# Effect of Bone Composition and Apparent Density on Inhomogeneity in Energy Dissipation during Tension

N.K. Sharma, Swati Sharma, D.K. Sehgal, and R.K. Pandey

*Abstract*—**In this study the inhomogeneity in energy dissipation during tensile deformation of cortical bone was analyzed with the help of toughness and plastic work parameters. The compositional parameters were also determined for corresponding locations of bone diaphysis to observe their effect on elastic and plastic part of energy dissipation. The plastic part of energy dissipation was found to be mainly influenced by the compositional parameters of cortical bone. This study suggests that the locational variation in energy dissipation along bone diaphysis is mainly controlled by the deformation mechanisms that take place during the plastic deformation of cortical bone.**

*Index Terms*—**Bone composition, Bone diaphysis, Inhomogeneity, Plastic work, Toughness**

## I. Introduction

BONE, a mixture of ductile protein polymer (collagen) and brittle calcium phosphate ceramic (hydroxyapatite), is considered as a remarkable natural material that has the ability to repair itself and to adapt to its mechanical environment. The mechanical properties of cortical bone are found to be significantly correlated to its compositional parameters such as minerals, organics, water, and density [1-7]. The locational variation in these compositional parameters along bone diaphysis is the main cause of mechanically heterogeneous nature of bone. Various earlier studies have been conducted to analyze the elastic heterogeneity in bone material [8-13]. These studies are somewhat useful for the development of numerical models used in the design of orthopedic implants and study of adoptive bone remodeling. However, bone material is considered to have sufficient amount of nonlinearity during deformation and failure [14-17]. Therefore, for the development of improved prosthetic implants and detailed study of bone remodeling, it is essential to incorporate plastic inhomogeneity to the numerical modeling and for the mechanical assessment of cortical bone.

Different other studies and numerical models are also used to assess the failure of cortical bone [18,19]. This assessment is important from both the engineering and clinical point of view in order to understand the quality of bone. Failure of bone is characterized by dissipation of stored energy from an applied load and since the bone material is mechanically heterogeneous the amount of energy dissipation may be different at different anatomic locations. The locational effect of bone compositional parameters and apparent density to energy dissipation is also obvious. In view of this, the investigation regarding the effect of bone composition and density to quantitative assessment of variation in energy dissipation at different locations of cortical bone diaphysis is important for detailed analysis of overall bone quality.

Toughness has been a key measure of bone quality [20] and is used to analyze the effect of compositional parameters on bones of different groups (according to age, gender, species etc) [21,22]. While toughness incorporates the total energy (elastic as well as plastic) until failure, the plastic work measures the energy dissipated during post-yield deformation of bone. These two parameters can be used together for detailed investigation of bone deformation behavior.

In the present work toughness and plastic work parameters are used to provide an estimate of inhomogeneity in energy dissipation along cortical bone diaphysis for tensile deformation of bone. Further, the influence of bone density and composition (mineral, organic and water content) on the locational variation in the amount of energy dissipation has been investigated.

## II. Materials and Method

The present study has been conducted in the tibiae cortical bones obtained from young bovine of age about 36 months. After removal of bone tissue from the body the surrounding soft tissue was removed and bone tissue was wrapped in gauze, soaked in normal saline, wrapped with plastic wrap and placed in sealed, airtight plastic bags. These plastic bags were placed in freezer and stored at -20°C within 1 hr after the bone tissues had been harvested. The bones were kept hydrated in saline upon removal from the freezer and during all stages of tissue preparation. For specimen preparation the epiphyses ends of the long bone were removed using vertical band saw leaving only the diaphysis section. The round cylindrical edges of the diaphysis were flattened into flat rectangular prismatic edges with the help of a belt sander. After flattening, the whole diaphysis of the cortical bone was sectioned into three equal segments namely; upper, middle and lower parts of the bone diaphysis.

Manuscript received March 23, 2013.
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Different anatomic quadrants (A = anterior, M = medial, P = posterior and L = lateral) of bone diaphysis were identified and marked accordingly on each one third segment of the diaphysis. Each segment of the diaphysis was then subsequently sectioned into number of specimens according to different anatomic quadrants. The preparation of specimens from different anatomic locations of the bone diaphysis is shown in Fig. 1. In all 15 dumbbell shape stripe type longitudinal tensile specimens were prepared from different locations (upper, middle and lower bone diaphysis) of bovine tibiae cortical bone with thickness 2.5 mm, gauge length 25 mm, gauge width 4 mm and total length 80 mm. All these specimens were stored at room temperature in a solution of 50% saline and 50% ethanol at all time until testing. In order to keep the specimens wet and to avoid heating during cutting and polishing a constant spray of water was supplied. The uniaxial tensile tests were performed on MTS 858 Table Top Universal Testing Machine and a miniature extensometer of gauge length 5 mm was used to measure strain during testing. These tensile tests were performed at a low displacement rate of 1.8 mm/min.

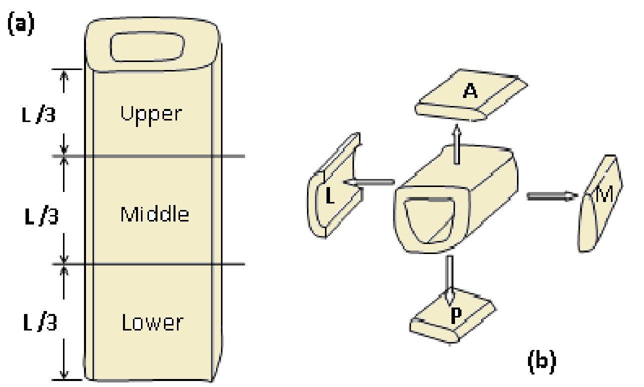


Fig.1 Schematic diagram showing sectioning of cortical bone diaphysis for preparation of tensile test specimens from different anatomic locations of the bone diaphysis (a) the flattened cortical bone diaphysis was sectioned into three equal length (L/3) segments. (b) each segment of the diaphysis was subsequently sectioned into four parts according to different anatomic quadrants (A = anterior, M = medial, P = posterior, and L = lateral) for further preparation of samples.

The stress-strain curves in case of uniaxial tensile test for longitudinal specimens obtained from different locations of the bone diaphysis are shown in Fig. 2. The yield strength values were obtained corresponding to 0.2% permanent set. The values of toughness ($U_t$) and plastic work ($W_p$) were determined respectively by calculating the area under the entire true stress -strain curve and the true stress - plastic strain curve. The formulas used for calculation of toughness and plastic work are given respectively in (1) and (2).

$$U_t = \int_0^{\varepsilon_f} \sigma \, d\varepsilon \qquad (1)$$

$$W_p = \int \sigma \, d\varepsilon^p \qquad (2)$$

where $\varepsilon_f$ and $\varepsilon^p$ are failure and plastic strain respectively.

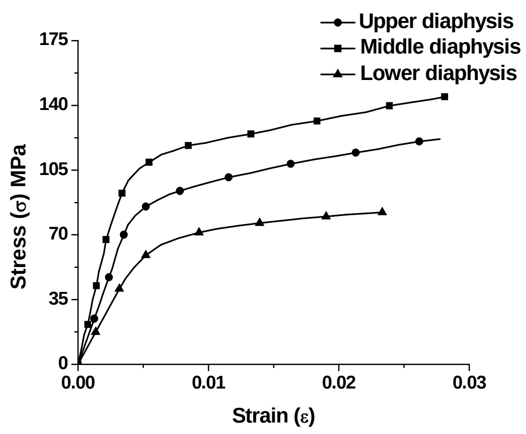


Fig.2 Stress-strain curve for different locations of bone diaphysis

To analyze the apparent density and composition of cortical bone at different anatomic locations of bone diaphysis, rectangular samples were cut from different test specimens using diamond cutter (Isomet 4000). From each tested specimen, three samples were randomly selected and analyzed to obtain the values of bone composition parameters and apparent density for that particular specimen. The dimensions of these samples were measured using a digital caliper to calculate their volumes. The samples were hydrated overnight and after weighing the samples the wet weight was recorded. After measuring the wet weight these specimens were placed in acetone for overnight and then placed in an oven at 60° C for 24 hrs along with silicate gel to remove the remaining moisture. These samples were then weighed to measure the dry weight. The samples were then placed in a furnace at 600° C for 24 hrs. After removing the samples from the furnace, they were placed in the desiccator to reach the room temperature and finally the weight of residue i.e. ash was recorded. For these samples different compositional parameters were calculated using the different equations from (3) to (9);

Wet density, $$\rho_w = \frac{\text{Wet weight}}{\text{Volume}} \qquad (3)$$

Dry density, $$\rho_d = \frac{\text{Dry weight}}{\text{Volume}} \qquad (4)$$

% Mineral, % Min = $$\frac{\text{Ash weight}}{\text{Dry weight}} \times 100 \qquad (5)$$

% Organic (dry),

$$\%\,Org_d = \frac{\text{Dry weight} - \text{Ash weight}}{\text{Dry weight}} \times 100 \qquad (6)$$

% Ash = $$\frac{\text{Ash weight}}{\text{Wet weight}} \times 100 \qquad (7)$$

% Organic (wet),

$$\%\,Org_w = \frac{\text{Dry weight} - \text{Ash weight}}{\text{Wet weight}} \times 100 \qquad (8)$$

$$\%\,H_2O = \frac{\text{Wet weight} - \text{Dry weight}}{\text{Wet weight}} \times 100 \qquad (9)$$

ISBN: 978-988-19253-5-0
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

(9)

In (7), % Ash is normalized with wet weight which can be referred as apparent mineral content, whereas as per (5), % Mineral can be referred to as material mineral content and is independent of porosity. The same concept is applied for % $Org_d$ and % $Org_w$.

## III. Results

The toughness and plastic work values of bovine tibia were calculated as described above for three different locations of bone diaphysis. Table I lists the yield strength ($\sigma_{ys}$), toughness ($U_t$) and plastic work ($W_p$) of upper, middle and lower locations of cortical bone diaphysis determined with the help of uniaxial tensile test in longitudinal direction. Table II lists the corresponding values of wet ($\rho_w$) and dry ($\rho_d$) densities, % Ash, % Mineral (% Min), % Organic wet (% $Org_w$), % Organic dry (% $Org_d$) and % Water ($H_2O$).

The elastic part of energy dissipation ($U_e$) was calculated by subtracting plastic work ($W_p$) from toughness ($U_t$) and the corresponding values of elastic energy dissipation ($U_e$) are also reported in Table 1.

TABLE I
Yield Strength and Energy dissipation Parameters for Different Locations of Cortical Bone Diaphysis

| | Upper | Middle | Lower |
|---|---|---|---|
| $\sigma_{ys}$ (MPa) | 90.1±3.05[b] | 111.0±7.05[a] | 67.0±4.52[a,b] |
| $U_t$ (kJ/m$^3$) | 2675.1±287.6[b] | 3311.5±246.5[a] | 1531.7±184.6[a,b] |
| $W_p$ (kJ/m$^3$) | 2278.9±187.0[b] | 2945.2±127.6[a] | 1257.5± 68.8[a,b] |
| $U_e$ (kJ/m$^3$) | 396.2±137.2 | 366.3±137.1 | 274.2±118.2 |

[a]Indicates a statistically significant difference compared with upper diaphysis ($p < 0.05$)
[b]Indicates a statistically significant difference compared with middle diaphysis ($p < 0.05$)

TABLE II
Bone Densities and Compositional Parameters for Different Locations of Cortical Bone Diaphysis

| | Upper | Middle | Lower | ANOVA |
|---|---|---|---|---|
| $\rho_{wet}$(g/cm$^3$) | 2.09 ± 0.01[b] | 2.19 ± 0.04[a] | 2.05 ± 0.05[b] | $p < 0.05$ |
| $\rho_{dry}$ (g/cm$^3$) | 1.89 ± 0.02[b] | 2.01 ± 0.02[a] | 1.86 ± 0.05[b] | $p < 0.05$ |
| %Ash | 63.63 ± 0.40[b] | 64.87 ± 0.70[a] | 62.28 ± 0.66[a,b] | $p < 0.05$ |
| % Min | 70.38 ± 0.17 | 70.63 ± 0.76 | 68.83 ± 0.30[a,b] | $p < 0.05$ |
| % $Org_w$ | 26.77 ± 0.18 | 26.98 ± 0.77 | 28.20 ± 0.33[a,b] | $p < 0.05$ |
| % $Org_d$ | 29.61 ± 0.17 | 29.37 ± 0.76 | 31.16 ± 0.30[a,b] | $p < 0.05$ |
| % $H_2O$ | 9.59 ± 0.48[b] | 8.14 ± 0.61[a] | 9.52 ± 0.80[b] | $p < 0.05$ |

[a]Indicates a statistically significant difference compared with upper diaphysis ($p < 0.05$)
[b]Indicates a statistically significant difference compared with middle diaphysis ($p < 0.05$)

A paired t-test analysis was conducted to compare the results obtained for different locations of bone diaphysis. Analysis of variance (ANOVA) test was conducted to analyze the variation in mean values of compositional parameters and densities for different diaphysis locations.

The values of yield strength, toughness and plastic work as reported in Table 1, were found to be significantly greater ($p < 0.001$ for $\sigma_{ys}$ and $p < 0.0001$ for $U_t$ and $W_p$) for the middle location as compared to the upper location of bone diaphysis. The latter values for upper location were observed to be significantly greater ($p < 0.001$ for $\sigma_{ys}$ and $p < 0.0001$ for $U_t$ and $W_p$) as compared to the lower location of bone diaphysis. However, no significant differences were found in elastic part of energy dissipation ($U_e$) for different locations of bone diaphysis.

Correlations between yield strength, and different energy parameters ($U_t$, $W_p$, and $U_e$) are presented in Table III. The correlations between the latter parameters and bone compositional parameters are presented in Tables IV a, b.

TABLE III
Correlations ($r$) among Yield Strength, Toughness, Plastic Work and Elastic part of Energy Dissipation

| | $\sigma_{ys}$ | $U_t$ | $W_p$ | $U_e$ |
|---|---|---|---|---|
| $\sigma_{ys}$ | 1 | 0.87[a] | 0.92[a] | 0.15 |
| $U_t$ | 0.87[a] | 1 | 0.99[a] | 0.55[a] |
| $W_p$ | 0.92[a] | 0.99[a] | 1 | 0.41 |
| $U_e$ | 0.15 | 0.55[a] | 0.41 | 1 |

[a]Statistical significance p < 0.05

TABLE IV (a)
Correlations ($r$) among Yield Strength, Toughness, Plastic Work, Elastic part of Energy Dissipation and Bone Compositional Parameters (densities, % Ash, and % Min)

| | $\rho_w$ | $\rho_d$ | % Ash | % Min |
|---|---|---|---|---|
| $\sigma_{ys}$ | 0.79[a] | 0.82[a] | 0.84[a] | 0.76[a] |
| $U_t$ | 0.65[a] | 0.67[a] | 0.80[a] | 0.80[a] |
| $W_p$ | 0.73[a] | 0.75[a] | 0.84[a] | 0.82[a] |
| $U_e$ | -0.11 | -0.08 | 0.19 | 0.26 |

[a]Statistical significance p < 0.05

TABLE IV (b)
Correlations ($r$) among Yield Strength, Toughness, Plastic Work, Elastic part of Energy Dissipation and Bone Compositional Parameters (% $Org_w$, % $Org_d$, and % $H_2O$)

| | %$Org_w$ | %$Org_d$ | % $H_2O$ |
|---|---|---|---|
| $\sigma_{ys}$ | -0.60[a] | -0.76[a] | -0.59[a] |
| $U_t$ | -0.68[a] | -0.80[a] | -0.47 |
| $W_p$ | -0.69[a] | -0.82[a] | -0.51 |
| $U_e$ | -0.27 | -0.26 | -0.01 |

[a]Statistical significance p < 0.05

Significant positive correlations between yield strength, toughness, and plastic work were found for bovine tibia bone (Table III, Fig. 3). However, the amount of elastic part of energy dissipation ($U_e$) was only found to be significantly correlated with the toughness of cortical bone. Both toughness and plastic work increased with increasing densities (wet and dry), % Ash, and % Mineral (Table IV a, Figs. 4 and 5), whereas, decreased with increasing wet and dry percentages of Organic (Table IV b).

The elastic and plastic parts of energy dissipation were compared with each other for different locations of bone diaphysis as shown in Fig. 6. The plastic part of energy dissipation was found to be 3.2 to 13.1 times greater as compared to the corresponding elastic part of energy

ISBN: 978-988-19253-5-0
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

dissipation for different diaphysis locations. The variation in ratios of plastic to elastic part of energy dissipation for upper middle and lower locations of bone diaphysis is shown in Fig. 7 with the help of "box and whisker" plots. The mean values of these ratios for different diaphysis locations were not found to be significantly different (ANOVA, $p > 0.05$).

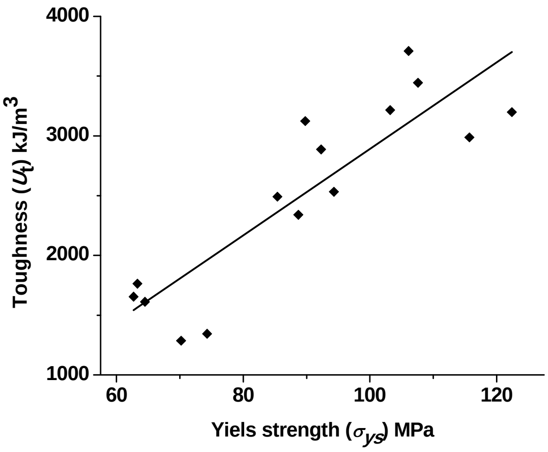


Fig.3 Variation in toughness ($U_t$) with yield strength ($\sigma_{ys}$) for bovine tibia. The data indicates that $U_t$ increases with increasing $\sigma_{ys}$ ($r^2$ = 0.76, $p$ < 0.0001). $U_t = 36.17\ \sigma_{ys} - 726.20$.

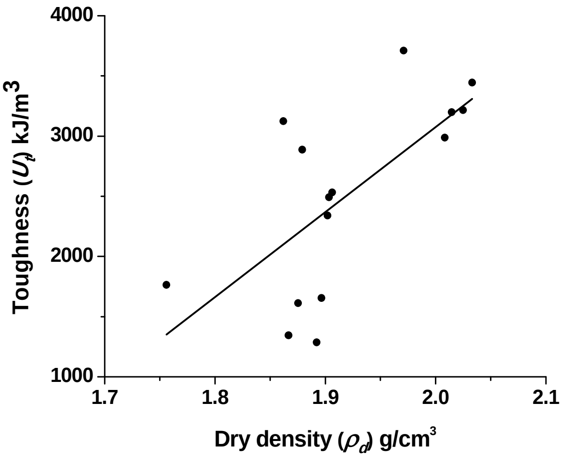


Fig.4 Variation in toughness ($U_t$) with dry density ($\rho_d$) for bovine tibia. The data indicates that $U_t$ increases with increasing $\rho_d$ ($r^2$ = 0.45, $p$ < 0.0059). $U_t = 7064.45\ \rho_d - 11053.82$.

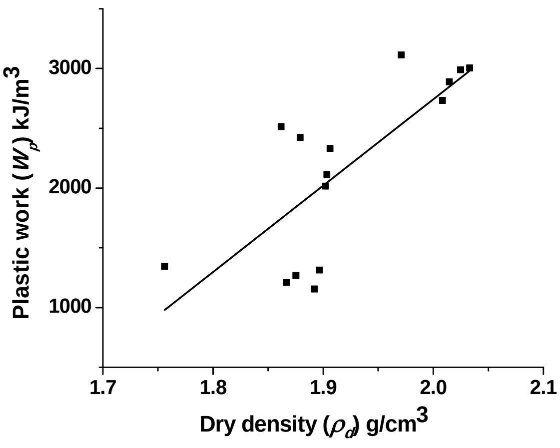


Fig.5 Variation in plastic work ($W_p$) with dry density ($\rho_d$) for bovine tibia. The data indicates that $W_p$ increases with increasing $\rho_d$ ($r^2$ = 0.57, $p$ < 0.0011). $W_p = 7225.50\ \rho_d - 11708.52$.

Multiple regression analysis was also carried out using more than one significantly correlated variables for estimating toughness and plastic work. The model with five compositional parameters (wet and dry density, % Ash, % Min, % Org$_w$) has $R^2$ = 0.79, adjusted $R^2$ = 0.67 ($p$ < 0.0075) for toughness and $R^2$ = 0.87 adjusted $R^2$ = 0.79 ($p$ < 0.0010) for plastic work.

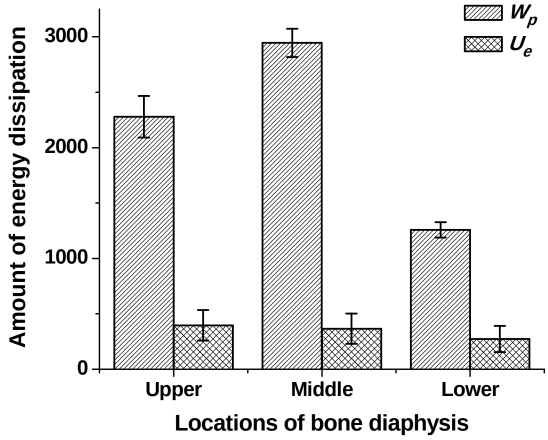


Fig.6 Comparison of elastic ($U_e$) and plastic ($W_p$) part of energy dissipations for different locations of bone diaphysis.

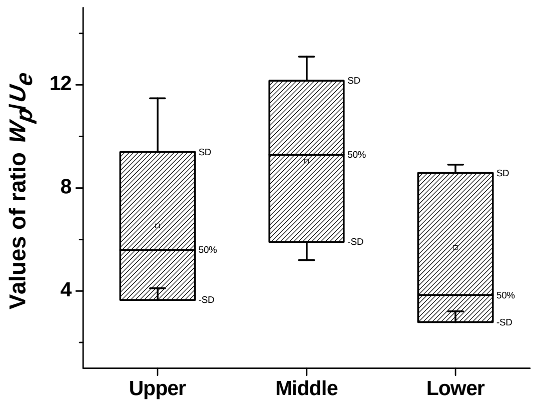


Fig.7 Comparison of variation in ratios of plastic to elastic dissipation energy ($W_p/U_t$) for different diaphysis locations of cortical bone

The correlation equations obtained from multiple regression analysis for determination of toughness and plastic work are given respectively as (10) and (11).

$$U_t = -3.5\times10^5\rho_w + 3.9\times10^5\rho_d - 1.4\times10^4\%Ash + 1.9\times10^4\%Min + 6.3\times10^3\%Org_w - 6.1\times10^5 \quad (10)$$

$$W_p = -2.9\times10^5\rho_w + 3.3\times10^5\rho_d - 1.2\times10^4\%Ash + 1.7\times10^4\%Min + 6.5\times10^3\%Org_w - 6.2\times10^5 \quad (11)$$

## IV. Discussion

The structural organization of different components was not considered in this study. Further the amount of energy dissipation was assumed to be homogeneous for each one third part of the bone diaphysis. The correlations between compositional parameters and amount of energy dissipation were established by collecting data from different locations of the bovine tibia diaphysis. However, in most of the earlier studies these data were computed for different groups

ISBN: 978-988-19253-5-0
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

of cortical bone to analyze the effect of age, gender, disease, preservation methods etc on mechanical properties of bone. This makes it difficult to compare the results of other studies and the current study.

The values of toughness and plastic work were observed to be maximum and minimum at respectively the middle and lower locations of bone diaphysis. The amount of plastic deformation was found to be much higher (3 to 13 times) as compared to the elastic part. This observation is consistent to the earlier results [14,15] and indicates that plastic part of energy dissipation dominates the bone toughness.

The amount of elastic energy dissipation was found to be statistically same for all three locations of bone diaphysis. Further it was not affected by the apparent values of bone compositional parameters. This shows that the mechanism of elastic deformation is same for locations of bone diaphysis irrespective of the mechanical heterogeneity (however, it is difficult to comment on the role of structural organization of these constituents in elastic deformation).

Both toughness and plastic work were found to be significantly correlated with the compositional parameters and densities in a similar manner. However, stronger correlations were observed between the latter parameters and the plastic work (Table IV a, b). The plasticity in bone materials is supposed to occur from multiple, concurrent deformation mechanisms such as breaking of hydrogen bonds and intermolecular sliding [23]. Strong correlations between compositional parameters and plastic work suggest that these parameters have major effect on the plastic deformation mechanisms at different locations of cortical bone diaphysis and subsequently result in heterogeneity in energy dissipation.

The percentage of water may be considered as an indicator of porosity and mineralization. In this study both toughness and plastic work were found to be negatively correlated with % $H_2O$, however, this correlation was nonsignificant for the present case. The previous researches suggest that water content does affect the fracture toughness of bone as wet bone has greater energy absorption than dry bone [24,25], but there are no data directly comparable to the results presented in this study.

## V. Conclusion

The effect of bone compositional parameters and densities on inhomogeneity in energy dissipation along bovine tibia bone diaphysis was analyzed in this study. The amount of plastic energy dissipation was found to be dominant during bone deformation. Irrespective of the elastic work, plastic work was found to be significantly different for different locations of cortical bone. The effect of variation in compositional parameters to the plastic deformation mechanism at different diaphysis locations was considered to be the main cause of inhomogeneity in energy dissipation during tensile deformation of cortical bone.

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ISBN: 978-988-19253-5-0
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)