ABUAD Journal of Engineering Research and Development (AJERD)
ISSN (online): 2645-2685; ISSN (print): 2756-6811

Volume 8, Issue 2, 223-232

Optimizing the Impact and Yield Strengths of Cattle Horn for Engineering Applications

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Date Submitted: 19/05/2025
Date Accepted: 22/07/2025
Date Published: 27/07/2025

Abstract: *Cattle horns are one of wastes materials littering our environment, yet they have potential value in engineering. The work examined the engineering application of cow horn's impact and yield strength. The physical and mechanical properties were examined to determine their levels of impacts and yield strengths. The horn structure contains keratin with lamellae tubules lapping over each other along the growing direction. The horn microstructures, density, water absorption, compression, flexural, hardness and impact test were examined. The samples have density of 1.303 g/cm^3 to 1.376 g/cm^3 along the body parts. The cow horns impact resiliencies vary along the parts due to animal maturity and ages. Cow horn withstands compressive stress and bending stress of 1,018.96 MPa and 981.4MPa respectively. The average values of hardness property for longitudinal and transverse are 51.735 N/mm^2 and 41.795 N/mm^2. The sustainability of the samples was analyzed using L_{25} Taguchi orthogonal array by examining chemical compatibility, temperature and pressure as variable factors. The properties variations of the horns are attributed to the concentration of keratin substance along the body parts. The work identified an appropriates applications area using an impact and fatigue analysis which provided opportunities to use the material to produce sustainable engineering applications.*

Keywords*: Biomaterial, Engineering Materials, Keratin, Horn Sheath, Impact*

1. INTRODUCTION

Biomaterials waste, primarily from plants and animals is widespread in our environment. They are source of wastes from living organisms, accumulated or scattered within our environment. [1]. The bio-materials like horns, bones, plant leaves, and cellulose are one of the viable and sustainable source of materials for various engineering and bio-medical applications [2, 3]. Biomaterial salvaging and application in an engineering application has become an overall interest in many nation [4]. Animal horn is biomaterial growing at the forehead of bovid animal, with biological function related to their structural nature. The purpose of defenses and attack are due to horn mechanical capability to withstand static and dynamic loads. [5-6] Animals horn is made up of inner bone core and outer keratin sheath. The horn sheath is a proteinous parts, which is the main load bearing of the applied forces [7]. The sheath of the cow horn possesses mechanical properties which enable cattle to apply force while pulling each other. Cow horn sheath is made of keratinous microstructure, which contains layers of laminae fibre keratin filament laying on each other. For these reasons, animal horns possess strong microstructures and mechanical properties to withstand impact load for production of various engineering applications, which this work revealed. Animal horn has been used in many applications to produce fittings and beautification devices.

Cow horn can be used to produces deformable materials like sealing (gasket) device which can be modelled in the shape of a ring or sheet. Gaskets produce a pressure-seal between two or more components, which relies on firmness seal to prevent undesirable gas or liquid discharges. These seals should be strong enough to resist pressure, temperature, and vibrations within the devices. A proper seal is essential to maintain the integrity of a mechanical system and ensure that it operates efficiently. A gasket can also help reduce vibration and noise and prevent the entry of contaminants such as dust and dirt. Also, bumper is an integrated structure attached to the front and rear ends of motor vehicles, to absorb impact on collision and minimizing repair cost. Numerous development improvement in material and technologies as well as greater focus on functionality for protecting vehicle component and improving safety have changed materials usage for bumper productions over years from plastics to bio-composite materials. Casing as enclosing shell, tube or surrounding materials are another vital application of bio-horn due to their microstructural properties. Animal horn physical and mechanical properties give an insight for its suitability to produce these aforementioned devices, having ability to be able to withstand compressed and have excellent scalability with high torque. Properties and nature of horn makes it possible for them to conform to the desired shape of the application. Aluminum alloys are outstanding in engineering application due to their ductility, toughness and resistance to fatigue. The aspirations for better, low density and inexpensive material demand changing from aluminium alloy to composite materials [8, 9]. In recent time, studies have shown that, most of animals' horn such as cow, presents excellent properties as reinforcements materials [10]. Many investigations have been carried out on biomaterial horn, in order to determine their mechanical properties and their application [7, 11]. The renewable polymers from organic products, such as starch, proteins and cellulose, have been explored. They exhibit important properties that offer new perceptions for designing unique biomaterials application [11, 12]. Among all these biodegradable natural polymers, Keratin-based materials revolutionized the field of modern biomaterials for biomedical applications due to their mechanical durability [13, 14]. Also, researches have been carried out using sheaths of cow horn to produce particle board panels and reinforced recycled aluminium alloy using composite material [15, 16]. A horn is thermoplastic in nature and can be used for many purposes in place of plastics [17]. Horn are used as a material in tools, fittings and beautification, among others. Apart from the hierarchical structures, chemical compositions of animals horns could also contribute to the mechanical properties for the design of synthetic materials with various range of engineering applications, such as safety equipment and impact systems as shown in figure 2 [18]. This study provides basic understanding of the impact and yield strengths of cattle horn for industrial used. Materials failures in operation and cost have been major worries amongst producers, which lead to development of modern materials for dissimilar engineering applications. The aim of the research is to optimizing the impact and yield strengths of cattle horn for engineering applications, based on their microstructural and mechanical Properties.

1.1 Comparisons of Plastic and Cattle horn properties

Cow horn and plastics share some similarity properties. It has good chemical resistance, excellent machinability, lightweight, resilience, stiffness, durability and higher strength that makes it ideal for the automotive and industrial applications. Cow horn has Thermoplastic property, which can be softened and malleable by heating. Animal horns are good in production of engineering materials used in automotive, medical, and aerospace industries.

Table 1: Comparisons of plastic and cattle horn properties. [19,20]

Items	Properties	Plastics (polyropylene)	Cattle horn
1	Rigid, Crystalline Thermoplastic	Good polymers	Very good polymers
2	Resistance to Acid and Chemical	Good resistance	Very good resistance
3	Tensile Strength	33.09 MPa	52.26 MPa
4	Impact Resistance	10.00KJ/m^2	16. 49KJ/m^2
5	Surface Hardness.	60-80	30-145
6	Water Absorption	less than 0.01% of its weight in water.	32.23%
7	Thermal stability	82.2^{oc}	320^{oc}
8	Machinability	Good	Very good

1.2. Theoretical Analysis of the Energy and Impact force

The materials relative deformation and displacement is directly proportional to the applied load. According to Hooke's law, an object returns to its original position or shape when applied load is removed provided is still within the elastic limit of the materials. The deforming force is applied to cow horn sample to cause stretching, compressing and bending. The cow horn sample exhibits elastic behaviour shows that small displacements of their component molecules and atoms, from normal positions is also proportional to the applied force that causes the displacement as display in Figure 1. Mathematically, force (F) is equal to extension (x) or change in length, multiply by constant of proportionality (k). The constant value depends on the dimensions, shape and kind of elastic material under use.

$$F = K.x \tag{1}$$

F = force (N)
K = stiffness constant (N/m)
X =extension (m)

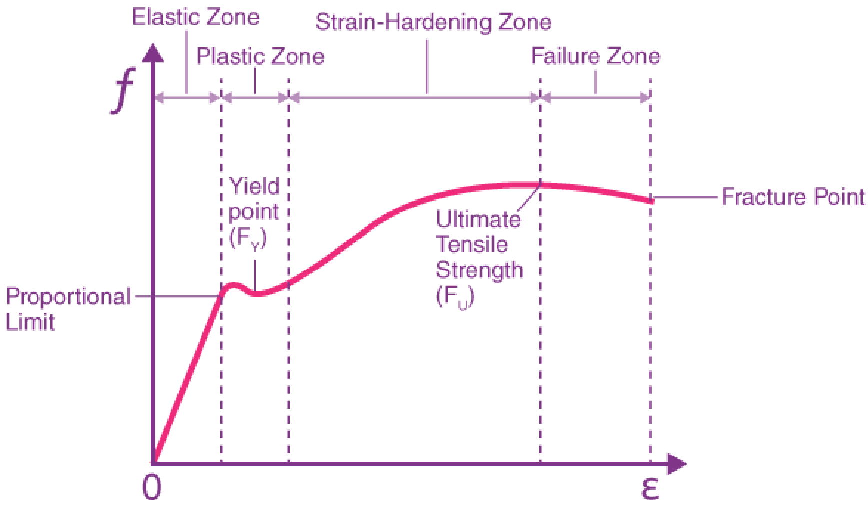

Figure 1: Hooke's law chart [21]

The cow horn displays elastic behavior up to the point of yield strength (proportion limit), the elastic materials loses elasticity and exhibits plasticity. [21]

2. MATERIALS AND METHODS

The cow horns were collected from Lugbe Abuja abattoir. Proper cleaning was carried on the horns using water and caustic soda to remove the stain blood and fat. The horns were dried and stored under control temperature before used. Tests were conducted on samples collected using pertinent ASTM standard for the study. The scanning electron microscope, universal testing machine and Izod impact machine were used for the test. Experimental tests involving both physical and mechanical were carried out to identify potentiality of the biomaterial for engineering application.

2.2. Structural Characterization

The biomaterial horn was scanned using scanning electron microscopy (SEM) to determine its microstructural nature and their arrangement. The samples were scanned using standard guide in tissue–engineering medical products characterization (ASTM F2150-19) [22] with dimension of 10 cm × 10 cm × 0.3 cm.

2.3. Density Test

The standard test used for density and specific gravity (ASTM D792-20) [23] was adopted using water displacement method. The density for each component obtained and recorded. The specimens were free from oil, grease, and other foreign matter. The procedure was repeated for the required number of specimens.

2.4. Water Absorption Test

Cow horn water absorptions rate were determined under specific conditions using ASTM D570-22 and ISO 62:2008 [24, 25] standard. The samples were cut into 50.80 mm diameter and 3.20 mm thickness according to ASTM D570-22 standard [24]. The samples were subjected to sunlight for 24 hours and allow to cool at room temperature, and weighed to nearest 0.001 g. The material was then soaked in water at 23oC ± 3oC (73.4oC ± 5.4oF) and weighed every 24 hours of the cycle. The test was repeated for one week till when the absorption substantively saturated and constant mass was achieved. The water was changed after daily used and measurement. The samples were taken out of the dish and dried with a clothe after one week. The samples were subjected to sunlight for 24 hours to dehydrate completely. The difference between dry and water absorbed weights was recorded. During the process of dehydration, each horn samples were weighed every 12 hours of time-lapse.

$$\text{The percentage of water absorption} = \frac{W1-W2}{W2}\ X\ 100 \quad (2)$$

Weight of saturated aggregates in air = W1 g and Weight of oven dry aggregates in air = W2 g

Water Absorption (%) = $\frac{W1-W2}{W2}\ X\ 100$

Water Absorption at the top part of the horn (%) = $\frac{48-41}{41}\ X\ 100$ = 17.07%

Water Absorption at the bottom part of the horn (%) = $\frac{38-28}{28}\ X\ 100$ = 35.71%

2.5. Compression Test

The behaviour of materials is determined when subjected to compressive loads. The test provides valuable insights into horn mechanical properties, which are valuable when selecting the right material for application. The circular samples of 258.00 mm^2 in area, 25.40 mm was placed on universal testing machine using force capacities of 10KN load cell according to ASTM D1621-16 [26]. The specimen was compressed at a constant rate until it fractures. The compressive load and stress were recorded along with stress-strain data.

2.6. Flexural Test

Flexural test was determined to know cow horn ability to resist breaking under bending stress. The samples were shape into rectangular shape of 3.20 mm x 12.70 mm x 125.00 mm using hacksaw according to ASTM D790-17 standard [27]. The samples were put on a support stand and load was applied at the center at specified rate.

2.7. Impact Test

The impact test was used to determine the horn material behaviour when struck by speed of object. The amount of energy absorbed and toughness of the materials were determined during loading. The test was performed on Izod impact machine using ASTM D256-23e1 standard [28]. The specimen was cut into 64.00 mm x 12.70 mm x 3.20 mm according to standard. The horn sample was positioned on a horizontal support, with a load of diamond cone depressed on the sample surface and the value of impact results recorded.

2.8. Materials Applications and Selection

The materials like gaskets and car bumpers are an integral part of engineering applications produced from sheath of cow horn, which provides a leak-proof seal between two surfaces and protect car front respectively. Therefore, selecting the suitable materials ensures the equipment operates safely and effectively. The materials must be compatible with the fluids or gases transported, withstand the pressure and temperature requirements of the application. Using right materials is crucial to prevent machine breakdown.

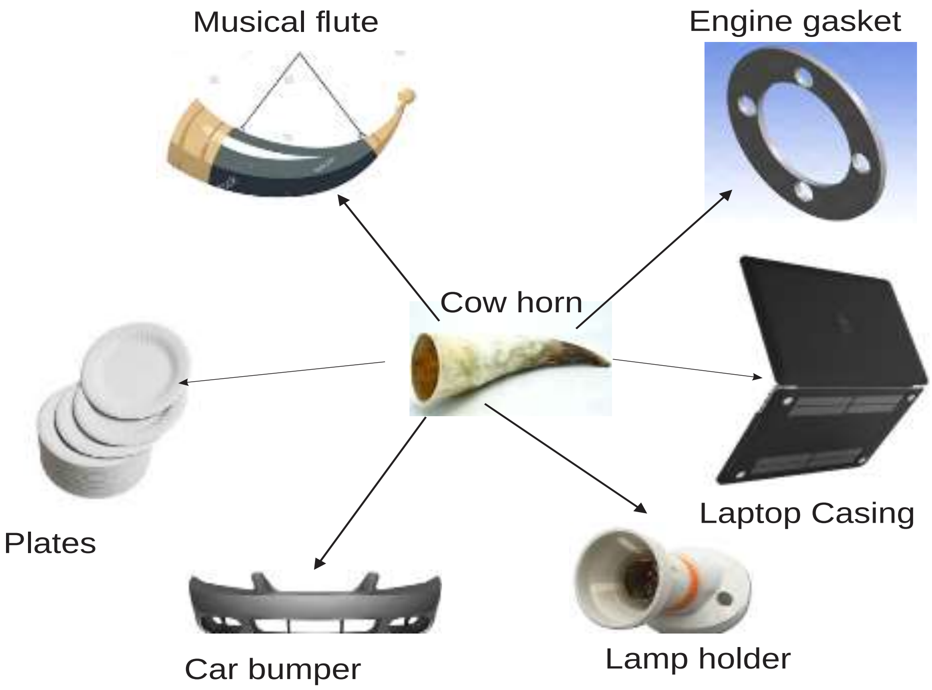

Figure 2: Cow horn engineering applications

2.9 Design of Experiments (DOE)

The experimental were analyzed using L25 Taguchi Orthogonal Array to determine the factors level of statistical significances. Three factors and five levels were considered using Taguchi Orthogonal array. The factors considered are pressure exerted on the load, Temperature on the load and chemical medium, which is chemical environment and their compatibility. The impact energy and yield strength response were measured.

3. RESULTS AND DISCUSSION

3.1 Structural Characterization

The results from scanning electron microscope (SEM), revealed microstructure tubules with their filament compressed toward the top of the horn than the bottom due to the concentration of more keratinous microstructure toward the tip of the horn. The horn contains hollow tubules penetrate in a short distance, along the longitudinal growth direction with wider pores toward the bottom lamellar as shown in Figure 3.

The horn has laminated keratin slices structure arranged with patterns distributed randomly. The keratin fibres are noticeably parallel to the longitudinal direction. During the cutting of the sample, the sheath fibres pulled out and the lamellas were separated as shown in Figure 4. The crystalline intermediate filaments are growth along the direction and curl up into hollow, entrenched in an amorphous keratin matrix.

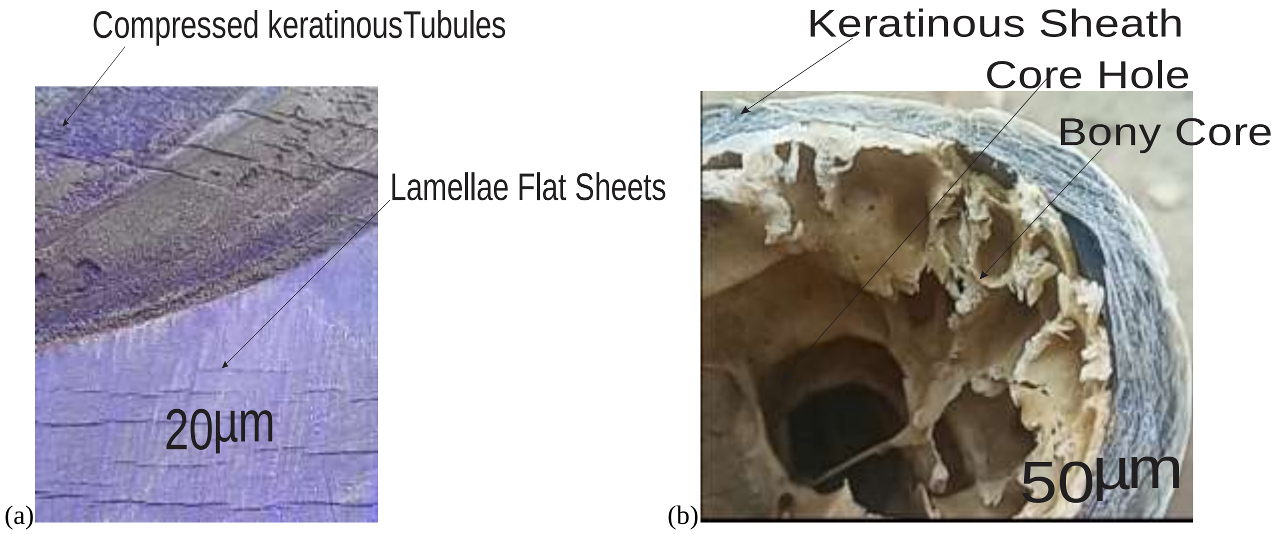

Figure 3: The microstructure of (a) top layer (b) lateral view showing inner core and outer sheath

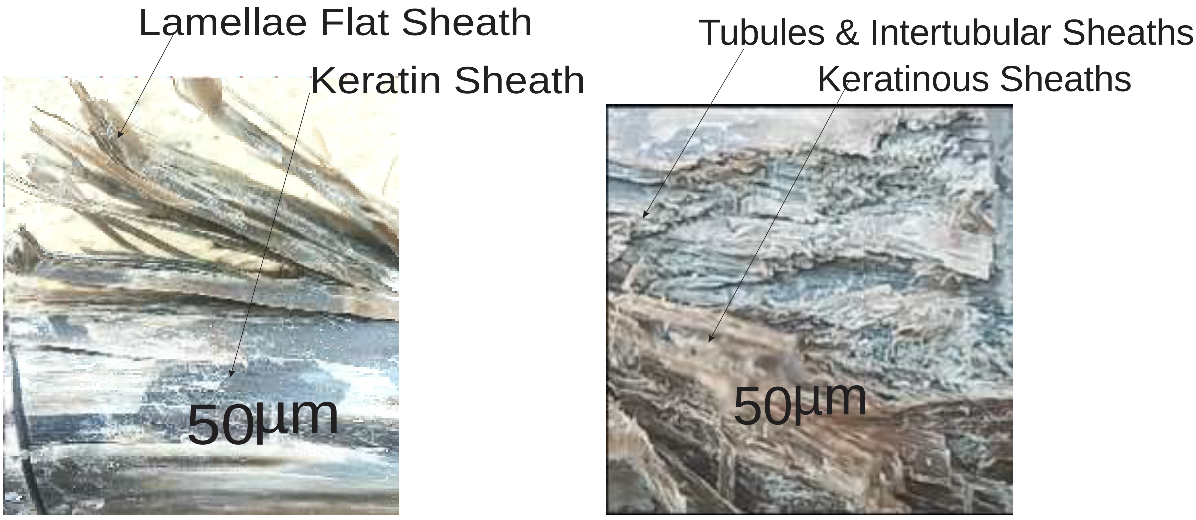

Figure 4: Micrograph of keratin fibers and the lamellas filament partially separated within the horn.

3.2 Density Test

The result of the density of cow horn showed that the top of the horn is denser than the bottom. The dry cow horn sheaths weight is 680 g to 270 g on the averages depending on the cow age and maturity.

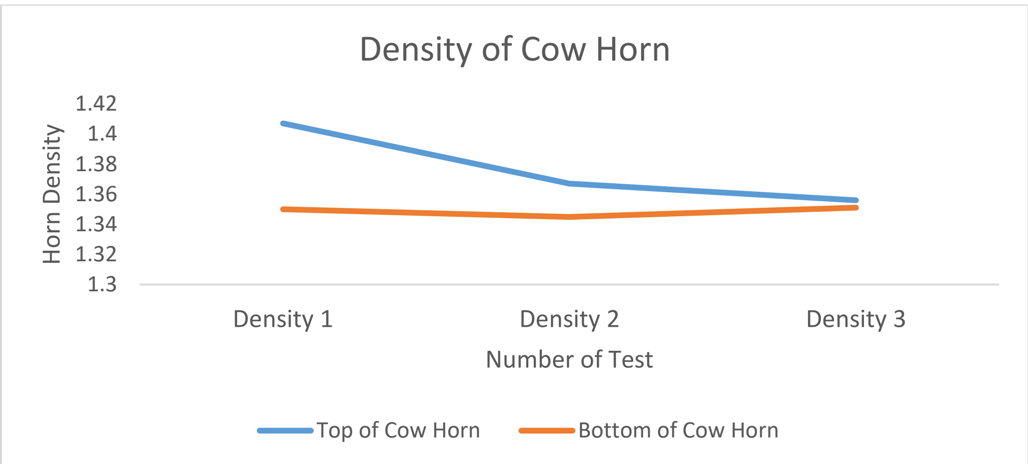

Figure 5: Density of top and bottom of cow horn

The microstructures are more compressed toward the top, which increase the pressure and decrease the volume of the object. Density is a significant property in describing the horn characteristics relative to its engineering application. The cow horn is having average density of 1.376 g/cm^3 and 1.350 g/cm^3 at top and bottom respectively showing their significant important for production of impact and protector devices.

3.3 The Absorption Test

The cow horn absorbed water under specified condition as determined by ASTM D570-22 standard [22].

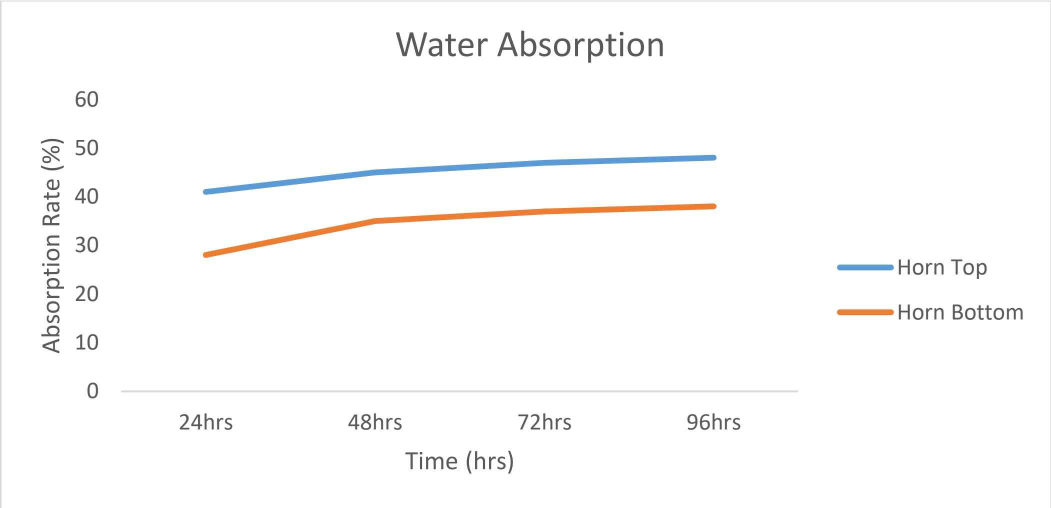

Figure 6: Water absorption between top and bottom part of cow horn

The material with more pores has high rate of water absorption and commonly considered not suitable except found satisfactory based on impacts strength and hardness. The structural nature of cow horn contributes to strength, toughness and energy absorption. The microstructures have more scattered voids, tubules that allowed more water absorption toward the bottom of the horn. The cow horn has water absorption range from 17.07% -37.71%, which give the body enough strength, toughness. However, hydrated big sheep horn revealed 27% absorption, 38% for pronghorn, and domestic horn 21% as reported by Johnson [29]. Tawe reported the mechanical behaviours of composite material manufactured with beef horn sheath's adhesives, having minimum values of 27.8 and 37% water absorption [30]. In comparison to all these, Cattle horn has suitable average water absorption that is good for engineering materials.

3.4 Compression Test

The animal horn has more strength toward the growing direction of the horn tip, having young's modulus increase from 247.47 MPa to 662.83 MPa and compressive stress increase from 626.09 to 1411.82 MPa, which show the hardest and strongest direction of the horn. The stress–strain curves depicted 10,030.97 N maximum test force, 2.13mm reduction at compressive strength and 140.69% compress at compressive strength toward tip direction. The bottom of the horn shown 10,017.51 N maximum test force, 2.53 mm reduction at compressive strength and 88.03% compress at compressive strength. The static and dynamic mechanical properties of cattle horns produced compressive modulus of 247.47-662.8 MPa and yield strength of 626.09 -1411.8 MPa [31]. These characteristics indicate that the material is suitable for a given application and more stable under a given set of pressures, which is suitable for engineering materials.

Table 2: Compressive test results for distal and bottom part of cow horn

S/N	Description	Symbol	Distal(Tip)	Proximal(Bottom)
1	Maximum compressive force(N)	FH	10030.97	10017.51
2	Compressive Stress(N/mm2)	RH	1411.82	626.09
3	Compressed of compressive strength(%)	AH	140.69%	88.03%
4	Reduction of compressive strength(mm)	dLH	2.13	2.53

The horns showed a long plastic region with nearly constant stress, which attributed to delamination and gradual buckling of lamellae, facilitating a large deformation without change of stress level along the top and bottom.

3.5 Flexural Test

The mechanical properties vary along the direction of the sheath, with more flexural resistance at the top of cow horn than the bottom as shown in Table 3 and 4.

Table 3: Flexural test for top longitudinal and transverse part of cow horn

S/N	Description	Symbol	Longitudinal	Transverse
1	Maximum bending force(N)	FH	565.27	256.89
2	Bending Stress(N/mm2)	RbB	1831.4	148.0
3	Edge fibre extension at maximum force (%)	AbB	2.11	8.55
4	Deflexion at maximum force (mm)	fAbB	3.95	13.03
5	Bending stress at sample break (N/mm2)	RBR	1831.4	126.1
6	Deflexion at sample break (mm)	fAbR	3.95	23.06

Table 4: Flexural test for bottom longitudinal and transverse part of cow horn

S/N	Description	Symbol	Longitudinal	Transverse
1	Maximum bending force(N)	FH	615.14	458.10
2	Bending Stress(N/mm2)	RbB	131.4	0.4
3	Edge fibre extension at maximum force (%)	AbB	7.31	59.42
4	Deflexion at maximum force(mm)	fAbB	6.87	4.63
5	Bending stress at sample break (N/mm2)	RBR	76.9	0.4
6	Deflexion at sample break (mm)	fAbR	9.77	6.78

The flexural tests conducted revealed varying feature in cattle horn sheaths as shown in figure 8.0. The horn withstood the applied force to reasonable extent before ruptured, due to keratinization and microstructures degrees along the parts. The flexural results show that cow horn has good loads bearing of bending stress and flex modulus of 989.7 N/mm2 and 2587.19 N/mm2 respectively, which is upright for engineering materials.

3.6 Impact Test

The mechanical impact property varies along the cow horn orientation, due to microstructural arrangement along the shape. The microstructure is more compressed with high density toward the tip of the horn than the proximate, which makes the top having higher resilience energy than the bottom as reported in Table 5. The drop weight of 5 kg with height varied from 0 to 0.74 m.

Table 5: Impact test on cow horn

Alignment	Top		Bottom	
	TRANSVERSE	LONGITUDINAL	TRANSVERSE	LONGITUDINAL
ENERGY (J)	2.00	2.00	1.99	2.00
RESILIENCE KJ/m^2	16.493	16.502	16.485	16.493
ANGLE	3.0	2.1	4.2	3.3
Sp m/s	2.867	2.867	2.872	2.875
Hardness	30.95	72.50	30.50	53.00

The horn sheath exhibited resistance to impacted load with a little crack and typical ductile fracture, due to their structure and property that varies along the parts. The resilient energy of 16.485 kJ/m2 to 16.502 kJ/m2 indicates the level of impact cow horn possess which give the materials usefulness as engineering materials. The gradient variations of the impact, hardness, stiffness and strength in a horn sheath could be accredited to level of keratinization in the top and bottom parts. The horn contains multi scale structure including wavy shape interface, keratinized fiber and tubular structure that contributed to the impact strength. The Mechanical Behaviors of Caprinae Horn Sheath under Pendulum Impact revealed by Yang exhibited 16 kg/m2 impact strength and animal horn potentiality [32,33]. In comparison to other materials, the resilient of Bovidae horns are apparent. They are more resilient to stress than most other biological and even synthetic materials [34]. The results from both impact test show that cow horn having significant value to produce engineering materials.

3.7 The Optimization of Data Response

Optimizing the impact and yield strengths of cattle horn for engineering applications requires some factors to be considered, such as temperature, pressure and chemical compatibility. Other factors such as thickness, stress to seal, storage and handling are influential in some unique applications and equipment.

Table 6: The Taguchi array L25 display factors and response of the process

Row	Medium (Chemical Compatibility)	Temperature[℃]	Pressure[MPa]	Impact strength [KJ/mm^2]	Yield strength [MPa]	SNRA1	MEAN1
1	1	10	40	16.53	52.26	26.9616	34.395
2	1	40	80	15.87	51.25	26.6242	33.560
3	1	70	120	14.95	50.34	26.1360	32.645
4	1	100	160	14.03	48.57	25.6034	31.300
5	1	130	200	13.75	46.55	25.4131	30.150
6	2	10	80	13.01	30.01	24.5479	21.510
7	2	40	120	12.85	27.34	24.3215	20.095
8	2	70	160	12.10	25.67	23.7946	18.885
9	2	100	200	11.75	21.34	23.2610	16.545
10	2	130	40	11.03	19.25	22.6288	15.140
11	3	10	120	10.86	15.47	21.9869	13.165
12	3	40	160	10.12	12.56	20.9412	11.340
13	3	70	200	9.84	11.57	20.5066	10.705
14	3	100	40	9.17	10.43	19.7706	9.800
15	3	130	80	8.92	9.45	19.2507	9.185
16	4	10	160	8.23	8.24	18.3133	8.235
17	4	40	200	7.85	7.65	17.7839	7.750
18	4	70	40	7.08	6.35	16.5024	6.715
19	4	100	80	6.79	5.42	15.5493	6.105
20	4	130	120	6.17	4.55	14.2846	5.360
21	5	10	200	5.86	3.64	12.8152	4.750
22	5	40	40	5.03	2.53	10.0932	3.780
23	5	70	80	4.67	2.05	8.4801	3.360
24	5	100	120	3.56	1.85	7.3155	2.705
25	5	130	160	3.01	1.32	4.6579	2.165

The optimum performance value of the response produced highest impact strength of 16.53 KJ/mm^2 and Yield strength of 52.26 MPa using, air medium (1), temperature (10℃) and pressure (40MPa) for factors. In the analysis, chemical compatibility produced the largest optimum value and contributory factor, with the highest delta and lowest rank as shown in Table 7.

Table 7: Response from signal to noise ratios

Level	Medium	Temperature	Pressure
1	26.148	20.925	19.191
2	23.711	19.953	18.890
3	20.491	19.084	18.809
4	16.487	18.300	18.662
5	8.672	17.247	19.956
Delta	17.475	3.678	1.294
Rank	1	2	3

Also the optimum performance value of the response from impact and yield strength analysis producing signal to noise ratio (SNR) using Taguchi method. In the analysis, chemical compatibility produced the largest optimum value, being the highest delta and rank as the main contributory factor to the process, follow by temperature and pressure. From the results, medium produced better signal to noise ratio with the highest value, larger is better and highest response characteristics value.

The regressions Equation (3) is:

$$IS = 19.0 - 2.61\,M - 0.0198\,T - 0.000675\,P \tag{3}$$

IS = Impact Strength
M = Medium
T = Temperature
P = Pressure

S = 0.249813 R-Sq = 99.6% R-Sq(adj) = 99.6%

The main effect exists when different levels of a factor affect the characteristics differently, by plotting the characteristic average for each factor level. The medium line on the plot is not horizontal, indicating main effect and different levels of factor affect the characteristic differently. The larger difference in vertical position plotted points, the larger magnitude of main effect. The pressure line closed to horizontal, showing no main effect. The medium has higher significant variable and signal-to-noise ratios than temperature and pressure.

4. CONCLUSION

The horn's superior mechanical and thermal properties make it a viable alternative to synthetic materials in impact-resistant applications. The horn structure contains keratin with lamellae tubules laying over each other along growing direction. Horn has microstructures properties such as: density, water absorption, compression, flexural and impact, that contributed to its engineering applications. Horn has density of 1.303 g/mm2 to 1.376 g/cm3, 1,018.96 MPa compressive stress and 981.4MPa bending stress that contributed to the materials performance. The properties variations of the horns are attributed to the concentration of keratin substance along the body parts. The resilient energy of 16.485 kJ/m^2 indicates the level of impact cow horn possess which give the materials usefulness as engineering materials. The animal horn has more strength toward the growing direction of the horn tip, having young's modulus increase from 247.47 MPa to 662.83 MPa and compressive stress increase from 626.09 to 1411.82 MPa, which show the hardest and strongest direction of the horn. The gradient variations of the impact and strength in a horn sheath could be accredited to level of keratinization in the top and bottom parts. The horn contains multi scale structure including wavy shape interface, keratinized fiber and tubular structure that contributed to the impact strength which could be used in automotive and aerospace applications. The materials can become an alternatives material for engineering applications, due to their excellent mechanical properties.

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