Review Article

A REVIEW ON MECHANICAL PROPERTIES OF ANIMAL BONE

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Abstract: The paper reviews the work done in the field of biomechanics of human and animal bone in the disciplines of physics. chemistry, biology and medicine. The review may be useful to the researchers whose interest lies in the development of bone technology.

Bone is a composite, formed by the mineralization of an organic matrix, *the collagen*, by the nucleation and growth of calcium hydroxyapatite within the matrix. The crystallinity and crystal morphology; size distribution and orientation of crystallites of bone mineral are some of the important parameters which are very much useful in understanding mechanical behaviour of bone and constituents.

Soft and hard tissues of vertebrate body provide a support against the gravitational force to the body. Most of the soft tissues are flexible and highly elastic. In general, their behaviour is viscoelastic. In contrast, hard tissues are more compact, rigid and less elastic and serve as endoskeleton and exoskeleton of the vertebrate body. Bone is a hard tissue. It contains both organic (collagen) and inorganic (calcium phosphate) materials. Hence, the bone can be considered as viscoelastic composite material. The organization of composite varies from animal to animal and is strongly influenced by anatomical and physiological alterations, unlike engineering composite materials. However, bone has fibrous structural component (collagen) and exhibits a composite behaviour microscopically as well as macroscopically. Since bone tissue is a part of biological structure and its mechanical properties can only be fully appreciated if one understands how the structural organization functions as a whole.

The main mechanical properties are deformation, strain, modulus of elasticity and strength. For a cylindrical bar in a simple elongation, the extensional strain is defined as the alterations in length per unit length of the bar. When a bar is pulled, its longitudinal elongation (ε) or shortening ($-\varepsilon$) is accompanied by transversal shortening ($+\varepsilon_a$) and transversal elongation ($-\varepsilon_a$). These are related to stresses in the material, which has the unit of force per unit area of

the cross section. For a simple elongation of a bar of an elastic material, the strain (ε) and stress (σ) connected with each other by Hook's Law.

$\varepsilon = \alpha . \sigma$

Curey [1] compared bone tissue with a two-phase material like fiber glass. He points out that appetite crystals of differing sites with an average cross section of 2400A° are oriented along the length of the collagen fibrils which are built up by 2800A° long tropocallagen where as the included crystals have a much higher modulus of elasticity. The volumes occupied by both collagen and appetite are about equal. In a two-phase material there should be found a modulus of elasticity intermediate between that of the two components, but a strength higher than either of the individual components. Curey [1] refers to Bhima Shanker [2] and reports a modulus $E = 24.10^6$ Ib in^{-2} for fluorapatite along the axis, the value for hydroxyapatite apparently has not been determined. On the other hand collagen does not obey Hook's law exactly; its tangent modulus of elasticity seems to be about 180,000 Ib in^{-2}. Curey concludes that two-phase materials can function efficiently only if there is very firm bonding between the fibers and the matrix. But the nature of bonding between the collagen and the appetite is uncertain.

Hence, extensive studies have been made, in the past, on the mechanical properties of biological macromolecules, cells, tissues and organs in order to understand the mechanical and thermal behaviour of different living systems.

As deformation of animal soft tissues is high compared to metals, they are put in the class of elastomers like rubber or synthetic polymers. Roy [3], for the first time, showed that a piece of artery behaves like a rubber band by measuring the strain in it.

Wohlisch et. al., [4] measured the degree of stretching and breaking point in animal tissues like human hair, skin and corium, tendons, cartilage, frog muscle, cocoon fibers. These values were compared with those of volcanised rubber.

Bar Ernst [5] determined the elasticity of cartilage, covering the heads of various long bones of man and ox, by using a modified man gold elastometer and Gildemeister ballistic elastometer.

Price [6] showed that the elastic properties of wood depend upon its internal structure. According to him the anisotropic character of elasticity is due to the fact that wood is built up of cells, which are long hollow cylinders, arranged parallel to the axis of the stem or branch.

Pfeiffer [7] developed an apparatus to measure the deformability of protoplasts without the risk of injuring the protoplasm and concluded that plasmalemma possesses elastic properties.

Saxton John [8] studied the elastic property of rabbit aorta of different age and observed that it does not age so rapidly as compared to other organs and is still a relatively young structure even at the end of the life span.

Treitel Otto [9] measured the elasticity of the rhizomes of equisetum fluviaticle together with other plant and animal tissues and in 1945 reported that stress strain curves of certain rhizomes become flatter with increasing age while breaking stress and strain decreases with increasing age due to decreasing respiration.

Brust Hanfred [10] determined the viscosity and elasticity of striated muscle, while Simonson et. al., [11] measured the elastic constants of skeletal muscle in situ. They reported the differences in elastic properties between natural and synthetic rubber, between rubber and muscle, and between relaxed and muscle under tension.

King and Lawton [12] reported a formula to evaluate the elasticity of different soft body tissues of different age. Hillav [13] showed that the muscle exhibits rubber – like and normal type of elasticity under different conditions.

Burton [14] determined the young's modulus of elastin and observed that a single fiber would appear to be stiffer than the aggregate. He also reported the elastic modulus of smooth muscle of arterial wall.

Hayashi Khiro [15] carried out tests on shell lines to find elongation, elasticity and breaking strength. Shimizu et al [16] studied the viscous flow and elastic modulus of typical noodles from Japanese domestic wheat flour.

Craig and Peyton [17] described suitable experimental techniques to evaluate the elastic modulus of human dentin and its ultimate compressive strength.

Plausak [18] determined the elasticity of human skin. Smith and Walmsley [19] studied the various factors affecting the elasticity of bone of ox, horse, sheep, dog and human and reported that Young's modulus varied with duration of applied stress, the fluid content of the tissue and temperature.

Karaisonyi and Andrews [20] designed and constructed an apparatus for measuring the torsional strength of macaroni. A highly significant correlation was found between torsional strength and bending strength of 25 samples.

Dempster and Coleman [21] determined the tensile strength of cortical bone along and across the grain. The samples were subjected to direct tension or bending till failure. Data on wet and dry bones was presented. The ultimate tensile strength of bone as tested across grain is less than its compressive strength. The results suggested that bone is weaker in the direction parallel to collagen fibers rather than in a direction perpendicular to it.

Weis-Fogh [22] analysed resilin, from elastic tendon of dragon flies (odonata), mechanically and optically over a large range of strain both in compression and extention. The protein resilin behaves as a typical rubber under all conditions. It was concluded that resilin consists of three dimensional network of long polypeptide chains which are randomly coiled under all conditions.

Viljanto and Kulonen [23], made a comparison of the tensile strength and chemical composition of the granulation tissue and also reported that soaking of the sponges with collagen increased the tensile strength of the granulation tissue.

Jensen and Weis-fogh [24] worked on locust flight and discussed the aerodynamic data in relation to the strength and elasticity of organic materials. A three component model of arthropod cuticle was suggested.

Frank et. al., [25] worked on egg shells and discussed the data on shell strength in relation to chemical properties.

Kikkawa and Sato [26] studied the viscoelastic properties of optalline lens using mechano electric transducer. It was found that the lens capsule has true elasticity, where as the lens substance has plastic properties.

Hiramoto [27] described a method to determine the surgance force and young's modulus of the cell membrane. In this method the force required to compress a cell between two parallel plates into its flattened form was measured. The value of he young's modulus was found to be dependent on the duration of compression and increased before cleavage. Price and Pierce [28] studied the elastic properties of the lung of frog. Miller and Sunderland [29] determined thermal conductivity of beef. Lusk et.al. [30] presented data on thermal conductivity of some freeze dried fish.

Charm [31] determined the tensile strength of ketchup tomato paste and other fluid food materials by forcing them slowly downward through a vertical tube. The fluid column will break when the weight of the column divided by the cross sectional area of the column equals the tensile strength of the fluid.

Currey [1] reported the bone as a brittle substance having a very high tensile strength. Harris et. al. [32] determined the tensile strength and stress-strain relationships in cadaveric human tendon.

Young et. al., [33] reported the mechanical strength of man finger nails. Chakraborty and Ramachandrudu [34] devised a simple method for measurement of elastic properties of tobacco leaf. The method consists of exposing a definite area of conditioned leaf under a stretching load of mercury and determining the elongation as well as weighing the mercury when the leaf gives way due to the load. It was found that the tensile strength of the leaf is inversely proportional to its moisture content.

Smith and Keiper [35] measured the elastic and viscous stiffness of compact bone, employing a highly sensitive electromechanical transducer. Cylindrical samples were prepared form rib, iliac crest and extremity bone. The young's modulus was found to be related to density but not to age. It was observed that the young's modulus of compact bone of iliac crest was significantly less than that of rib. Itoli et. al. [36] worked on human, monkey and rabbit lenses using a dynamic rheometer. Elastic modulus showed poor dependence on temperature.

Barney et. al. [37] studied the relationship between viscoelastic properties and chemical nature of wheat glutin and glutenin. The influence of water content, pH, salt urea, lipids, soluble proteins, free amino groups and free carboxyl groups on the viscoelastic properties of crude glutin. Purified glutin and glutenin has been studied.

Bartley Murray et. al. [38] correlated the ash content and crushing strength of hydrated bone of human lumbar vertebral bodies obtained at autopsy. The crushing strength reached a maximum value between 25 and 35 years and decreased from there on into middle and old age.

Tyter and Thomas [39] mentioned various basic methods for measuring shell strength namely by impact, crushing, snapping and dyormation. Significant correlation was found between strength and thickness. Translucent areas of the shell are weaker than opaque areas of the same shell.

Ueda et. al. [40] worked on viscoelasticity of muscle under various environmental conditions. It was found that the dynamic elastic modulus of Sartorius muscle was slightly lower in summer compared to that in winter. Peripheral parts revealed lower elastic values compared to pelvic sides. There was no difference in lateral and medial part values of the muscle. Plain muscle showed higher values than those of skeletal muscle. Similar values of

dynamic elastic modulus were observed in muscles of frogs, bull frogs, mice and rabbits, while higher values were observed in cat and man.

Demicher and Tupitsyn [41] reported the elastic properties of tendon during the process of refrigeration for the periods ranging from 5 days to 90 days of storage. 69 fresh and preserved tendons of dogs were studied.

Lehman [42] determined tensile strength of human dentin using Hoonsfield transometer. Sound, Caries free, fresh teeth whose roots were of sufficient size to permit the preparation of such specimens, were used. The results of 100 tests were presented. The tensile strength of human dentin is only 1/6 or 1/7 of its compressive strength.

Tamolang et. al. [43] determined fiber strength and stiffness for 17 tropical hardwood fibers. Cell wall area alone was found to account for 89% of total variation in breaking load, with fibrilliar angle having lesser but significant influence.

King [44] analysed the fatigue strength of human compact bone by the weibull method. Tayler [45] determined the elastic properties of arteries at different physiological conditions of the arterial system.

Tickner and Sacks [46] presented a theory for determining all of the parameters required to describe the elastic behaviour of blood vessels under any static loading. Selected specimens of fresh excised human and canine arteries have been tested and their elastic behaviour was determined.

Gibson and Kenedi [47] determined the biomechanical properties of skin. the discussion was oriented towards the surgical needs.

Schmutt [48] worked on the relationship between density and compressive strength of bone of human femora by conducting tests on 200 cross sections of 40 femora and 12 women and 12 men.

Amtamann [49] experimented with cortical bone of 398 male and 337 female for the determination of breaking-strength and its variation with density. The breaking strength of specimens of equal density is different in two age groups being lower in older ones.

Mather [50] studied the variation of breaking strength and tensile strength of 145 fresh adult femora compact bone with age and sex. The mean breaking load of femora of female is less than that of male. Mechanical deterioration of bone tissue was found to be responsible for reduction in strength of the femor with age.

Paterson et. al. [51] determined the elastic properties of human bone. The study was carried out on 2 dry femurs in their diaphyseal zone making hollow cylindrical samples. The

young's modulus was calculated by measuring the deformation with an optical and auto collimator extensometer of the tuckerman type.

Dinnar [52] proposed an analytical model for tissue behaviour under pressure. The model consists of an arrangement of springs and dashpots. Viscoelastic properties of human skin tissue could be determined by this model.

Gilmore et. al. [53] measured the young's modulus of bovine dentin and enamel using ultrasonic interferometry. Since the structures of dentin and enamel are not isotropic the values given are orientation dependent.

Blanton and Biggs [54] determined the mechanical properties of nearly 50 human tendons. The values of strength were tabulated.

Friesen and Bilbro [55] designed and constructed an instrument that can accurately and rapidly measure the forces and energies associated with biological materials. The breaking strength of stems and other biological tissues was also presented.

Rabkin et. al. [56] subjected specimens of canine pericardium to uniaxial loading on a universal testing machine. Data on elastic modulus and tensile strength was reported.

Reilly et.al. [57] compared the elastic modulie for human and bovine bone specimens by compression and tension tests and found no statistical difference between the value of modulie determined in the two loading modes.

Berry et. al [58] performed tests on developing and mature rat Oorta to evaluate the elastic moduli. Variations in elastic modulus in younger animals were related to the alterations in relative wall thickness.

Viano et. al. [59] evaluated the moduli of elasticity of cortical bone in female human femurs by measuring the resonance frequencies of found the decrease in the values of young's modulus of cortical bone with age.

Ambardar [60] designed an inexpensive instrumentation system for making very occurate measurements of elastic modulus of bovine and ovine bones.

Saha et. al. [61] determined the mechanical properties of canine long bones. In all cases the bones sustained a considerable amount of plastic deformation before failure. Data on the modulus of elasticity, ultimate tensile stress and yield stress was presented. The tibia specimens showed a statistically significant higher ultimate strength than the humeral specimens.

Paavolainen [62] studied the biomechanical properties of bones and their dependence on the body weight of the test animal and transverse dimensions of the bone. It was observed

that the small variations in chemical composition of normal bone do not influence the mechanical properties.

Vezaki et. al. [63] presented a study on mechanical and physical properties of semilunar cartilage in the knee of the pig and human. Young's modulus was calculated from linear portion of stress and strain curve.

Inove [64] studied the mechanical properties of cancallous bone dependence of strength and elastic modulus on trabecular orientation. Using instron testing machine at a cross head speed of 0.1 mm/min and suggested that the young's moduli and ultimate strength of the specimen with any trabecular orientation were estimated effectively by the trabecular volume fraction and the distribution function of the trabecular under application of the image analysis for the specimen.

Einhorn et. al. [65] studied mineral and mechanical properties of bone in chronic experimental diabetes in eight male lewis rats. The results suggested that in experimental diabetes certain aspects of bone mineralization are adversely affected and lead to reduced strength related properties. However a compensatory increase in stiffness occurs.

Currey [66] studied the evolution of the mechanical properties of amniote bone. They reported that the earliest reptiles probably had rather compliant bone, but it was probably tough. Modern types of bone appeared over two hundred million years ago. Very specialized bone like that of the bullae of whales and antlers, may have evolved only in the mammals, but the fossil record is not complete enough to assert this confidently.

Cheng et. al. [67] studied, vibrational wave propagation in vivo on the tribal bone of both legs of 56 female volunteers, and suggested that the age differences were related to the differences in the mechanical properties of bone, with reduction of bone mineral density, the velocity of the vibrational wave propagation would decrease, with simultaneous increase in impedance.

Rohl et. al. [68] investigated the relationship between the mechanical properties of tranbecular bone in tension and compression by non destructive testing of the same specimens in tension and compression, followed by random allocation to a destructive test in either tension or compression. They reported that there was no difference between young's modulus in tension and compression. Strength ultimate strain and work to failure was significantly higher in tensile testing than in compressive testing.

Antich et. al. [69] studied the mechanical properties of bone using the ultra sound reflection technique. In assessing the mechanical properties of bone specimens by ultrasound,

the reflection technique samples a discrete bone surface element and the transmission method analyzes the entire volume of the specimen. This, the reflection technique may yield a measure of the mechanical property of bone trabeculae that is largely unaffected by the mass of the entire specimen, but mass and the structural density of the specimen affect the transmission method.

Anderson et. al. [70] studied compressive mechanical properties of human cancellous bone after "GAMMA" irradiation. They reported that compressive failure stress and elastic modulus of cancellous tibial bone in human decrease significantly when the bone is irradiated 60,000 gray (5 megarad)

Martin and Boardman [71] studied the relation between the mechanical properties of bone is three point bending and eight histo-compositional variable using standard ASTM method. Analysis variance showed that ultimate stress was similar in the plexiform and osteonal specimens, but elastic modulus was reduced. Stepuise multiple regression analysis showed that collagen fiber ranked highly as a predictor of bending properties. When all the specimens were pooled, 62% of the variability in elastic modulus was attributable to variations in collagen fiber orientation, density and porosity due to haversion canals.

Sugiura et. al. [72] studied, mechanical compression strength and biological affects on bone induction of surface – demineralized and heat treated cortical fone in rats. They reported that the alogeneic bones heated at 50-70 degree C and had preserved bone inductive properties, where as autoclave treatment suppressed these properties. New bone formation was found when demineralization exceeded 30 min in each group, viz non heated bone, 50° created bone, and 70° C treated bone. Mechanical compression strength of allogragte demineralized for 30 min was about 60% and calcium content was 70% of that of non-dimineralized bone.

Murphy et. al. [73] studied, stress in bone adjacent to dental implants after applying the loads through an attached distal extension cantilever. They reported that under all loading conditions, the higher stress occurred at the distal cervical bone margin adjacent to cantilever.

Saulgozias et. al. [74] studied the effect of fracture and fracture fixation on ultrasonic velocity and attenuation. They reported that the effects of internal plate fixation and gradually cutting through the cortex on the ultrasound velocity and alttenuation were studied in situ. There results demonstrate the clinical potential of their technique for the non-invasive assessment of bone fracture healing.

Drewnial et. al. [75] examined an experimentally obtained heat source due to absorption of ultrasound in biological media. They reported that the deposition of heat as a result of loss in an ultrasonic wave may results in damage to biological tissues. The extensive use of ultrasound for diagnostic purpose during pregnancy necessitates the evaluation of thermal risk to a developing fetus during routine clinical exposures.

Mehta et. al. [76] measured shear wave velocity by ultrasound angle reflectometry. They describe its application to the measurement of shear – ware velocity in bone, whether directly accessible or covered by soft tissue.

Kobayashi et. al. [77] studied mechanical and biological properties of bioactive bone cement containing silica glass powder (SGP). They reported that the compressive, bending and tensile strengths and fracture toughness of the cements increased with SGP content. The viscosity of cements also increased with SGP content and every cement could be handled manually.

Wang et. al. [78] studied the changes in fracture toughness, bone mineral density, elastic modulus, yield and ultimate strength, porosity and micro hardness of bone as a function of age in a baboon model. They reported that with increasing age. The fracture toughness of bone decreased and micro hardness increased. They conclude that changes in bone fracture toughness may not be necessarily reflected in its mineral density, porosity, elastic modulus, yield strength, and ultimate strength.

Ding et. al. [79] investigated the age related variation in the mechanical properties of the normal human tibial cartilage. Bone complex and the relationship between cartilage and bone, using a novel technique. They reported that the stiffness and elastic energies of both cartilage and bone showed an initial increase, with maxima at 40 years, followed by a steady decline. The viscoelastic energy was maxima at younger ages 16-19 years, followed by steady decline. The energy absorption capacity did not vary with age. They conclude that similar age related trends were seen in cartilage and bone, as if they behaved as a single mechanical unit.

Fernandez et. al. [80] investigated the hardening properties of calcium phosphate cements in the $CaHPO_4$ – alhpa – Ca_3 (PO_4). They reported that, the addition of 10% w/w of cc to the initial DCP – alpha – TCP powder mixture resulted, with tine, in a retardation of the development of compressive strength. However, the optimum compressive strength reached values up to 40% higher than CC free samples.

Sugita et. al. [81] investigated mechanical anisotropy of the primary compressive group by comparing differences in its mechanical properties, depending on the loading direction. They concluded that the bone strength of the proximal femur decreases more when stress is applied in the longitudinal direction (as in walking) and less when stress is applied in the transverse direction (as in a fall) when bone density decreases.

Zysset, et. al. [82] determined the mechanical properties of bone tissue by composition as well as structural micro structural and nano structural organization. Using nano indentation technique with a custom irrigation system. They concluded that the nanostructure of bone tissue must differ substantially among lamellar types. Anatomical sites and individuals and suggests that tissue heterogeneity is of potential importance in bone fragility and adaptation.

Harper and Bonfield [83] studied "Tensile characteristics of ten commercial acrylic bone cements". They reported those significant differences in both static and both fatigue properties were found between the various bone cements.

Ludger et. al. [84] examined the anisotropy age and gender dependence of lamellar osteon ensembles of human cortical bone using multiplayer analysis. They reported that statistical analysis of age and gender specific subgroups showed a general increase of impedance with age and a reversal for the oldest male age group only.

Currey et. al. [85] studied the mechanical properties of nacre and highly mineralized bone. They reported that the rosteral bone is much weaker and more brittle than nacre, which in these properties is to ordinary bone. In the rostrum the organic material, mainly collagen, is poorly organized and continuous, allowing the mineral to join up to form, in effect a brittle stony material.

Ding-Ming et. al. [86] studied the concept that "Bone density does not reflect mechanical properties in early stage arthrosis". They reported that bone volume fraction, apparent density, apparent ash density, and collagen density were higher in cancellous bone with arthrosis, but no differences were found in tissue density, mineral and collagen concentrations between arthrotic cancellous bone and the 3 controls. They concluded that the increase in bone tissue in early stage arthrotic cancellous bone did not make up for the loss of mechanical properties, which suggests a deterioration in the quality of arthrotic cancellous bone.

Isles-Blances et. al. [87] studied the characterization of bone cements prepared with functionalized methacrylates and hydroxyapatite. They reported that, the mechanical

properties of filled bone cements depended mainly on composition and type of testing. Hydroxyapatite filled bone cements fulfilled the minimum compressive strength (70 Mpa) required for bone cement use. The minimum tensile strength (30 Mpa) was only fulfilled by cements prepared without camenomer and those containing methacrylic acid.

Burr [88] studied the contribution of the organic matrix to bones material properties they reported that collagen may have less effect on bones strength and stiffness than does mineral, may have a profound effect on bone fragility. Collagen changes that occur with age and reduce bones toughness may be an important factor in the risk of fracture in older women with low bone mass.

Actis et. al. [89] studied influence of different sterilization, procedures and partial demineralization of screws made of bone on their mechanical properties. They reported that a standard screw made of bone and autoclaved at 134°C, 2-2.4 m bars, 5 min seems to be the most appreciate, from a biomechanical point of view, to be used as osteosynthesis material.

Siddiq mohiuddin et. al. [90] determined the elastic constants of animal bone (scapula) of buffalo by employing static methods. He reported that the significant variation in the elastic constants in the same bone are attributed to molecular composition both organic and inorganic, and water present in the pores, bound to collagen and in the mineral crystallites of the bone tissues.

Abdul Rauf et, al. [91] measured the mechanical energy dissipation by animal bone using the uniform bending method. A horizontal bar made by bone of different type and different animals was placed on two knife edges and equal load were suspended on both ends. The elevation at the centre of bar was measured using dial gauge. It was observed that the amount of energy dissipated is more in case of decalcified bone than that of a normal bone, for the same range of load applied.

Abdul Rauf et, al. [92] studied the mechanical properties of animal calcified and decalcified bone samples using the UTM machine. Samples were prepared as per the requirement of UTM machine. It was concluded that the compact bone like femur is more brittle than the spongy bone like rib. Due to decalcification bone loses its toughness, and its compressive strength decreases considerably.

In sum, from the literature it is evident that the mechanical properties of animal bone depend not only on molecular architecture, but also its cellular assembly.

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