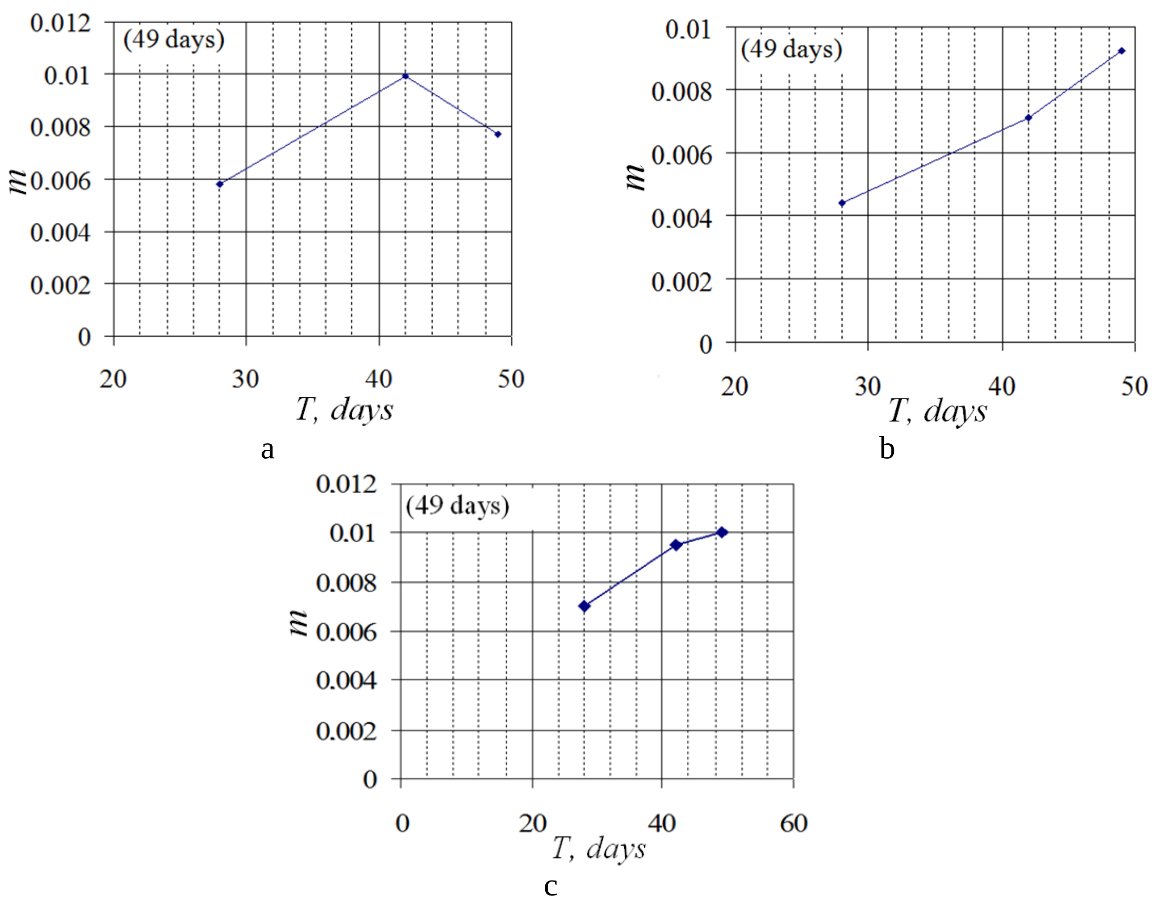

Fig. 8. Dependence of the homogeneity coefficient of the bone hardness on the age of broiler chickens: a - femoral bone; b - tibia; c - shoulder bone

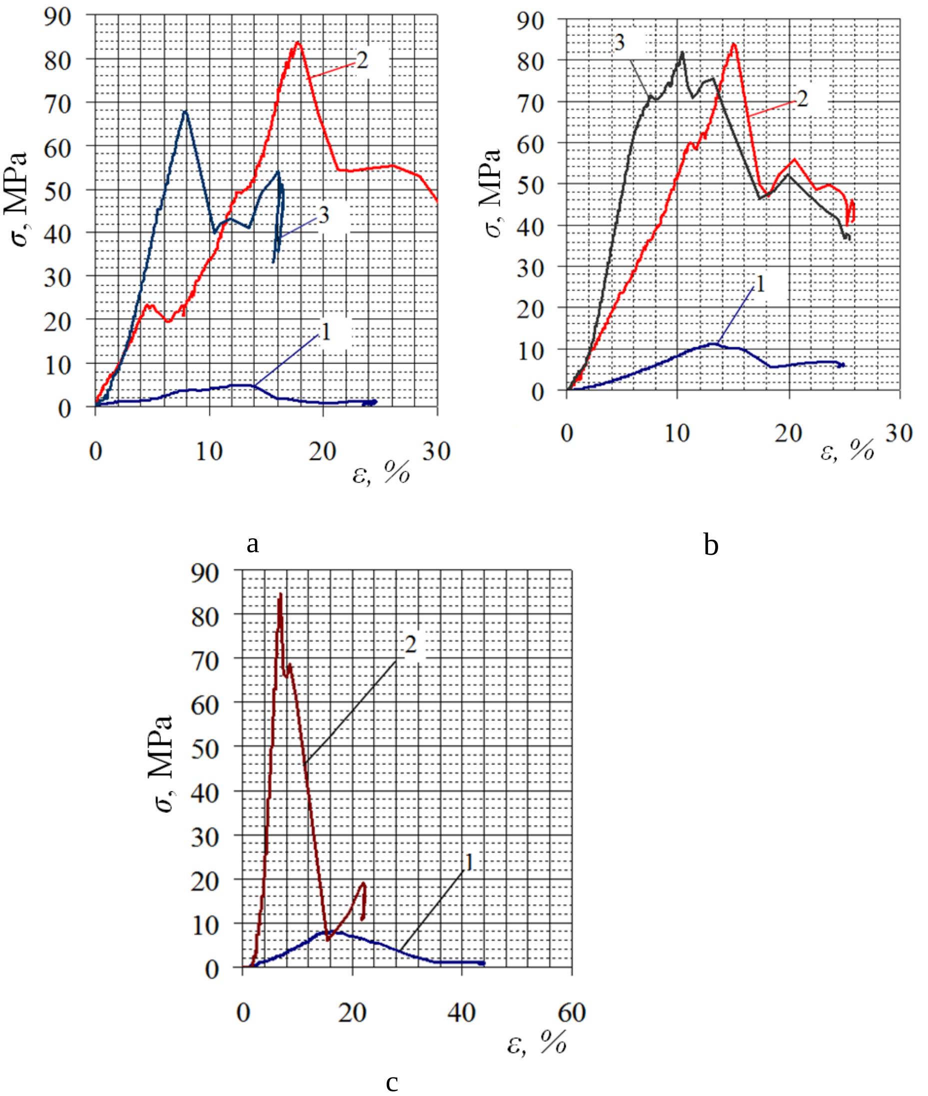

Fig. 9. Stress-strain curves of the bone material of chickens of different ages: a - femoral bone; b - tibia; c-shoulder bone: 1 - 28 days, 2-42 days, 3-49 days

However, it should be noted that this process is associated with a better organization of the structure of the bone material, as evidenced by a comparison of the homogeneity coefficient of hardness *m* with compressive strength values (Fig. 10). For the bone material of chicken broilers, there is a direct relationship between a better organisation of the bone structure and the compressive strength values. The obtained results are basic for calculating the growth kinetics of the body weight of chickens for different feeding schemes, and the developed test method can be used to create and study the degradation of natural and artificial composites [10, 11].

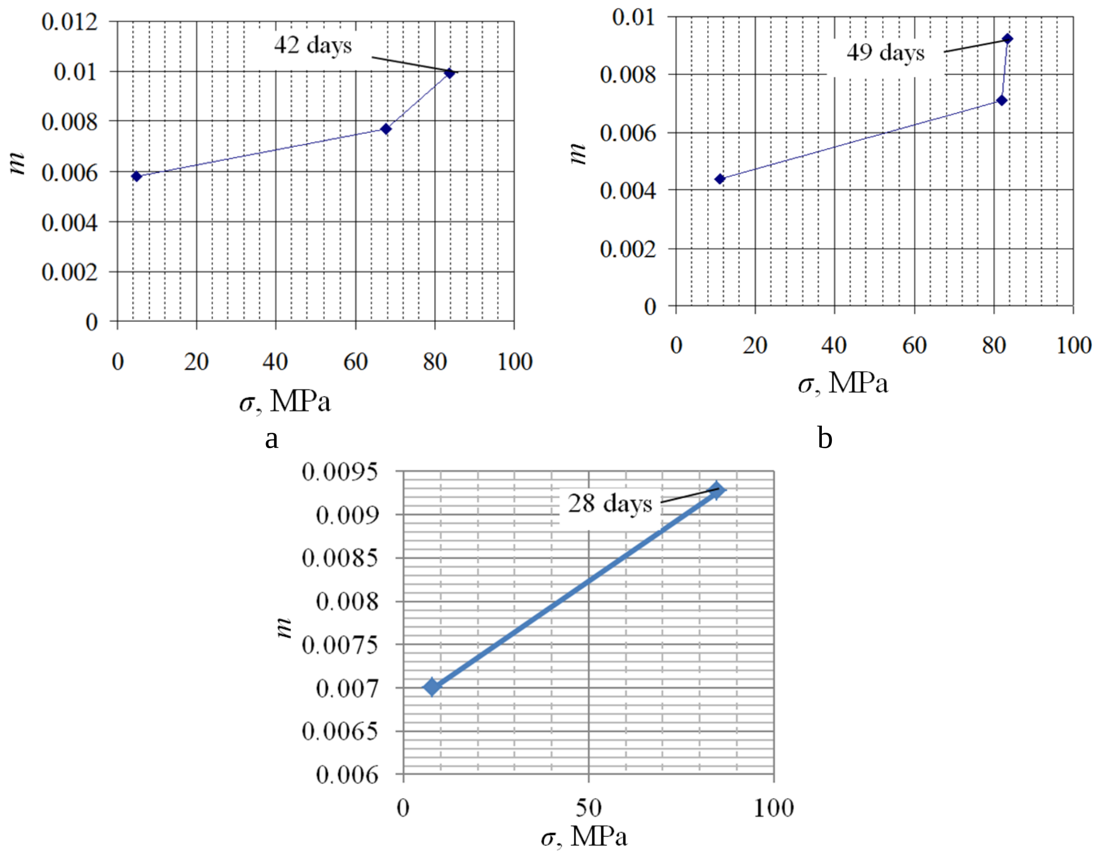

Fig. 10. Comparison of the homogeneity coefficient of hardness and strength of the bone material in the process of age-related changes in broiler chickens: a - femoral bone; b - tibia; c - shoulder bone.

CONCLUSIONS

A new method of investigating the state of the bone material based on the scattering parameter of hardness indexes is proposed and tested on bird bones (Weibull homogeneity coefficient *m*). The established dependencies between the hardness homogeneity coefficient *m*, the age of birds and the durability of bone material make it possible to reliably estimate the qualitative state of the tubular bones, depending on the influence of the internal and external environment. Based on the developed approach it is easy to trace the developmental peculiarities of individual bones in the skeleton of any animal.

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