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Comparison of the structure and mechanical properties of bovine femur bone and antler of the North American elk (*Cervus elaphus canadensis*)

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Abstract

Antler and limb bone have a similar microstructure and chemical composition. Both are primarily composed of type I collagen and a mineral phase (carbonated apatite), arranged in osteons in compact (cortical bone) sections and a lamellar structure in the cancellous (spongy or trabecular bone) sections. The mineral content is lower in antler bone and it has a core of cancellous bone surrounded by compact bone running through the main beam and tines. The mineral content is higher in the compact compared with the cancellous bone, although there is no difference in ratios of the mineral elements with calcium. Mechanical tests (bend and compression) on longitudinal and transverse orientations of dry and rehydrated compact bone of North American elk (*Cervus elaphus canadensis*) antlers are compared with known data on other antlers as well as bovine femora. Both dry and rehydrated bones are highly anisotropic, with the bending and compressive strength and elastic modulus higher in the longitudinal than in the transverse direction. There is no significant difference between the bend strength and elastic modulus between dry and rehydrated samples tested in the transverse direction. The elastic modulus measured from the bending tests is compared with composite models. The elastic modulus and bend strengths are lower in the rehydrated condition, but the strain to failure and fracture toughness is much higher fracture toughness compared with bovine femora, which correlates with their main function in intraspecific combat as a high impact resistant, energy absorbent material. A model of compression deformation is proposed, which is based on osteon sliding during shear.

Keywords: Antler; Bone; Mechanical properties; Deformation

1. Introduction

Antlers are the bony protuberances that form on the heads on animals from the family Cervidae (deer) and have been in recorded existence for over 25 million years [1]. Elk (wapiti), reindeer (caribou) and moose are included in the 40 species of deer that have antlers, and there are an additional four species that are antlerless. Normally, antlers

grow on male deer with the exception of reindeer, where antlers appear on both males and females. Blood supply to the growing antler arises from two sources: from the highly vascularized tissue (the velvet) on the surface of the antler and internally through the base of the antler (pedicle) [1], which results in an extraordinary growth rate. The interior supply is important as ligation of the velvet does not affect antler growth [1]. Antlers are one of the fastest growing tissues in the animal kingdom, growing as much as 14 kg in 6 months, with a peak growth rate of $2-4 \text{ cm day}^{-1}$ [2,3]. Once antlers are fully grown, the velvet is shed leaving the antler bare. Most antlers start growing in the spring (March–April) and reach full maturity in

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the fall at the start of the rut (September–November) [1]. Antlers are deciduous and are cast off (dropped) at the end of the rut. The antler is the only mammalian bone that is capable of regeneration; thus it offers unique insights into bone mineralization and growth.

The function of antlers is in some dispute, and it has been suggested that antlers are superfluous and will eventually disappear [3]. Stonehouse [4] proposed that the primary function of antlers is as a cooling mechanism, due to the presence of the velvet during the summer months. However, the main consensus is that antlers have two primary functions: they serve as visual signs of social rank within bachelor groups [5–9] and they are used in combat, as both a shield and a weapon [5,8–10]. On the other hand, Lincoln [7] observed that male red deer *(Cervus elaphus)* without antlers (from amputation) seem to suffer no catastrophic consequences in terms of competition for and defense of a harem. They were found to be quite capable at both tasks.

During the rut, male deer fight for control of harems, charging at each other, butting heads and clashing antlers, as shown in Fig. 1. After the antlers are interlocked, Kitchener describes the process in which the bulls wrestle, trying to force their opponent to the ground or pierce it with their antlers [11]. The antlers undergo high impact loading and large bending moments without fracture. The unusual toughness of antlers has been attested by the very few observations of antler breakage during fighting in large groups of caribou and moose [6]. The mechanical properties of antlers are believed to result from a combination of the dense outer sheath surrounding a porous core, which during antler growth (antlerogenesis) is filled with blood. There are inconsistent reports about whether blood flow is present in the antlers after the velvet is shed. Antlers had been thought to be dead tissue with all fluid removed once the velvet was shed, as no fluid was found in recently cast antlers [3,12,13]. In light of the high impact loads absorbed by antlers, this has been questioned. More recently, blood-filled fallow deer antlers, with living osteocytes and active osteoblasts, have been found 1 h after casting [14]. This fluid-filled interior is thought to contribute to the excellent toughness of the antler [12,14], although the relative contribution to impact resistance is unknown.

Antlers have a composition very similar to other mammalian long bones, but there are distinct differences. Given the long, slender appearance of most antlers, the natural comparison is to mammalian long bones. Skeletal bones provide structural support and protection of organs whereas antlers provide neither. Long bones are hollow and contain interior fluids (blood, marrow, etc.), and produce vital cells and minerals necessary for the body. In contrast, antlers remove fluids and minerals from the body in order to grow. Antlerogenesis necessitates a large amount of calcium and phosphorus in a short period of time. Red deer (C. elaphus, a European deer almost identical to the North American elk, Cervus elaphus canadensis) antlers require $\sim 100 \text{ g day}^{-1}$ of bone material in order to grow, in comparison to growing fawn skeletons, which require \sim 34 g day⁻¹ [1]. This quantity of minerals cannot be obtained through food sources and has been shown to come from the skeleton of the animal [1,2,15-17]. The long bones of the legs and the ribs are the richest source, and are found to decrease in density as the antlers increase in size [15]. Thus, structural bone resorption occurs along side bone remodeling during antlerogenesis.



Fig. 1. Two North American elk bucks engaged in combat. Reproduced with permission from Michael Dougherty, http://www.arkansasnaturephotography.com.

2. Background

2.1. Structure

Fig. 2 shows the hierarchical structure of antlers. Antlers contain a core of cancellous (trabecular or spongy) bone surrounded by compact (cortical) bone that runs longitudinally through the main beam of the antler and the prongs. The cancellous bone is porous, with channels somewhat aligned parallel to the long axis of the antler beam. It has a high surface area to accommodate the vascular system and transportation of nutrients. The compact bone consists of osteons that have a laminated structure of concentric rings extending from the main channel (blood vessel). The concentric rings (lamellae) contain aligned type I collagen fibrils that have the mineral, a calcium phosphate (hydroxylapatite) of composition $Ca_{10}(PO_4)_6(OH)_2$, dispersed on or between fibrils of length \sim 300 nm. Between 4% and 6% of the carbonate groups replace phosphate groups, resulting a structure that is more similar to a carbonated apatite, dahllite [18,19]. Cancellous bone contains few of these cylindrical components; rather, the bone is composed of parallel lamellae of the collagen/mineral composite.

2.2. Mechanical properties

There are few reports on the mechanical properties of antlers. Currey was the first to perform strength, fatigue,

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sue from various taxa [20-29]. The general findings were that the elastic modulus and strength increased with increasing ash (mineral) content [21] while the work of fracture decreased. Antler was found to have the lowest mineral content and consequently the lowest elastic modulus, with a mineral content of 45-65 wt.%, in contrast to the highly mineralized whale rostrum at 98% [21,28,30]. Mammalian, reptilian and avian skeletal bones fall between these values. Red deer antler and bovine femur bone were found to have similar ultimate tensile strengths, which varied between 100 and 140 MPa; however, the strain at failure (8-10%) and work of fracture ($6186 \pm 552 \text{ Jm}^{-2}$) for antler were 4–5 times greater than bovine femora [20,31]. The modulus of elasticity (7.4 GPa) was roughly half that of the femur. In antler, the post-yield region of the stress-strain curve was considerably longer and accompanied by a long gradual slope to failure (stress at failure is $\sim 5/3$ stress at yield), compared with bovine femora. In this bone, after the ultimate strength was reached, the stress dropped rapidly until failure or increased slightly by about 10% to failure [26]. Microcrack formation resulted in both types of specimens, but the antler showed the macrocrack path to be torturous, resulting is a toughening mechanism that is akin to what is observed in nacre [32,33]. Additionally, in antler, the osteons tended to delaminate, which was attributed to an additional toughening mechanism over limb bone.

Kitchener [11,34] studied the horns and antlers from various taxa. He found that the specific strength of Sika





and hog deer antlers were higher than that of mild steel and determined that antlers appear to be structured to resist deflection [34]. Tropical deer, such as the muntjak, hog and spotted deer, have a lower fraction of cancellous bone than other deer, resulting in a higher elastic modulus (11–14 GPa) compared with other deer species (5–7 GPa) (see Table 1) [11].

Rajaram and Ramanathan [13] examined the antlers from the spotted deer (*Axis axis*) that had an ash content of 55 wt.%. The tensile strength was 188 MPa, the elastic modulus was 17.1 GPa, the strain to failure was 1.5%and the work of fracture was 13.5 kJ m^{-3} . The high work of fracture and modulus of elasticity is surprising, given that the ash content is similar to that of the Currey's red deer, which had roughly half the value of the fracture toughness and elastic modulus. They also observed a distinct plastic region. Fracture surfaces showed that the osteons delaminated, corroborating Piekarski's observation, compared with bovine femora in which whole osteons are pulled out intact [35].

Blob et al. [36–38] studied the elastic moduli of both moose (*Alces alces*) and white-tailed deer (*Odocoileus virginianus*). They found no correlation of the elastic modulus as a function of the position along the antler, suggesting that other mechanical properties may not be influenced by the location of the test specimen. Moose antlers had a higher elastic modulus (11.6 GPa) compared with the white-tailed deer (6.8 GPa). The difference was attributed to the different fighting behavior between moose and the white-tailed deer as a consequence (or a predicator) of the different antler structure. Moose have large palmate antlers, with small prongs. Deer have a long antler beam with prongs extending from this central beam. As a result,

fighting moose cannot interlock their antlers and are thus subjected to higher bending moments.

Landete-Castilleios et al. [39] studied antlers from freerange and captive Iberian red deer (Cervus elaphus hispani*cus*). The captive deer antlers had a higher elastic modulus; bend strength and work of fracture; yet the ash and Ca contents were not different. There were small but measurable differences in Mg, Na, K, Zn, Fe and Si, and the difference in mechanical properties was attributed to this, not the Ca or ash content. For both antlers, a higher elastic modulus, bending strength and work of fracture was found for specimens taken closer to the pedical compared with ones taken from further along the beam, in contrast to Blob et al. [38]. This group had previously suggested that there is a chemical composition difference from the pedical to the end of the beam, resulting from increasingly better nutrition of the animal during antlerogenesis. Table 1 summarizes mechanical property data found measured on various antlers, along with a comparison to bovine femur.

In this study, we report on the structure and mechanical properties of an antler from the North American elk, *C. elaphus canadensis.* This is the first comprehensive report on these antlers, providing chemical and microstructural analysis as well as mechanical behavior studies, and the first to report on the compressive properties, transverse bending properties and fracture toughness values of antler. Additionally, we report dry and rehydrated properties, side by side. Our ultimate aim is to produce bioinspired antler-like, energy absorbent, tough materials. To this end, a thorough understanding of all of the mechanical properties is necessary. The compressive properties are important to understand deformation of the antler under bending loads, which is how they are loaded during combat. Although the

Table 1

Summary of the properties of the compact bone from antlers of various species. E = elastic modulus, σ_b = bending strength, σ_{uts} = ultimate tensile strength, ε_f = strain to failure, WOF = work of fracture, ash = percentage of ash, ρ = density

Species	E (GPa)	$\sigma_{\rm b}~({\rm MPa})$	$\sigma_{\rm uts}$ (MPa)	$\epsilon_{\rm f}~(\%)$	WOF $(kJ m^{-2})$	Ash (%)	$ ho~({\rm g~cm^{-3}})$	Ref.
Cervus elaphus (red deer)	7.4	179			6.2	59.3	1.86	[20]
	7.2		158	11.4	93,000 ^c	48 ^b	0.91	[29]
Axis axis (spotted deer)	17.1		188	1.46	13.5	55	1.86	[13]
	11.6	233			9		1.9	[11]
Rangifer tarandus (reindeer)	8.1		95	5.1	32,000 ^c	50 ^a	0.83	[29]
	6.4							[23]
Cervus nippon (Sika deer)	13.7	239			9		1.9	[34]
Cervus porcinus (hog deer)	12.7	246			10		2	[11,34]
Alces alces (moose)	11.8							[36]
Odocoileus virginanus (white-tailed deer)	6.8					61–64		[38]
Cervus elaphus hispanicus (Iberian red deer)	5.3	81.9			18.2	61.6		[39]
Muntiacus muntjak (muntjac deer)	11.4				2.99			[22]
Capreolus capreolus (roe deer)	2.2				2.99			[22]
Elaphrus davidianus (Père David deer)	12					63.3	1.87	[55]
Cervus elaphus canadensis (North American elk)	7.6	145		13.3	13.9	56.9	1.72	This work
Bovine femur	13.5				1.7	66.7	2.06	[20]

Work of fracture calculated from a notched 3-point bend sample. The area under the load-deformation curve was divided by twice the cross-sectional area [20].

^a Corresponds to published volume fractions of 0.3.

^b 0.287 using 1.35 g cm⁻³ for collagen and 3.15 g cm⁻³ for hydroxyapatite.

^c Values taken from integrating the area under the stress–strain curve, in kJ m $^{-3}$.

first loading condition is impact, when the antlers are interlocked static loads are present. Bending produces both tensile and compressive stresses in the antler bone, and damage can accumulate (microbuckling) under repeated compressive loads, inducing stress concentrators. Because the mechanical properties of antler are relatively unknown, we have compared our values to bovine femora wherever possible, as well as to reported properties of antlers from other species. The elastic modulus of elk antler is discussed and compared with the predicted values from various composite models.

3. Materials and methods

The North American elk (Cervus canadensis) antler was purchased from Into the Wilderness Trading Company (Pinedale, WY). The antler, from a large, mature bull, was shed approximately 1 year before we obtained it for testing. The length of the antler was 1.05 m and it had six tines. The thickest cross-sectional diameter at the pedical was 7.2 cm. The tines ranged in diameter from 3.5 to 6.0 cm. The main beam was cut into sections (~ 10 cm) using a band saw, as was a bovine femur, which was purchased from a local butcher. The slaughter age of the cattle was approximately 18 months. Samples used for bending and compressive tests were obtained from the central region of the beam portion of the antler. For bending tests, samples from compact region of the antler were dissected into rectangles $(30 \text{ mm} \times 3 \text{ mm} \times 2 \text{ mm})$ with a diamond saw and lightly sanded. Twenty-four pieces were cut to prepare two equal sets of samples, one in the dry condition and one in the rehydrated condition. Rehydration was accomplished by immersion of the samples in Hank's balanced saline solution (Mediatech Inc., VA) at room temperature for 24 h, which were then weighed before testing. Each set of samples was further divided into two groups, six to be tested in the longitudinal direction and six in the transverse direction. The transverse direction is taken as perpendicular to both the radial and longitudinal direction. For compressive tests, samples were cut into cubes with an edge of 0.5 cm. Twenty-four cubes were prepared for the two testing groups: longitudinal and transverse compression. The density was calculated from weighing and measuring the dimensions of the compression test samples. For fracture toughness measurements, 12 samples (six in dry and six in rehydrated conditions) were dissected into rectangles $(25 \text{ mm} \times 3 \text{ mm} \times 4 \text{ mm})$ with a diamond saw and notches $\sim 1 \text{ mm}$ in length were made using a wire saw. The ash content was obtained from 0.6 g powder samples from the antler. Samples were first dried in a muffle furnace at 105 °C for 4 h and weighed. They were then ashed at 550 °C for 24 h and the ashed weight was measured. The ash content was calculated by dividing the weight of the ashed antler by the weight of the dried antler. X-ray diffraction (XRD) was performed on the antler powder by a Rigaku MiniFlex[™] II benchtop XRD system (Rigaku Company, Texas, USA).

The bending tests were performed on a laboratorydesigned fixture consisting of three knife edges, such that the specimen is place on top of two knife edges with a span of 20 mm while the third knife edge applies stress from the top. A universal testing machine (Instron 3346 Single Column Testing Systems, Instron, MA, USA) equipped with a 500 N load cell was used. The crosshead speed was 0.3 mm min^{-1} , which corresponded to a strain rate of $1.5 \times 10^{-4} \text{ s}^{-1}$. Compressive tests were conducted on the cubic samples in the longitudinal and transverse directions. A universal testing machine (Instron 3367 Dual Column Testing Systems, Instron, MA, USA) equipped with a 30 kN load cell was used. Specimens were tested at a 0.03 mm min^{-1} crosshead speed, which translated to a strain rate of $1 \times 10^{-4} \, \text{s}^{-1}$, close to that of the bending tests. All samples were tested to failure. Fracture toughness was measured by the ASTM C1421 pre-cracked beam method using a four-point bend fixture [40]. Bending and fracture toughness tests were performed on dry and rehydrated antler. Compression testing was performed on dry antler only.

The fracture surface was characterized by using a field emission scanning electron microscope (SEM) equipped with electron dispersive spectroscopy (EDS) (FEI-XL30, FEI Company, OR). The fractured samples were mounted on aluminum sample holders, air dried for 5 min and coated with 10 nm of gold in a sputter coater. They were then observed in the secondary electron mode at 20 kV accelerating voltage. Samples prepared for optical microscopy were observed under a Zeiss Axio imager equipped with a CCD camera (Zeiss MicoImaging Inc., Thornwood, New York, USA). Transmission electron microscopy (TEM) was performed on a 200 kV microscope equipped with a LaB₆ electron gun (Technai Sphera, FEI Company, Oregon, USA). The TEM samples were prepared following the procedures developed by Weiner and Price [41].

4. Results and discussion

A cross-section, perpendicular to the growth of an antler, is shown in Fig. 3, identifying the four main regions radiating outward from the center: cancellous bone, a transition zone between cancellous and compact bone, compact bone and subvelvet [14]. Optical micrographs show the subvelvet to be 100–150 μ m thick, which has layered structure. Beneath the subvelvet is the compact bone. Moving from the compact bone to the cancellous bone shows an increase in the size of the porosity, with the pore size ranging from 300 μ m at the compact/cancellous interface to several millimeters at the interior of the cancellous region.

The cross-sectional and longitudinal microstructures in compact antler bone are shown in Fig. 4(a) and (b), respectively. In Fig. 4(a), osteons (100–225 μ m diameter), Volkmann canals, vascular channels (15–25 μ m diameter) and lacunae spaces (~10 μ m diameter) are observed. The majority of the osteons appear to be aligned along the growth direction. Depending on the age of the bone,



Fig. 3. Antler cross-section showing optical micrographs of the (a) subvelvet/compact interface, (b) compact and (c) transition (compact to cancellous) zone, (d) a SEM micrograph of the cancellous bone.

human osteons range from 200 to 300 μ m [42], substantially larger than what is found in the antler. This is likely due to the age difference between the reported values for human bone, typically taken from adults, as opposed to what is found in the relatively young antler. In Fig. 4(b), the Volkmann canals are roughly perpendicular to and have smaller diameters than the vascular channels. The Volkmann canals also appear to have a somewhat circular laminated structure, similar to the longitudinal osteons.

Two types of osteons can be present in bone: primary and secondary. Primary osteons contain vascular channels surrounded by concentric bone lamellae. Primary osteons are generally smaller and do not have a cement line surrounding them. Secondary osteons result from bone remodeling, often intersect each other and have a more rounded, uniform shape than primary osteons. Currey and others have shown that bone with primary osteons is stronger than bone with secondary osteons [18,42,43]. Using quantitative backscattered electron imaging and EDS analysis, Skedros et al. [44] recently showed that cement lines are highly mineralized, in contrast to earlier conclusions that they were poorly mineralized [45-48]. The hypermineralized cement lines are thought to play an important role in enhancing mechanical properties by attenuating the propagation of microcracks [43,49]. We could not completely distinguish between the two types in the micrograph; however, the majority appears to be primary osteons, since they show a somewhat distorted cross-section. Additionally, based on observations in backscattered electron images, Skedros et al. [49] have pointed out that antlers undergo limited secondary osteon remodeling. Although primary osteons do not develop cement lines



Fig. 4. Optical micrographs of compact bone from the elk antler and bovine femur: (a) cross-sectional area and (b) longitudinal area of elk antler; (c) cross-sectional area and (d) longitudinal area of bovine femur (Os, osteons; Va, vascular canals; Vo, Volkmann canals; L, lacuna; I, interstitial bone).

in bone, hypermineralized lamellae around primary osteons have been found in deer antlers, which might be functionally analogous to cement lines in secondary bone [49]. Secondary osteons can also arise in response to mechanical stress [18]. The antler does not undergo mechanical forces during the growth process and only spends 1-2 months in sporadic combat, if at all. It seems unlikely that secondary osteons would develop under these conditions. The antler porosity is estimated to be ~9.1% by area, counting the vascular channels and lacunae void spaces.

Fig. 4(c) and (d) shows the cross-sectional and longitudinal optical micrographs of a compact region of a bovine femur. In Fig. 4(c), the osteons in the bovine femur are more sparsely distributed compared with those in the antlers. These appear to be secondary osteons, given the uniform, circular shape of the majority. These osteons are embedded in parallel fiber (interstitial) bone, which is continually remodeled to form secondary osteons. Several elongated pores are observed, which actually are sections of the Volkmann canals (also appearing in the antler micrograph), along with lacunae. The void space is estimated to be 5.1%, in agreement with a porosity of 5.8%measured in other bovine femora [50,51]. The interstitial bone was found to have a higher strength and elastic modulus than secondary osteonal bone [52-54], with an average modulus of \sim 27 GPa for mixed bone. In the femur, secondary osteons occupy $\sim 41\%$ by area. In Fig. 4(d), the size and shape of the void spaces appear similar to antler bone.

The mineral composition and densities of the compact bone, cancellous bone and total antler are shown in Table 2. The compact bone had an overall mineral content of 56.9 wt.%, which is in good agreement with measurements on red [20] and spotted [13] deer, somewhat higher than in reindeer [29] and lower than in white-tailed [38], Iberian red [39] and Père David deer [55] (see Table 1). Using a density of collagen of 1.35 g cm^{-3} and of hydroxyapatite of 3.15 g cm^{-3} , these weight percentages corresponds to a volume fraction of mineral phase in the compact, cancellous and total antler of 0.36, 0.25 and 0.30, respectively, also in agreement with others [29]. The compact bone is more mineralized than cancellous bone, which is also the case for mammalian skeletal bones. The density scales with the mineral content: compact bone has a higher density than cancellous bone due to its higher mineral content. EDS analysis showed no significant variation in the mineral content of compact bone samples takes near the pedical compared with ones taken from the tines. The elements Ca, P, Sr, Na, Mg, Ba and K were identified in decreasing order of amount. These results are similar with chemical analysis results obtained on the antlers from the Iberian red deer [39], in which the trace elements Na, Mg, K, Si, Zn and Fe appeared in decreasing amounts. However, we could find no difference

Table 2
Density and mineral content of compact and cancellous antler bone

Property		Compact b	Compact bone		Cancellous bone		r	
Density (g Mineral c	g cm ⁻³) ontent	1.72 ± 0.04		0.50 ± 0.05		1.35 ± 0.10		
Wt.%		56.9 ± 1.0		43.4 ± 0.4		50.1 ± 0.5		
Volume fi	raction	0.36		0.25		0.30		
Chemical	composition (wt.%)	E = element						
	Compact				Cancellous			
	Pedical	E/Ca	Tine	E/Ca	Pedical	E/Ca	Tine	E/Ca
Ca	20.02	1.00	20.08	1.00	15.17	1.00	13.81	1.00
Р	8.92	0.46	8.59	0.43	6.09	0.40	6.19	0.45
Sr	0.68	0.03	0.60	0.03	0.48	0.03	0.50	0.04
Na	0.43	0.02	0.57	0.03	0.44	0.03	0.54	0.04
Mg	0.33	0.02	0.42	0.02	0.28	0.02	0.31	0.02
Ba	0.12		0.07		0.07		0.07	
Κ	0.03		0.03		0.18		0.09	
С	20.19		28.55		31.20		37.46	
0	48.81		41.22		46.21		41.17	

in chemical composition from samples taken near the pedical compared with those at the tines, in contrast to Landete-Castillejos et al. [56]. They measured the ash content, Ca, Na, Mg, Zn and Fe, and found that in the tines, compared with the base, there was a smaller amount of all these minerals except Ca, which was higher. They used atomic absorption spectroscopy, a more sensitive chemical analysis technique than EDS, which is possibly why we did not identify any difference in chemical composition along the length of the antler. Bloebaum et al. [57], on a molar basis, reported Ca/P values for mule deer (*Odocoileus hemionus*) antlers for compact (1.55) and cancellous (1.61) regions. Our values for Ca/P, on a molar basis, are slightly higher: 1.76 for compact and 1.81 for cancellous bone.

The cancellous regions showed a smaller weight fraction of the elements, but in proportion to Ca, there was no significant difference in the mineral composition between the cancellous and compact bone regions, as shown in Table 2.

XRD on the ash revealed the mineral is hydroxylapatite and can be indexed to JCPDS # 00-001-1008 [58], as shown in Fig. 5(a). The peaks are broad, indicating that the crystallites are nanocrystalline. The size of the crystallites was determined using the Scherrer [59] formula:

$$t = \frac{0.9\lambda}{B\cos\theta}$$

where t is the crystallite size, λ is the wavelength of X-rays and B is the full-width at half-maximum size of a peak diffracting at angle θ_B . This formula indicates that as the peaks broaden the size of the crystallites decreases. The crystallite size was calculated to be ~4 nm. Using this analysis, only the smallest dimensions are calculated, thus it does not imply that larger crystallite sizes do not exist.

A TEM micrograph is shown in Fig. 5(b), which shows the morphology and size of the individual mineral crystallites. The crystallites have a platelet shape, with a thickness of 4 nm, corroborating by the XRD results. The platelets range in length and width from 20 to 70 nm. The dimensions of the crystallites in antler are very similar to those in skeletal bone, which are in the range of 25–50 nm, with a thickness of 3 nm [19,30,41,60].

The mechanical property data from the elk antler is shown in Table 3. The elastic modulus in three-point bending was calculated from:

$$E = \frac{PS^3}{4\delta wt^3}$$

where P is the load, S is the span = 20 mm, w is the width of specimen, t is the thickness of specimen and δ is the maximum deflection of the beam. This expression ignores the Timoshenko shear component [61]. Bend tests reveal that the elastic modulus is higher for longitudinal samples (dry: 7.6 ± 0.25 GPa; rehydrated: 6.98 ± 0.26 GPa) compared with transverse ones (dry: 3.76 ± 0.68 GPa; rehydrated: 3.26 ± 0.35 GPa), attesting to the predominant alignment of the osteons in the longitudinal (growth) direction. The rehydrated samples show a lower modulus both in the longitudinal and transverse directions. The amount of fluid retained was determined to be 9.15 ± 0.72 wt.%. The ratio of the transverse/longitudinal moduli for dry and rehydrated samples is ~ 0.5 . For osteonal bovine femur, the longitudinal and transverse moduli are 23 and 10 GPa, respectively [62], resulting in transverse/longitudinal moduli similar to that of antler.

If the antler is considered to be a composite of collagen (E = 1.3 GPa [63]) and hydroxylapatite (E = 114 GPa [64]), using the Voight model,

$$E_{\rm V} = V_{\rm C} E_{\rm C} + V_{\rm H} E_{\rm H}.$$

Here E_V is the Voight modulus, V_C and V_H are the volume fractions of collagen and hydroxyapatite, respectively, and E_C and E_H are the respective elastic moduli. The estimated longitudinal modulus is 42 GPa, much higher than what is measured for the longitudinal orientation. If the Reuss model is considered,

$$1/E_{\rm R} = V_{\rm C}/E_{\rm C} + V_{\rm H}/E_{\rm H}$$



Fig. 5. (a) X-ray diffraction patterns from the compact antler bone. All peaks correspond to JCPDS file 00-001-1008 for hydroxylapatite [58] and (b) TEM micrograph of the hydroxylapatite crystals.

the modulus is estimated to be 2 GPa, lower than what is measured for the transverse orientations. However, other limb bones also fall between these two values, indicating a mechanical similarity. Others researchers have investigated modified composite models to predict the elastic modulus of bone and have found that the mineral orientation, shape of the mineral [63], presence of lamellae [63], collagen fiber orientation [50,65,66], porosity [50,65,66], mineralization [50,65,66], osteon orientation [67] and fraction of secondary osteons [66,68] affect the mechanical properties. All of these cause deviations from the Voight and Reuss models.

Considering porosity alone, Bonfield and Clark [63] have expressed a modified Mackenzie [69] equation to account for porosity as:

$$E = E_{\rm o}(1 - 1.9p + 0.9p^2)$$

where E = measured elastic modulus, $E_0 =$ elastic modulus of sample containing no porosity and p = porosity volume fraction. Using this expression, the calculated value for E_{0} is 8.6 GPa, which is higher, but still not close to the composite value of 40 GPa estimated from the Voigt model, indicating that porosity is not the only factor that has influence on the elastic modulus. Carter and Hayes [54] have proposed an expression for the elastic modulus that is proportional to $(1-p)^3$, and this expression also does not approximate the measured elastic modulus. Thus, the elastic modulus of elk antlers is a complex function of the variables listed above. Another important point is that the transverse modulus is relatively high when compared with the longitudinal modulus. Taking the ratio of the Reuss/ Voight moduli, a value of 0.05 is calculated, which is an order of magnitude lower that what is found for antler and limb bone. This further demonstrates the inadequacy of using these two models to describe the elastic modulus of longitudinal compact antler bone.

As shown in Table 3, the longitudinal modulus value is in the middle of the range of longitudinal moduli for other deer (2.2–17.1 GPa). What is surprising is that the spotted deer modulus (17.1 GPa [13]) is over twice that of the elk, even though the mineral content varies by <1%. The roe deer (*Capreolus capreolus*) has a dry low elastic modulus of 2.2 GPa [23] but, since no mineral data were provided, it is difficult to make any statements about this unusually low value. The rehydrated longitudinal elastic modulus is similar to that of red [29] and white-tailed [38] deer and reindeer [22,23].

Fig. 6 shows a representative stress-strain curve for a three-point bend test in the longitudinal and transverse directions for both dry and rehydrated antler. The failures were graceful and many specimens never completely broke in half. The bending strength was calculated from:

$$\sigma = \frac{3PS}{2wt^2}$$

The longitudinal strength (dry: 197.3 ± 24.0 MPa; rehydrated: 145.1 ± 9.0 MPa) was higher than the transverse strength (dry: 66.7 ± 10.7 MPa; rehydrated: 64.9 ± 6.8 MPa), also indicative of osteon alignment in the longitudinal direction. The hydrated longitudinal bend strength is less than that of other deer species and bovine femora (238 MPa [70]). For the dry longitudinal specimen, the curve shows a linear elastic region and a plastic region with a gradual increase in stress until fracture, which occurs at a strain of 6.5%. The rehydrated antler shows a much larger strain to failure (12.3%), an increase of 83% over that of dry antler. This indicates that a rehydrated antler can withstand much more deflection during fighting than dry antler, suggesting that antlers are not dead tissue, but are living organs during combat. The rehydrated bend strength is lower than what is reported for most other deer. The difference between the transverse strengths in the dry and rehyTable 3

Mechanical properties of compact bone in North American elk antlers and bovine femora (references are for femora) tested in the dry and rehydrated conditions

Property	Elk antler (dry)	Elk antler (rehydrated)	Bovine femur	Ref.
Density (g cm ⁻³)	1.72		2.06	[18]
Mineral content (% ash)	56.9		67	[18]
Elastic modulus				
Bending (longitudinal)	7.60 ± 0.25	6.98 ± 0.26	26.1	[28]
Bending (transverse)	3.76 ± 0.68	3.26 ± 0.35		
Bending strength (MPa)				
Longitudinal	197.3 ± 24.0	145.1 ± 9.0	238	[70]
Transverse	66.7 ± 10.7	64.9 ± 6.8		
Compressive strength				
Longitudinal	125.6 ± 11.3		272	[67]
Transverse	44.5 ± 17.1		146	[67]
Tensile strength (MPa)				
Longitudinal	$115.4\pm16.6^{\rm a}$		144	[67]
Transverse	$20.3\pm 6.0^{\mathrm{a}}$		46	[67]
Fracture toughness (MPa·m ^{1/2})	7.9 ± 2.2	10.3 ± 3.3	2–5	[73–75]

^a Taken from Ref. [72].



Fig. 6. Flexure stress-strain curves from three-point bend tests for longitudinal and transverse samples in the dry and rehydrated conditions (N = 6 for each orientation; span = 20 mm).

drated condition is very small, indicating that the presence of a fluid does not affect fracture between osteons. The effect of hydration is more significant in the longitudinal direction, where the difference is $\sim 25\%$.

The post-yield behavior is thought to result from microcracking, which remains isolated and dispersed until a macrocrack forms and the specimen fails [25]. Currey [28] found that the longitudinal bending strength for bone from a large variety of taxa is 0.01 of the elastic modulus, indicating a linear relationship and a dependence of failure on the strain. In antler, a ratio of 0.03 is found for elk, 0.02 for red deer and 0.02 for spotted deer, indicating a similar trend with limb bone. Kitchener [11,34] report an elastic modulus for the Sika and hog deer compact antler bone that is approximately twice that for red, spotted and white-tailed deer and reindeer, resulting in a ratio of bending strength to elastic modulus that is approximately twice that for other deer: 0.17 for the Sika deer, and 0.19 for hog deer. This may be due to the fact that these are tropical deer species [11].

The fracture surface is very uneven and fibrous, indicating a ductile failure, as shown in the angled side view SEM micrograph in Fig. 7(a). The appearance of extensive fiber pullout is similar to what is observed for fiber-reinforced composite failure. The fibrous nature of the surface also indicates that the preferred orientation of the osteons is along the growth direction. The top view (Fig. 7(b)) shows the presence of transverse cracks and delamination around the osteons, in agreement with other reports of osteon delamination [25,71].

We previously reported that the longitudinal and transverse tensile strengths were 115.4 ± 16.6 and 20.3 ± 6.0 MPa, respectively [72]. These values are less than the bending strengths in both directions. Longitudinal and transverse tensile strengths of bovine femur were reported to be 144 and 46 MPa, respectively [67]. The increased mineralization of the bovine femora accounts for the higher strengths.

A representative example of a stress-strain curve from compression tests in the longitudinal and transverse directions is shown in Fig. 8. Both sample orientations deformed to tremendous strains and no "fracture" strength could be identified. The samples did not break or buckle; the tests were stopped when the samples had completely flattened. The longitudinal orientation showed a yield point at ~120 MPa, after which point the deformation increased rapidly with a small increase in stress. At ~200 MPa and a strain of ~60%, the slope of the curve dramatically increased, indicating that the material has strain hardened. The transverse specimens showed interesting features in the stress-strain curve. At small strains, the



Fig. 7. SEM micrographs of the fracture surface of a dry longitudinal specimen broken in bending. (a) Side view showing the fibrous nature of the fracture. (b) Top surface showing the osteons. Arrows point to where delamination around the osteons occurred.



Fig. 8. The representative compression stress-strain curves for longitudinal and transverse directions, showing deformation mechanisms in the transverse direction.

deformation is elastic where the sample is expected to bulge slightly. As the stress is increased, there is a yield point at \sim 80 GPa. Beyond this stress, shear deformation occurs through blocks of osteons sliding past each other at a 45° angle. This configuration is stable and the continued loading shows a linear relationship with increasing strain. Microcracking may be occurring in this region. After \sim 170 GPa, an abrupt decrease in stress is observed. This is attributed to further shear deformation that occurs by blocks of osteons sliding past each other, causing more flattening of the sample. This causes the stress to decrease as the cross-sectional area increases. The increasing stress was accompanied by linearly increasing strain until the test was stopped. Fig. 9 shows SEM micrographs of the compression test samples, confirming the shear deformation scenario. The macrocracks extend through the osteons, and delamination of the osteons can be observed. The 45° crack angles can be easily observed. Bovine femur was reported to have compressive strengths of 272 and 146 MPa in the longitudinal and transverse directions, respectively [62].

The rehydrated antler bone had a fracture toughness value of 10.3 ± 3.3 MPa m^{1/2}, compared with a bovine femur of 2–5 MPa $m^{1/2}$ [73–75]. This high fracture toughness has been attributed to the relatively low mineral content and the microcrack propagation of antlers [25,75,76].

а





Fig. 9. Optical micrographs of compact bone after compression, showing the (a) osteons sliding during the shear (b) crack propagation through and around osteons.

The dry fracture toughness was 7.9 ± 2.2 MPa m^{1/2}, lower than the rehydrated samples but higher than wet bovine femora. Both limb and antler bone derive their toughness by forming microcracks during the process of crack propagation, yet in the case of antler bone, microcracks are more isolated and dispersed from each other than those in limb bone before the formation of the fatal macrocrack. The macrocracks, once formed, follow a much more tortuous route, resulting in rougher fracture surfaces compared with limb bone [25]. Another possible toughening mechanism is the hypermineralized peripheral lamellae in primary osteons, which may enhance the fracture toughness by attenuating the propagation of microcracks [49].

5. Conclusions

Physical and mechanical properties were measured on an antler from the North American elk (*C. elaphus canadensis*) and compared with published values for bovine femora. The major findings are:

- Elk antler consists of an interior core of cancellous bone and exterior sheath of compact bone. Osteons, vascular channels, Volkmann canals, lacunae voids and interlaminar bone are observed in the compact bone region, which has ~9.1% porosity accounting for all the void space.
- The mineral content in the compact bone regions (56.9% ash) is higher than the cancellous bone regions (43.4% ash) but lower than bovine femora (67% ash). The EDS results show no significant difference in the chemical composition between the compact and cancellous bone or along the length of the antler, when normalized to calcium. The fraction of the mineral phase is similar to that of red and spotted deer, somewhat higher than that of reindeer, but lower than that of white-tailed, Iberian red and Père David deer.
- For the first time, the mineral phase in antler was imaged by TEM. The mineral phase can be indexed to hydroxylapatite and has a plate-like morphology, with a thickness of 4 nm and length and width between 20 and 70 nm, similar to the mineral size found in skeletal bone.
- The mechanical properties are highly anisotropic: the longitudinal elastic modulus and bending, tensile and compressive strengths are higher than in the transverse direction in both dry and rehydrated conditions. This is the first report on the transverse properties.
- For the first time, dry and rehydrated antler bone data are presented side by side. The rehydrated longitudinal elastic modulus is comparable to that of red and white-tailed deer and reindeer but lower than that of other deer species. The rehydrated bend strength is lower than in most other deer species.
- The elastic modulus cannot be modeled by the Voigt or Reuss models and appears to be a complex function of mineral content, mineral orientation, osteon orientation and collagen fiber orientation.

- Longitudinal bending failure is characterized by a large strain to failure and is ductile with a fibrous fracture surface. The rehydrated samples have lower bending strengths in both directions compared with dry samples; however, the strain to failure is increased by 83%.
- The difference between the transverse strengths in the dry and rehydrated condition is very small, indicating that the presence of a fluid does not affect fracture between osteons.
- Compressive properties are reported for the first time. A compression failure mechanism is proposed: compressive failure in the transverse direction occurred by shear and involved the successive movement of block-like segments along 45° angles.
- The fracture toughness of rehydrated antler bone is over twice that of bovine femora. The dry fracture toughness is also higher than that of femora. This is the first report on fracture toughness values on antler bone.

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