Published in final edited form as:

Bone. 2012 June ; 50(6): 1275–1280. doi:10.1016/j.bone.2012.02.018.

EFFECTS OF MINERAL CONTENT ON THE FRACTURE PROPERTIES OF EQUINE CORTICAL BONE IN DOUBLE-NOTCHED BEAMS

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Abstract

We recently developed a method to measure cortical bone fracture initiation toughness using a double-notched beam in four-point bending. This method was used to test the hypothesis that mineralization around the two notch roots is correlated with fracture toughness and crack extension (physical damage). Total energy absorbed to failure negatively correlated with average mineralization of the beam ($r^2=0.62$), but not with notch root mineralization. Fracture initiation toughness was positively correlated to mineralization at the broken notch root ($r^2=0.34$). Crack length extension at the unbroken notch was strongly negatively correlated with the average mineralization of the notch roots ($r^2=0.81$) whereas crack length extension at the broken notch did not correlate with any of the mineralization measurements. Mineralization at the notch roots and the average mineralization contributed independently to the mechanical and damage properties. The data are consistent with an hypothesis that a) high *notch root* mineralization results in less stable crack length extension but high force to initiate unstable crack propagation while b) higher *average* mineralization leads to low post-yield (and total) energy absorption to failure.

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Conflict of Interest Statement: None of the authors have any financial or personal relationships with other people or organizations that could inappropriately influence (bias) this work.

Introduction

An understanding of the microstructural influences on the failure process in bone has long been sought. Despite a long history of investigations there remain many questions about the exact relationship between bone mineralization, bone damage and bone toughness.

Bone constantly adapts to its loading conditions [1]. As a result, the accumulation of large amounts of damage is mostly avoided in healthy, living bone. This is a result of the remodeling process where old damaged bone is replaced by new undamaged tissue. In the rare instances when damage accumulates faster than it can be repaired, catastrophic fracture can occur. Damage accumulation and complete fracture can occur under high loading rates, many loading cycles, and traumatic loading. How the microstructure of bone affects the damage process has yet to be fully explained.

Many studies have been performed using various testing protocols to explore the relationship between fracture behavior and mineral content and its distribution with varying results [2–7]. It is generally agreed that increased average mineralization increases cortical bone strength and decreases measures of toughness but this is not a universal finding. For example, using cortical bone samples from female baboons, Phelps et al. did not find a correlation between fracture initiation toughness, average microhardness or average mineral content [8]. However, this study did not measure microhardness or mineral content at the notch root where crack propagation occurred. A previous study using baboon cortical tissue did find significant correlations between fracture toughness, average bone mineral density, porosity and other tensile mechanical properties [9]. As in the more recent study, local measurements of the bone mineral density at the site of crack propagation were not performed. There are many other studies of cortical bone that observed a significant correlation between average bone density and fracture toughness however none, to our knowledge, included localized measurement of mineralization at the notch root [e.g., 10, 11].

The current study was designed to test whether local bone mineralization, measured at the notch root (the site of crack extension) affects fracture initiation toughness and damage accumulation independently of average mineralization. The hypothesis was that *local* mineralization of bone at the notch root of a fracture specimen plays a significant role in predicting the fracture toughness of the specimen. A recently developed doublenotch four point bending specimen (DN4PB) was used to measure the fracture initiation toughness of cortical bone [12] and quantitative backscattered electron imaging (qBSE) to quantify tissue mineralization and post-testing crack lengths.

Materials & Methods

Fourteen cortical bone beams ($\sim 2 \times 2 \times 22$ mm) were cut using an Exakt cutting system (Exakt Technologies, Oklahoma City, OK) and a custom built specimen jig. Specimens were cut from the diaphysis of the third metacarpal (cannon) bone of three female, Thoroughbred racehorse cadavers (2, 4, and 6 years old). Beams were cut such that the long axis of the beam was parallel with the long axis of the bone. Both the left and right legs were used from

each horse. The bones were kept frozen prior to and in between machining and testing, and kept moist with tap-water during cutting.

To simulate preexisting flaws, two notches spaced 4 mm apart were cut in the cortical bone beams using a 150 μm thick diamond-coated dental cutting disk (22-mm diameter SummaDisk, Shofu Dental Corporation, San Marcos, CA) mounted to a proLIGHT 1000 CNC milling machine (Light Machines Corp., Manchester, NH). Due to vibrations during cutting the actual notch width was consistently around 240 μm with a notch root radius of 120 μm . All of the notch depths were cut to an a/W (ratio of notch depth to beam width) as close to 0.3 as possible. Notches were placed on the endosteal side of the beams so that all cracks propagated in the transverse plane from an endosteal to periosteal direction. A dial indicator (The L.S. Starrett Co., Athol, MA) was used to make three measurements (accurate to within 0.001 in) for each notch depth, which were averaged. The beam width, height, and length were measured using digital calipers (accurate to within 0.01 mm) (Mitutoyo Corp., Aurora, IL).

To measure the fracture initiation toughness of the bone, the double notch beams were loaded in 4-point bending, hence the tests are denoted DN4PB. Commercially available 4 point bending platforms (DMA 7e, PerkinElmer Life And Analytical Sciences, Inc., Norwalk, CT), with spans of 15 mm and 5 mm were used for the outer and inner supports, respectively (Fig. 1). The bending test fixture and specimens were submerged in a bath of Hanks' Balanced Salt Solution (HBSS) during testing. An ELF 3200 series (EnduraTEC Inc., Minnetonka, MN) mechanical testing system was used [13, 14].

The specimen was preconditioned before testing by applying a 1–2 N preload (equivalent to approximately 0.003–0.008 mm displacement) to each beam followed by 0.5 Hz sine wave loading at a magnitude of 0.01 mm (equivalent to approximately 5.5 N), for 100 cycles to provide for good contact between the specimen and the loading supports. Monotonic loading was performed in load-point displacement control using a constant displacement rate of 0.0008 mm/s. Displacement was continued until the load fell below 50% of the peak value. All testing was done at ambient temperature ($\sim 25^\circ\text{C}$).

Determining the Failure and Yield Forces

An accepted ASTM method [15] based on a 95% secant line was used to determine the failure force for the linearly elastic fracture mechanics (LEFM) calculations (Fig. 1). To best understand the following presentation it is important to recognize that the 95% secant line method we used to determine the *failure force* for LEFM is also the means that we used to define the *yield force*. Therefore, the *yield force* and the *failure force* will have the same numerical value. The slope of the linear portion of the curve was measured between 20% and 50% of the maximum load. The secant line with a slope of 95% of the linear fit was constructed with its intersection having the same intersection with the ordinate as the original curve fit line. The force at which the secant line intersected the data was defined as the failure force for calculating the fracture toughness[15].

Fracture Initiation Toughness

The mode I fracture initiation toughness was determined for the DN4PB specimens using our recently published methods [12]. In brief, the measured failure force was multiplied by 1.04 to account for the presence of the second notch and by 1.076 to correct for a systematic effect due to the small size of the specimen. After correction, the apparent fracture initiation toughness (K_{Co}) was calculated using the equations for a single notch four point bending specimen (SN4PB) as validated previously. The equation for the apparent toughness was,

$$K_{Co} = \gamma \frac{6F_{DN4PB}c}{2BW^{3/2}} f_{SN4PB} \left(\frac{a}{W} \right) \quad \text{Eq. 1}$$

with $\gamma = 1.04 \times 1.076$ the correction factor, B the beam width, W the beam depth, a the notch length, c the moment arm of the force (distance from the outer to inner loading points, 5 mm), F_{DN4PB} the failure force and f_{SN4PB} as used by Donadon et al. [16]:

$$f_{SN4PB} \left(\frac{a}{W} \right) = \sqrt{\pi \frac{a}{W}} \left(1.12 - 1.39 \left(\frac{a}{W} \right) + 7.32 \left(\frac{a}{W} \right)^2 - 13.1 \left(\frac{a}{W} \right)^3 + 14.0 \left(\frac{a}{W} \right)^4 \right) \quad \text{Eq. 2}$$

Quantitative Backscattered Scanning Electron Microscopy (QBSE)

To obtain a quantitative map of the mineralization levels in each damaged double-notched specimen, quantitative backscattered scanning electron microscopy (qBSE) was used [17–21]. The grayscale SEM images were converted to a calibrated atomic number map by linear calibration using the atomic numbers of known materials [22]. The standard used in the current study had nine materials: boron nitride ($Z = 6.13$), carbon ($Z = 6$), aluminum ($Z = 13$), sodium chloride ($Z = 14.64$), aluminum nitride ($Z = 10.95$), calcium carbonate ($Z = 12.57$), magnesium oxide ($Z = 10.41$), silicon dioxide ($Z = 10.80$), and titanium ($Z = 22$) (Micro-Analysis Consultants Limited, St. Ives, Cambridgeshire, United Kingdom). The standard was coated with a 250 Å film of carbon in the same manner as the specimen. The average atomic number, $\bar{Z}$, of the standard compounds was calculated using the weight fraction method [20, 23] with a weighted sum *over the chemical formula* as:

$$\bar{Z} = \frac{\sum (NAZ)}{\sum (NA)} \quad \text{Eq. 3}$$

where N is the number of atoms of each element of atomic weight A , and atomic number Z . The denominator is the molecular weight of the standard compound. Following published methods [18, 24] an image of the standard was taken before and after each image from the specimen. If the mean atomic numbers of the standard materials changed between the before and after images then the calibrations were averaged.

The fractured bone beams were embedded in benzoyl peroxide catalyzed polymethylmethacrylate under vacuum and cured at in a water bath ($\sim 95^\circ\text{C}$) for two weeks to solidify the plastic. Excess plastic was removed using a milling machine and to ensure that the top and bottom surfaces were parallel. Final surface preparation was with an Exakt polishing system (Exakt Technologies, Oklahoma City, OK) using a microcloth and a series

of silicon carbide and aluminum oxide polishing powders (Buehler Ltd., Lake Bluff, IL). A 5.0 micrometer powder was used first, and then 1.0 micrometer powder and finally a 0.05 micrometer powder was used to ensure a flat, mirror surface. The surface was sputter-coated with carbon (coat thickness of ~ 250 Å) to facilitate imaging (British Oxygen Company, Ltd., Sussex, England). Carbon film thickness was measured using polished brass substrates coated along with the specimens that show interference color changes from orange-yellow (100 Å), to orange-red (200 Å), then to light blue (250 Å), and finally blue-green (300 Å). Once the film turned light blue in color with purple on the edges the 250 Å layer had been reached.

Of the fourteen specimens, nine were examined under identical operating conditions in backscatter mode (FEI XL 30, model PW6843/00 backscatter detector, FEI, Hillsboro, OR): a brightness of 62.0, a contrast of 42.0, 18x magnification, a working distance of 12 mm, a beam accelerating voltage of 30 kV, and a spot size of 6. For the last five specimens the electron microscope began drifting substantially such that the brightness and contrast had to be adjusted for each specimen. Contrast was increased as high as 76.0 while the brightness reached a high of 46.0. Although it is ideal to keep the operating conditions the same for all specimens, the fact that images of the standards were taken before and after each bone image allows adjustment for these differences. Filament current varied from 65–95 μ A across the imaging sessions; however fluctuations in the probe current during imaging of a single specimen were not more than 5 μ A.

Preliminary imaging studies were performed using practice specimens to determine the optimum brightness and contrast so that both the standard materials and bone specimens were visible in the backscatter mode. In order to obtain the highest resolution of mineralization the operating conditions were selected to maximize the range of graylevels representing bone tissue. Once the brightness and contrast across the specimens were examined, three of the standard materials (boron nitride, carbon, and titanium) were not used in the analysis due to their atomic numbers falling far outside the range for normal bone. (The carbon and boron nitride appeared black and the titanium was oversaturated with the chosen operating parameters.)

The images were calibrated and analyzed using ImageJ (National Institute of Health, Bethesda, MD). Bone was separated from plastic using a uniform threshold on the grayscale histogram. The sharp contrast between the bone and the embedding plastic, which appeared black, provided consistency for each specimen (see Fig. 2 for an example). After discarding the unwanted 'black' pixels the weighted mean atomic number was calculated from the calibrated image.

The presence of charging at the crack faces meant that a simple average of the calibrated mineralization around the notch would not provide an accurate measure of the mineralization at the notch root. To avoid the charged regions and to obtain an appropriate sample for mineralization three 30 pixel diameter circular regions were sampled (Fig. 2). The circles were selected in areas near the notch root and the crack faces, but away from regions of obvious charging. The weighted mean atomic number for the combined circular regions was then calculated as the arithmetic average of the values. A representative

“average” mineralization for the beam was determined using a 200×200 pixel region chosen manually from between the notch roots, avoiding cracks and also large pores to the extent that it was possible.

Measuring Crack Length

The lengths of the load induced cracks (i.e., the extensions of cracks beyond the original notch length) were measured manually by a single operator (JM) using the segmented line tool in Image J. One side of the primary crack was selected from the images and traced starting from the notch root. The scale bar from the scanning electron microscopy images was used to scale each measurement to micrometers.

Energy Calculations

The pre- and post-yield energies were calculated using the area under the force-displacement curve. Pre-yield energy was defined as the energy input prior to the failure force. Area was calculated using the trapezoid rule. The energy between the failure force and peak (ultimate) force was calculated in a similar manner. To calculate the energy between the ultimate force and the end of the test, an end force had to be identified that represented failure. The end of the test was defined as the displacement at which force dropped to fifty percent of its maximum value.

Results

Separation of the notches into “broken” and “unbroken” was done visually and also according to the length of the crack extension at each notch (Figs. 2–3). The average and standard deviation of crack extension at the unbroken notch was 0.66(0.29) mm and at the broken notch it was 3.27(0.78) mm (Table 1). The broken notch was significantly longer than the unbroken notch by Student’s t test ($p < 0.0001$). Chi-square analysis gave no statistical indication ($p > 0.59$) of a preference for the specimens breaking more often at the left or right notch. The actual distribution (6 left, 8 right) did not differ from the expected distribution of seven fractures at each notch.

Pair-wise correlations between fracture initiation toughness, total energy, crack lengths and mineralization measures (from the notch roots and average) were examined (Table 2). There were a number of significant correlations, notably that of fracture initiation toughness (K_{Co}) with mineralization at the broken notch (Z_{broken}), pre-yield energy (U_{yield}) with mineralization at both notch roots (Z_{broken} , $Z_{unbroken}$), total energy (U_{total}) with average mineralization ($Z_{avg(200 \times 200)}$) and crack length extension at the unbroken notch ($Cr.L_{unbroken}$) with notch root mineralization, particularly the average ($[Z_{broken} + Z_{unbroken}]/2$).

Exploration of the data using linear regression of the mechanical/morphometric parameters across all variables (i.e., the top labels of Table 2 by the left labels) gave simple linear regressions matched with the correlation analysis (Table 3, Figs. 4 to 6). U_{yield} was blocked from entering the regressions for K_{Co} (and vice versa) because both are calculated using the failure force. There were multiple regressions with 2–4 entered variables that were

significant, however these are not presented due to the small sample size of the study (14) making the validity of multiple regression questionable.

Chi-Square analysis of the relative values of mineralization at the notch roots found no support for the hypothesis that either notch had a mineralization systematically different from the other either left versus right or broken versus unbroken. The expected number of samples in each quadrant is $3.5=14/4$. Actual pairs in each quadrant (1,3,5,5) (Fig. 7) did not show a statistically significant clustering of the pairs in any quadrant ($p>0.37$). The conclusion was that with 14 samples, that there is no statistical tendency for either notch root to be different from the other in mineralization. Similarly, repeated measures ANOVA found no difference in mean between the mineralizations at the notch roots and the average (200×200) mineralization ($p>0.7$).

Discussion

Fracture initiation toughness, total energy to failure and the length of crack extension at the unbroken notch were all correlated to mineralization measures; however, it was very interesting that initiation toughness correlated positively to mineralization at the notch that broke, that total energy to failure correlated negatively to average mineralization of the beam and that crack extension at the unbroken notch correlated negatively with the average notch tip mineralization. These correlations occurred with no statistically significant difference in the means of the notch tip or average mineralizations. We conclude that mechanical and damage parameters are strongly dependent upon mineralization at the *sites where the crack is propagating* at the time that the property is measured. Hence, fracture initiation toughness is affected by mineralization at the notch tip that breaks, total energy to failure by the average mineralization of the material that the (long) crack is propagating through and increased mineralization at the notch tips *reduces* stable crack extension (i.e., $Cr.L_{unbroken}$) prior to unstable crack extension.

If the same specimen could be made and broken repeatedly, then random placement of the notches would cause a full range of mineralization to fall at the notch root and then the average notch root mineralization would approach the average value of mineralization of the entire specimen. This would occur as a result of the notch roots sampling randomly from the mineralization distribution of the beam. For a single beam, however, the notch root mineralization is determined by the random nature of where the specimen preparation puts the notch root. As a consequence, one would expect fracture initiation toughness to be correlated to average mineralization for a large sample. Our result that the fracture initiation toughness is correlated to the broken notch root mineralization suggests that the dependence of fracture initiation toughness on mineralization is likely more directly related to the mineralization at the notch root than upon the average mineralization. In retrospect, this would seem reasonable since the crack extension begins at the notch root. Of course, since the variability of mineralization will affect the likelihood of the notch ending in tissue of any particular mineralization, then the probability of seeing a particular fracture initiation toughness will be affected by the variability of the mineralization. The clinical significance of this is not clear, however, drugs, diseases or age effects that change mineralization

variability (even if the average value remains unchanged) can be expected to change the observed values of fracture initiation toughness.

The negative and strong correlation of unbroken crack length extension with average notch root mineralization suggests that in the initial period of specimen damage that both notch roots will accumulate relatively short cracks that are stable under load. However, when one of the cracks exceeds a critical size, then one of the notches will have extensive unstable crack growth and become the “broken” notch. Therefore, the negative dependence of unbroken crack length supports the hypothesis that greater mineralization strongly decreases the critical crack length for unstable crack propagation of equine cortical bone. Note that crack extension at the unbroken notch is an upper bound on the critical crack length extension since it is possible that even as the broken notch has rapid crack growth, the unbroken notch has slow growth beyond the critical length.

Negative dependence of total energy to failure on average mineralization is consistent with the observation that crack growth resistance decreases with mineralization [13, 25]. Hence, the overall conclusion is that high average (or notch root) mineralization should tend to increase fracture initiation toughness but will negatively affect propagation toughness and critical crack length.

Neither notch (broken or unbroken) had statistically higher mineralization, so which notch failed first was not predicted by mineralization measured using the circular regions. This suggests that other features such as small holes, more detailed features of mineralization or even collagen matrix differences underlie which crack continues to extend to complete fracture.

Conclusion

The mineralization of a double notched specimen of equine cortical bone helps to explain fracture initiation toughness, total energy to failure of the specimen and crack extension at the unbroken notch. Fracture initiation toughness depends positively on mineralization of the notch root that sustains total failure, total energy to failure of the specimen negatively upon average mineralization of the beam away from the notch and crack extension at the unbroken notch negatively upon average mineralization at the notches. The conclusion is that higher mineralization at the notch increases the load required to initiate crack propagation, but that once propagation begins that stable crack growth is decreased and that increased average mineralization makes the overall structure less able to dissipate energy.

- Fracture initiation toughness was measured using a double-notched beam in four-point bending and mineral quantified using backscattered electron imaging.
- Mineralization around the two notch roots was positively correlated with fracture toughness ($r^2=0.34$) and negatively with crack extension ($r^2=0.81$).
- Energy absorbed was negatively correlated with average mineralization of the beam ($r^2=0.62$), but not with notch root mineralization.

- High *notch root* mineralization decreases stable crack growth and increases the force to initiate unstable crack growth.
- High *average* mineralization reduces energy absorption to failure.

Acknowledgments

The David Linn Endowed Chair in Orthopaedic Surgery and National Institutes of Health Grant AR040776.

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Figure 1.

Schematic of specimen design and method for calculation of the failure force. The linear region of the test was from 20% to 50% of the rising data. A linear fit to that data and the intersection of the 95% secant line with the data curve defined the linear (pre-yield/pre-failure) region. The pre- and postyield energies are the labeled areas under the curve. Examination of the test data ended when applied force fell to 50% of the maximum force achieved. The inset is the specimen design based on the 2 mm by 2 mm beam specimens.

Figure 2.

Analysis of mineral content in bone by sampling in 1) three 30 pixel diameter circles around the notch root of the broken (left) and unbroken (right) notches and 2) a 200×200 pixel region away from both the notches and the cracked regions.

Figure 3.

The crack extension at the right notch (Cr.L Right) was related to crack extension at the left notch (Cr.L Left). The dividing line " $y=x$ " was used to separate between whether the right notch (upper section) or left notch (lower section) was broken. As a general observation, one notch had "large" crack extension and the other "small" for all cases.

Figure 4.

Simple linear regression between fracture initiation toughness and the mineralization of the *broken* notch. Slope was significant at $p=0.028$ and intercept not significant.

Figure 5.

Simple linear regression between total energy to failure and average mineralization of the beam. Both slope and intercept were significant at $p=0.001$.

Figure 6.

Simple linear regression between extension of the crack length at the unbroken notch as a function of average mineralization of the notch roots. Slope and intercept were significant at $p < 0.001$.

Figure 7.

The mineralization at the notch roots (diamonds) varies around the average mineralization of the specimens (triangle). The dashed line is a cross-plot of the average mineralization against itself, showing that the notch root density pairs vary above and below the mean. The rectangular grid is centered at the mean values of the notch root pairs and has vertical and horizontal dimensions of two standard deviations from the mean for the two notch densities. Locations of the notch densities were not systematically different from uniformly random (Chi-Square, $p=0.37$).

Table 1

Data for the fourteen DN4PB tests. Failure force (F_{secant}), apparent fracture initiation toughness (K_{Co}), energy to yield (force for initiation of crack extension) (U_{yld}), total energy to failure (U_{total}), broken and unbroken crack length extension ($\text{Cr.L}_{\text{broken}}$, $\text{Cr.L}_{\text{unbroken}}$), mineralization at the broken and unbroken notch roots (Z_{broken} , Z_{unbroken}), average and standard deviation of mineralization of the 200 $\times$ 200 region. (Mineralization in units of atomic number.)

Specimen	Broken L or R	F_{secant} (N)	K_{Co} (MPa-m ^{1/2})	U_{yld} (N-mm)	U_{total} (N-mm)	(Cr.L) _{broken} (mm)	(Cr.L) _{unbroken} (mm)	Z_{broken}	Z_{unbroken}	Z_{avg} (200 $\times$ 200)	Z_{SD} (200 $\times$ 200)
1	L	32.01	3.12	2.38	32.97	3.35	0.76	12.00	11.99	11.94	0.65
2	R	38.78	3.84	2.70	21.17	3.22	0.60	12.04	12.41	12.35	0.44
3	R	33.55	3.49	2.51	32.80	2.20	0.88	11.85	12.01	12.07	0.48
4	R	34.66	3.63	2.64	30.15	3.47	0.48	11.99	12.27	11.96	0.48
5	L	30.68	3.06	2.58	30.08	4.09	1.12	11.71	11.93	12.04	0.65
6	R	38.01	3.66	3.07	24.53	3.55	0.23	12.68	12.04	12.25	0.82
7	R	31.33	3.07	2.52	24.12	2.78	0.41	12.01	12.31	12.14	0.43
8	L	41.10	3.89	3.95	30.01	4.36	0.95	12.05	12.07	12.07	0.65
9	L	36.49	3.69	2.93	22.63	2.61	0.83	12.09	12.05	12.07	0.47
10	R	37.88	3.65	3.05	22.31	3.11	0.68	12.43	11.89	12.17	0.61
11	L	26.05	2.64	1.95	18.00	2.23	1.01	11.43	12.64	12.46	0.76
12	L	26.97	2.76	2.04	13.63	4.26	0.57	11.93	12.38	12.28	0.51
13	R	37.42	3.73	3.17	19.32	4.30	0.15	13.14	11.87	12.21	0.78
14	R	36.30	3.50	2.41	16.54	2.27	0.62	12.11	12.26	12.22	0.47
Mean		34.37	3.41	2.71	24.16	3.27	0.66	12.10	12.15	12.16	0.59
SD		4.48	0.40	0.51	6.22	0.78	0.29	0.42	0.23	0.15	0.14

Table 2

Pair-wise Pearson's r correlations (p-value) between fracture initiation toughness (K_{Co}), energy to yield (U_{yield}), total absorbed energy (U_{total}), crack length extension at the broken ($Cr.L_{broken}$), unbroken ($Cr.L_{unbroken}$) notches, the average mineralization (Z_{avg}) and mineralization at the two notch roots (Z_{broken} , $Z_{unbroken}$). Significant relationships with $p < 0.05$ are in boldface. Note that K_{Co} is calculated using the *notch length* a (defined above) and that the values of $Cr.L_{xx}$ are the lengths of crack extension at the notch roots measured after conclusion of the test.

	K_{Co} (MPa-m ^{1/2})	U_{yield} (N-mm)	U_{total} (N-mm)	$Cr.L_{broken}$	$Cr.L_{unbroken}$
K_{Co} (MPa-m ^{1/2})	1	-	-	-	-
U_{yield} (N-mm)	0.80(<0.001)	1	-	-	-
U_{total} (N-mm)	0.23(0.43)	0.30(0.29)	1	-	-
$Cr.L_{broken}$	0.14(0.64)	0.45(0.11)	0.06(0.82)	1	-
$Cr.L_{unbroken}$	-0.29(0.30)	-0.13(0.64)	0.32(0.26)	-0.21(0.46)	1
$Z_{avg(200-200)}$	-0.25(0.38)	-0.29(0.31)	-0.79(<0.001)	-0.18(0.55)	-0.15(0.62)
Z_{broken}	0.59(0.03)	0.55(0.04)	-0.17(0.56)	0.38(0.18)	-0.78(<0.001)
$Z_{unbroken}$	-0.47(0.09)	-0.58(0.03)	-0.47(0.09)	-0.36(0.23)	0.08(0.78)
$(Z_{broken} + Z_{unbroken})/2$	0.40(0.16)	0.28(0.32)	-0.53(0.0525)	0.23(0.42)	-0.90(<0.001)
$Z_{broken} - Z_{unbroken}$	0.61(0.02)	0.62(0.02)	0.06(0.83)	0.42(0.14)	-0.60(0.03)

Table 3

Simple linear regression results predicting various fracture variables by the mineralization at the broken notch root, unbroken notch root and average mineralization of the beam measured as average atomic number.

Regression Variables	Slope	Intercept	R ²	p-value
K _{Co} (MPa*m ^{1/2}), Z _{broken}	0.565924	-3.43986	0.34	0.028
K _{Co} (MPa*m ^{1/2}), (Z _{broken} -Z _{unbroken})	0.42239	3.43007	0.37	0.029
U _{yield} (N-mm), Z _{broken}	0.673458	-5.44345	0.30	0.042
U _{yield} (N-mm), Z _{unbroken}	-1.27884	18.24755	0.33	0.031
U _{yield} (N-mm), (Z _{broken} -Z _{unbroken})	0.54862	2.73408	0.34	0.017
U _{total} (N-mm), Z _{avg(200×200)}	-33.4607	431.0375	0.62	0.001
Cr.L _{unbroken} (mm), Z _{broken}	-0.53681	7.160744	0.62	0.001
Cr.L _{unbroken} ·(Z _{broken} +Z _{unbroken})/2)	-1.5048	18.9131	0.81	<0.001
Cr.L _{unbroken} ·(Z _{broken} -Z _{unbroken})	-0.29346	0.64944	0.35	0.025