Biomaterials for Bone Tissue Engineering Applications
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Module 2
Lecture 08

Welcome to the module on bone tissue property. In the last module we have discussed about the bone structure and if you remember the couple of terms that I have introduced in the last module.

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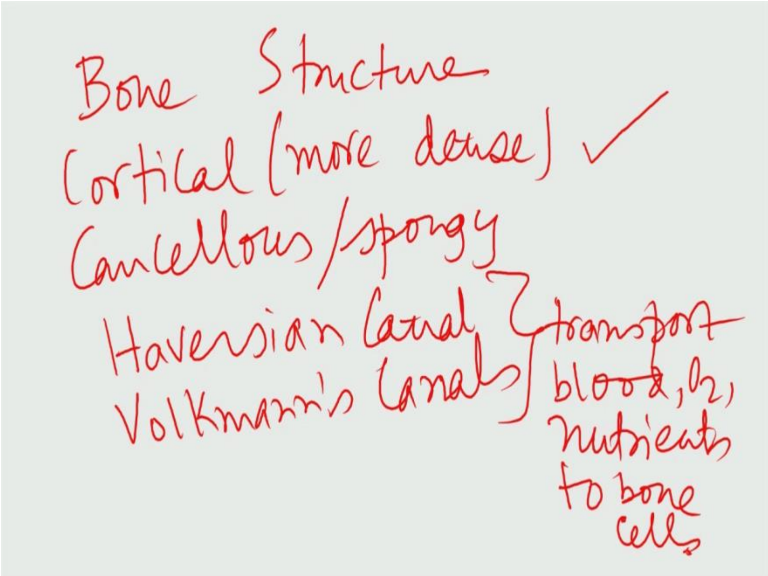

One of the term is the Cortical bone, and the other is the Cancellous bone. So, Cortical bone is the hardest part of the bone which is mostly the outside part and Cancellous bone has more spongy structure. So, this has a very large macro porous structure whereas Cortical bone also has some pores, but it is largely more dense in structure. So, it is relatively denser in structure. And because of that, typically Cortical bone has much better superior mechanical properties than Cancellous bone.

Other things that if I recall, I have mentioned, then there are several canals in the bone structure. One is the Haversian canal and another one is the Volkmann's canal. So, the function of these different canals in the bone is to transport blood, oxygen and nutrients to bone cells and as well as to take the waste products from internal part of the bone, to outside the blood stream. Okay.

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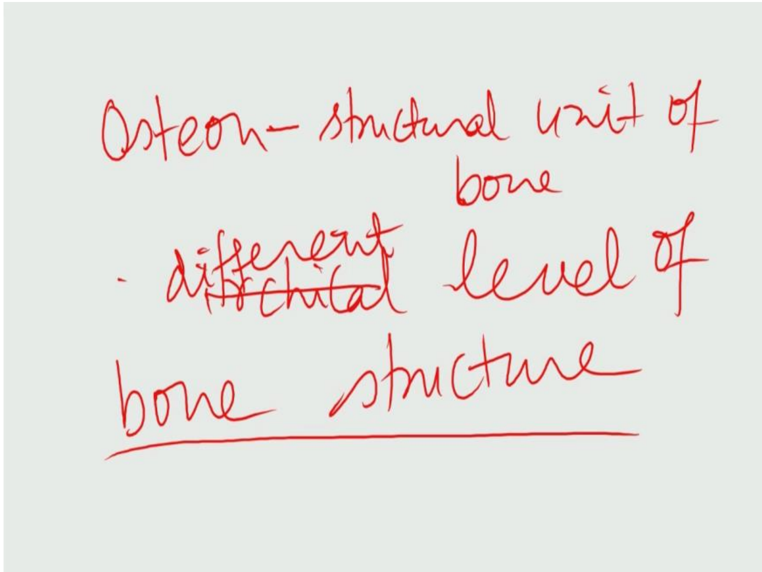

These are the things that I have mentioned. The other things that I have mentioned is, typically the structural unit of a bone is known as Osteon. So, this is the structural unit of a bone structure. This Osteon is the hierarchical level of bone structure. I have explained with sufficient details. So, this hierarchical level of bone structure starts with this Hydroxyapatitenano-platelets. Okay.

So, this different or various level of bone structure were discussed in terms of how this Hydroxyapatite nano-platelets were attached to the Collagen Fibrils. And this Collagen Fibrils make this smaller part of this Osteon structure. The Osteon structures are concentric circles and these concentric circles are arranged in a very random manner in this entire Cortical bone structure.

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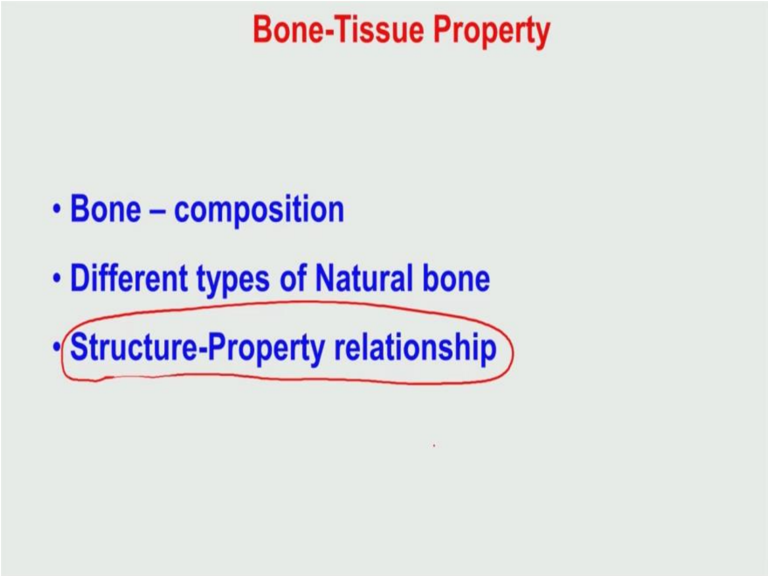

Now today we will start with this bone composition, followed by different types of natural bone and also some aspects of the structure property relationship of the natural bone. Remember that the structural property relationship is the key in the material science because when you consider the different materials, for example, metals, ceramics or polymers, their structure property relationship is very important. So, therefore we need to understand, how the structure property relationship is relevant for this natural bone.

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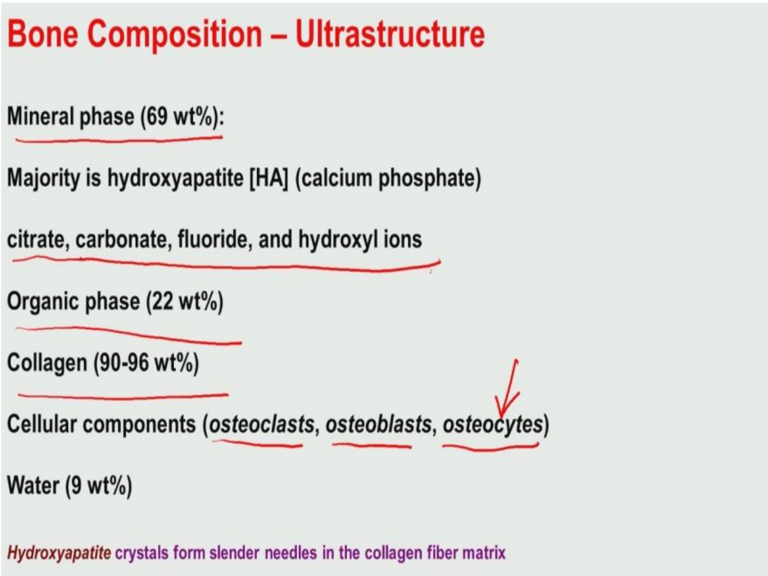

So, as per the gross composition of the natural bone is concerned, the minerals phase in it is 69 weight% and the majority is Hydroxyapatite or some Non Psychometric hydroxyapatite to be precise. The organic phase is the Collagenous protein phase. This is 22 weight%, out of which, Collagen is 92-96% and there are several cellular components.

The three particular cellular components are Osteoclasts, Osteoblasts and Osteocytes, which were referred in earlier lectures, multiple times. So, Osteocytes is the more matured bone cells. And also among this mineral phase, in addition to the abundance of the Hydroxyapatite, we have citrate, carbonate, fluoride and hydroxyl ions. And water is around 9 weight%.

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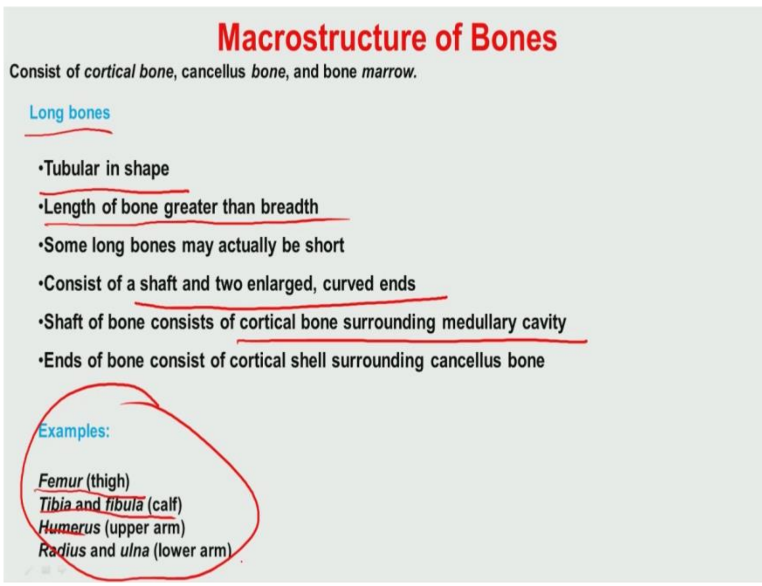

So, there are different types of bones. And the types of bones essentially reflects on the size or shape of the bone structure, itself. For example, long bone, as the name suggests, is larger in length. So, it is a tubular in shape. The length of the bone is certainly greater than the width or breadth of the bone. It consists of a shaft and two enlarged curve ends. This is mostly the Cortical bone surrounding the Medullary cavity. The examples of this long bone structure is Femur. During the bone implantation, people mostly use some cylindrical defects in the Femur. Tibia, Humerus, Radius are other examples of the long bone.

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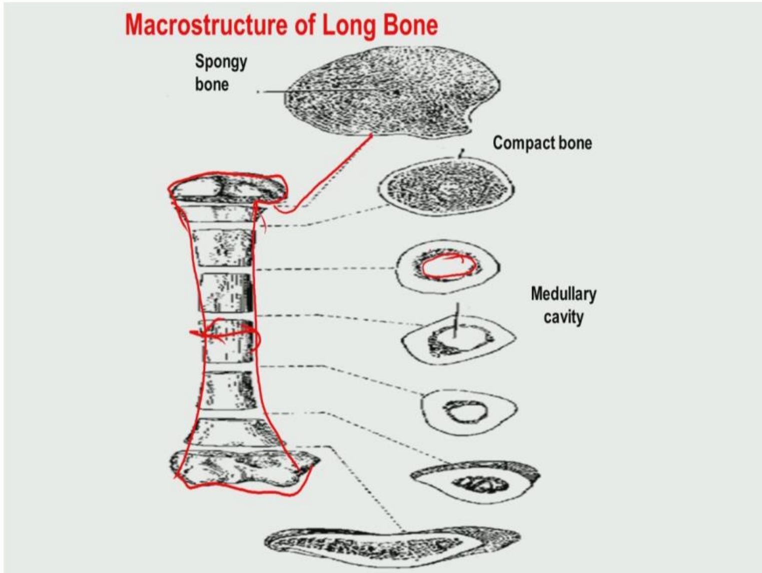

So, this is the macrostructure of the long bone structure. As you can see this is relatively large bone structure where length of this bone is much greater than the width of the bone. Now, various sections of this long bone structure has been shown. This is the 2D sections. Now in the 2D sections, you can see that. If you take the internal structure, it shows more like a spongy whole structure. And also a hollow region which goes along the length of this bone structure. So, here we have the Medullary cavity and we have this Compact bone as well. Okay.

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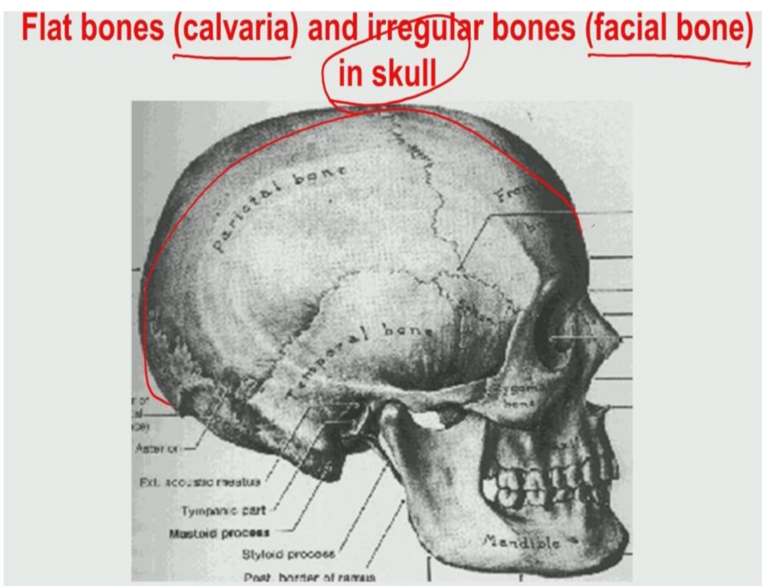

So, other examples of the flat bone are like Calvaria and irregular bones that is facial bones in the skull. So, here you can see that this is more carved like a bone structure.

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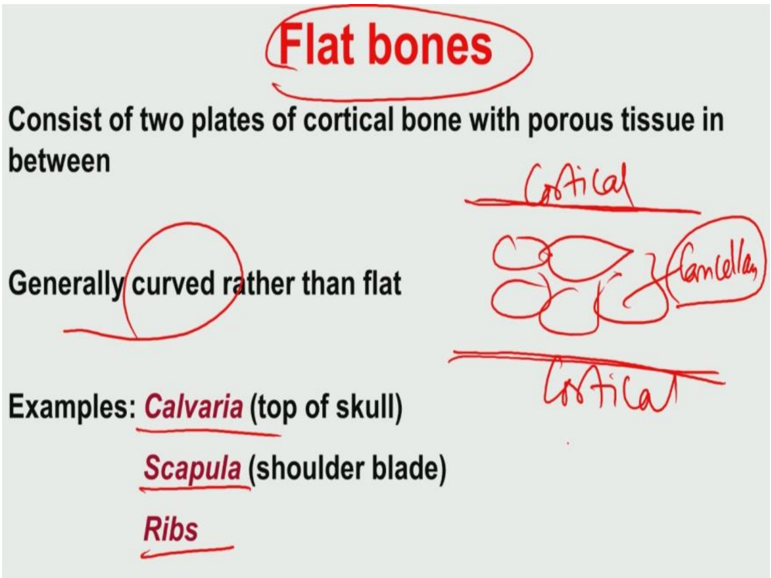

Now, there is another thing called the flat bone structure. So, essentially we have two flat plates like structure. These two flat plates are essentially, the Cortical bone structure. So, two sides are Cortical and in the intermediate, we have a large porous structure. And this is your Cancellous bone structure. So, this is a typical morphological features of the flat bone structure like Calvaria, Scapula and Ribs. Although, mostly it is said that it is flat, but it is mostly carved rather than being flat.

And then unique arrangement of having the Cancellous or porous type of structure that is Cancellous bone structure in between the two solid Cortical structure, actually is very helpful because the Cortical structure is more dense. It helps in protecting or giving mechanical support to the intermediate Cancellous structure.

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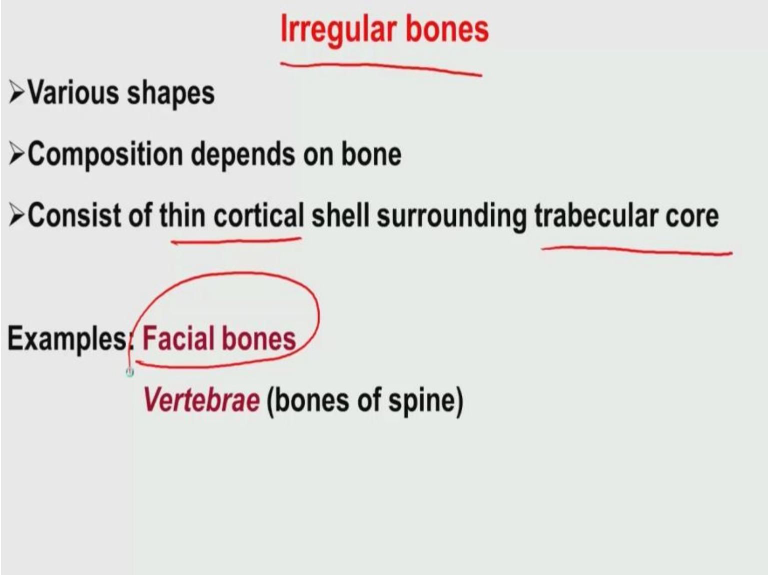

The other bone structure include irregular bone structure. As the name suggests, it essentially does not have any regular geometric shape. And also it consists of a very thin Cortical shell core surrounding Trabecular core. The examples are facial bone structure. This is the regular bone structure.

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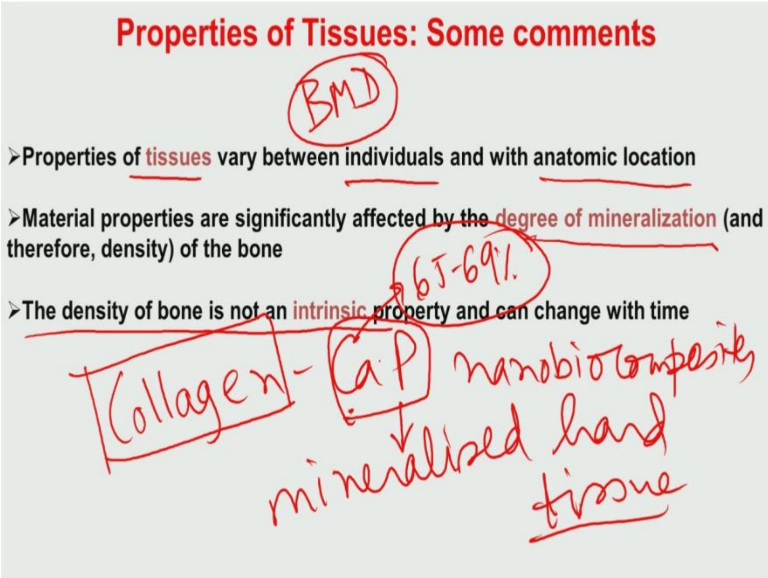

Now, this bone, as I started discussing in the last to last module that the bone has collagen, Calcium phosphate paste and nano-biocomposite. Now the presence of collagen, actually provides the bone with the required elastic modulus or elastic stiffness as well as the strength properties. The presence of collagen provides some other set of properties, which I will discuss soon. Now, since bone is known as a mineralized hard tissue. Mineralized hard tissue means the presence of Calcium phosphate. Actually this is considered in the materials nomenclature, as the mineral content in the bone.

So, in a very normal healthy bone structure in an adult, typically is 65-69% and in older patients, the mineral contents gets lower and lower. So, therefore, since the mineral content goes down or mineral content is much lesser than the healthy adult bone structure, the bones in the older patients, they are more prone to fracture and it becomes more fragile.

Some of the things about the properties of the tissue are that some properties of tissues, varies between individuals and it also varies within a same human patient in different anatomical location. This is significantly affected by the degree of Mineralization. So, that is something called BMD, Bone Mineralization Density which depends on the Calcium phosphate content or Hydroxyapatite or Non Psychometric hydroxyapatite content in the bone.

The density of the bone depends largely on the Calcium phosphate content in the bone. It is not an intrinsic property and it changes with time. That is what I just mentioned that in older human patients, these density decreases. In other words the Calcium phosphate content in the bone decreases. Therefore, they much more fragile.

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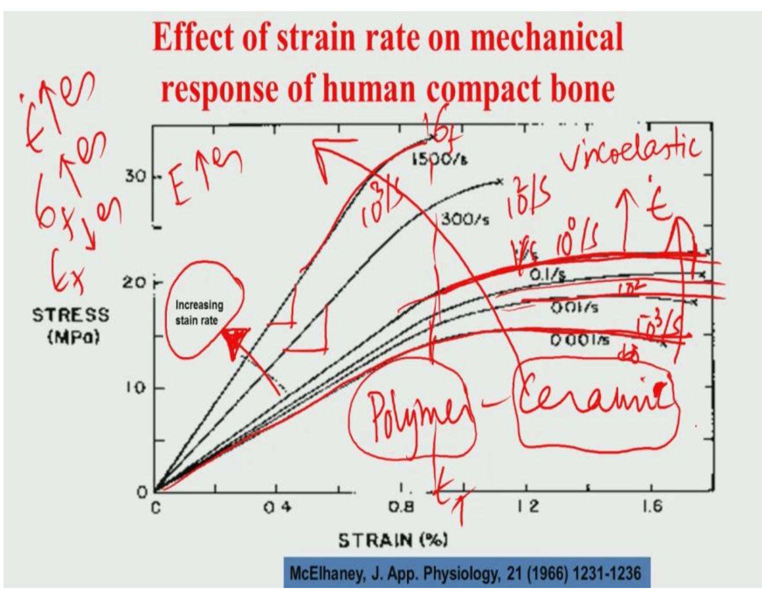

Now since bone has a polymer as well as ceramic paste. I have also mentioned in last to last module that bone is a unique example of the polymer ceramic based hybrid composite. So, mechanical property-wise, bone does show some characteristic features like visco-elastic features of a polymer, as well as to some extent, the brittle behavior of a ceramic material. And that is what is being shown here. Since, it has visco -elastic property, the bone also exhibits the strain rate dependent mechanical property and a strain rate dependent mechanical response.

What you see here, in the lowest curve, it has been obtained by the strain rate response, when the strain rate is 10 to the power -3 per second. 10 to the power -3 per second. Now, if you increase the strain rate, Epsilon dot increases. If it increases, then what happens in the next case? 10 to the power -2. The strain rate response goes up. If you go to one per second, means 10 to the power 0 per second, then what will happen?

It still goes up. That means it still has a unique ability to exuviate constant unique ability to exhibit deformation at a constant stress level, for relatively larger strain values. But if you go to the very large strain behavior, like 10 to the power 2, 10 to the power 2 per second or 10 to the power 3 per second. As you can see here and here. So, this shift is more towards the up but also towards the left.

So, there are two things that you can see, that with increasing the strain rate, the fracture strain increases. If you consider this a sigma F, Epsilon dot increases, the strain rate increases, then sigma F, fracture strain also increases, but at the expense of the failure strain. So, this is your failure strain. So, Epsilon actually decreases.

What is the other thing that increases? Your slope in the linear curve, also increases because it becomes much stiffer and stiffer. So, therefore elastic modulus also increases. So, higher is the strain rate, higher is the fracture strain. Higher is elastic modulus, however lower is the fracture strain. So, lower is the ability for the bones on bends to deform.

So, from these stress strain response, it must be clear to you that during high strain impact or due to an accident, why a person can undergo bone fracture very easily. Because in an accident case, where bone experiences large impact, then, although it shows little bit higher strength, but the fracture strain in fairly low. So, therefore natural bone is more prone to fracture because of limited plasticity.

The other things that you can see here that the typically stress strain response of the bone has two unique components- one is the elastic component followed by visco elastic component. So, this is your visco elastic component. Visco elastic means that it behaves like a viscous fluid as well as elastic solid. So, it is a combination of the viscous fluid property plus elastic solid property that makes the bone like something that is undergoing deformation, crossed and curved. And also it shows strain rate dependence.

So, normally if a material is purely elastic like a ceramic material, it will not exhibit any strain rate dependence. If a material is polymer, it will show strain rate dependent property. If a material is metal, it does not show strain rate dependent property because it has a ductile deformation which is essentially attributed to the dislocations in metals. So, because of the difference in the characteristic between metals, ceramics and polymers, polymers is the only material which shows strain rate dependent deformation behavior. In the mechanics literature, it is also described as an Anelasticity behavior. So it is not like a pure elastic behavior.

So, from these brief discussion, it should be clear to you that bone has a strain rate dependent property. Bone has a visco elastic property. And with increasing strain rate the fracture strain of the bone increases, elastic modulus increases and failure strain decreases. And therefore, bone is more prone to fracture.

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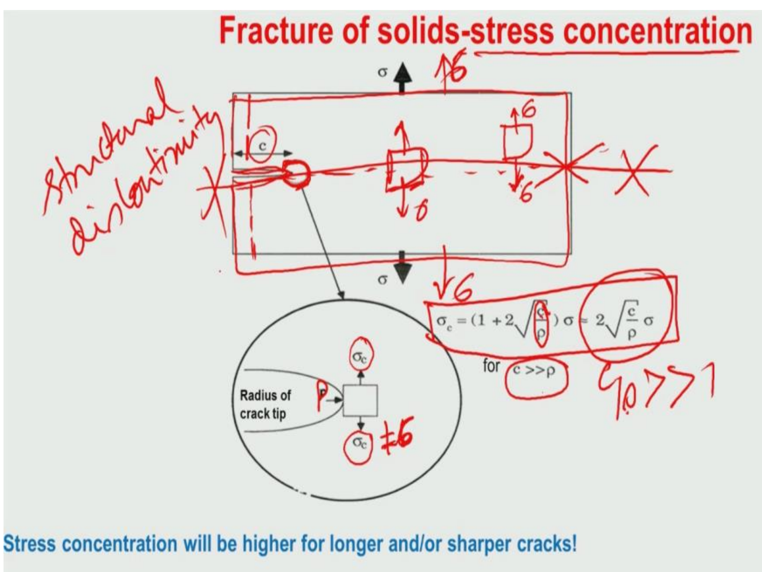

Now, little bit element of the fracture may connect its importance, because it will give you some idea, why this bone is prone to sudden fracture. So, this is a rectangular plate. So, rectangular plate has an age crack. This crack is shown here like an age crack. So, this age crack has a length C. Now you are pulling the rectangular plate with a stress sigma. So you are applying a tensile stress sigma. So, what happens? Everywhere in the plate, if you take any volume element here, this volume element will experience sigma stress. Okay.

Now, you look at any falling element, ahead of the crack T or adjacent to the crack T if you zoom it here. Now this particular falling element will experience some stress which is denoted as sigma C. Subscript C essentially denotes at the crack T. So, that is why it is called sigma C. Now this sigma C is certainly not equivalent to sigma. Why it is so? Although, anywhere else in the rectangular plate, this material will experience sigma, but at the crack T, it is not sigma, simply because, crack essentially or crack physically is described as a localized region of bond rupture.

Or in other words, if you have a covalent bonds, so this covalent bond is not directly continuous across the crack. So, crack essentially represents some discontinuity. So, it is kind of structural discontinuity that is represented by crack. And because of this, around the crack there is something called stress concentration. And this stress concentration has been mathematically expressed here. And what you see here it is 1+2 into square root C up and rho. So, what is C? C is your cracking. What is rho? O is the radius of the cracked tip. So, radius of the formation of the cracked tip.

Now, if a crack is very sharp, then what it means? That C is greater and is within rho.C is much larger than rho. Or in other word, if the crack is long or crack is sharp, then in that case, the C is much larger than rho. Then C by rho, essentially is much greater than 1. And if that is the case, sigma C can be approximated as 2 into square root C by rho into sigma.

So, what you see now immediately? The stress concentration of the cracked tip essentially scales with the square root of the crack size. Okay. So, larger the crack length, more is the stress concentration at the cracked tip. And in case of metals what will happen that this stress concentration somehow is consumed because of dislocation of the plasticity. But in ceramics, this dislocation plasticity is not possible. And like in case of the Hydroxyapatite based materials, and therefore this crack can go in an uninterpret manner, leading to fracture of this samples into two pieces.

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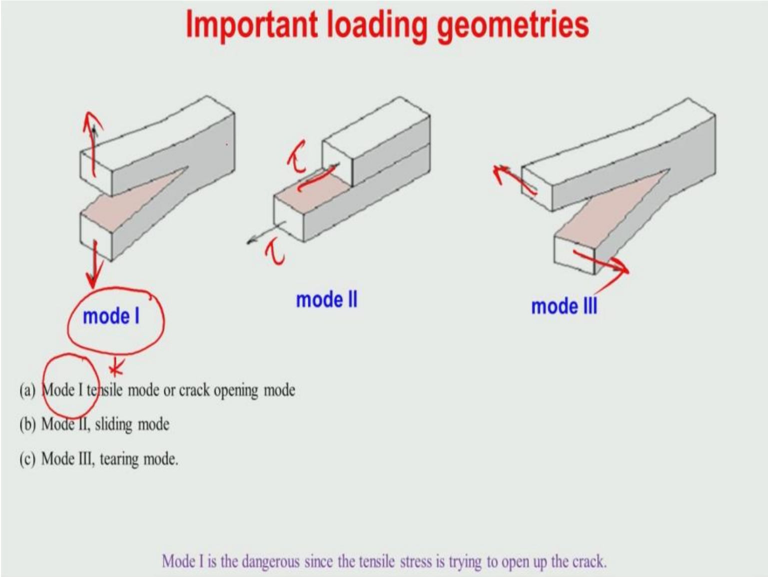

So, therefore it is important for one to understand the basic concept of stress concentration. How one can determine it experimentally is that there are three ways this loading can take place in a cracked body. If you remember it, this is a rectangular cracked body. Now, this rectangular cracked body, I am showing the three different ways, you can load it. One is the mode 1. That is the shear tensile. This is the mode 1. Now, mode 2 is the sliding mode, like you are applying, shear stress on the cracked surfaces.

Mode 3 is also tearing mode, but you are applying the shear stress, in a direction which is perpendicular to the mode 2 direction. So out of these mode 1 is more dangerous. So, I will put a star here. Why I had put a star? Because in the mode 1, it is crack opening mode of tensile surfaces. So, this crack can easily go across the material, leading to fracture of the material. So, this mode 1, therefore, it is much more critical.

And in case of the mode 2, you see that it is a more sliding mode. So, in case of mode 2 and mode 3, the fracture toughness values are not really stick towards the fracture toughness one can determine experimentally by mode 1. And this is how, experimentally one can measure.

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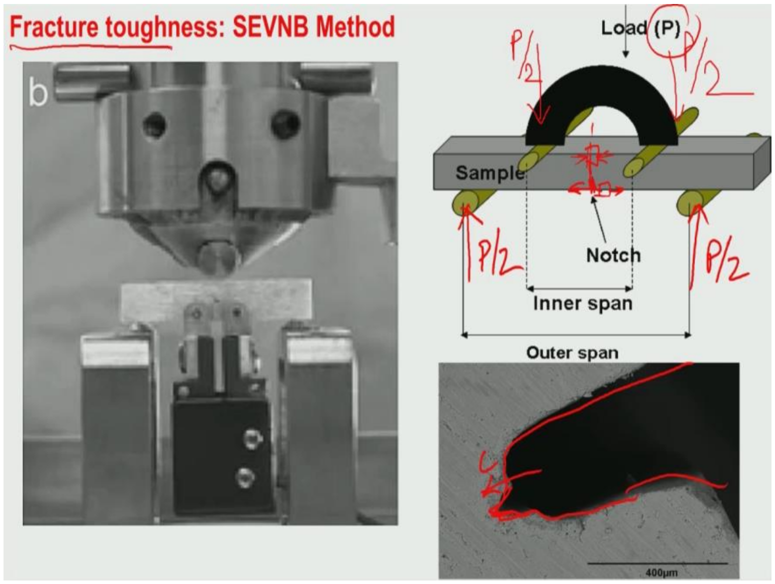

So, what you see here? This is a 4 point loading assembly. So, if you apply this is you P by 2, then the load is distributed at arms. So, this is P by 2, P by 2. And now what is the result put forth? There is P by 2 and P by 2. So, for every action there is equivalent and opposite reaction. So, if P by 2, P by 2 load is there from the top, so P by 2 load, P by 2 load, also would experience at the 2 rollers which are kept at the end of the outer span.

So, if you put a P notch here on the tensile surfaces, then under this kind of loading configuration, any falling element would experience compression at the top surface and any volume element, at the bottom surfaces will experience tension. So, in the tensile surfaces, you now produce these kind of V notch. You can see this is the kind of V notch. The depth of V notch will actually extent into the bulk of the material. That determines, what could be the fracture purpose of the material.

So, idea of introducing the crack on the tensile surfaces is that once it experiences tensile stresses, and the cracks will propagate from this V notch, leading to the fracture into two pieces. So you know, what is the load at which the inter sample fractures. If you know, the total crack length of this V notch, then you can essentially calculate what is the fracture toughness. So, this fracture toughness essentially means, the resistance towards the crack propagation. Okay.

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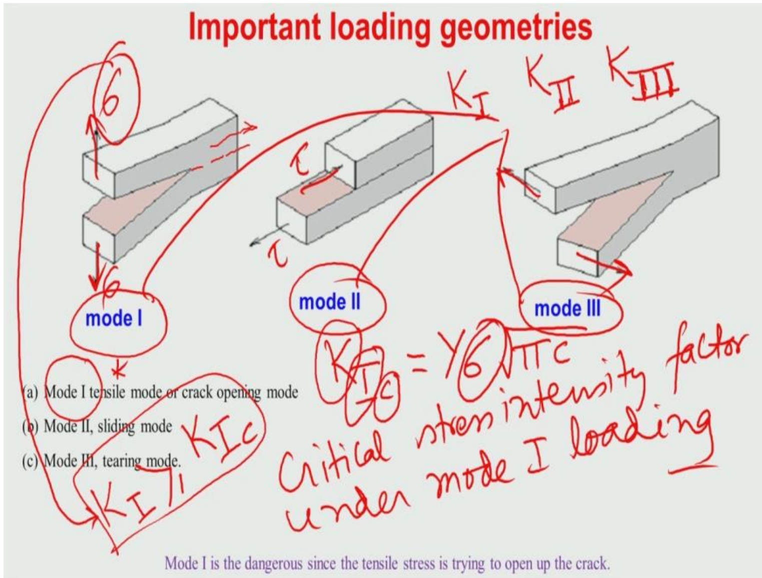

So, one can write fracture toughness K1C is equal to Y sigma square root pi C. So, C is your crack length. Sigma is the stress value at which the failure takes place and K means stress intensity factor. 1 means, mode 1. C means critical. So, this is essentially critical, stress, intensity factor, under mode 1 loading. So, often students are confused. They often pronounce this as KIC. KIC is wrong, so you have to pronounce it as K1C, because 1 has a specific meaning. 1 means that this is mode 1 type of loading.

Similarly since you have K1, stress intensity factor and the mode 1, one can also designate K2 and one can also designate K3. So, K1, K2 and K3 essentially means stress intensity factor under mode 1, under mode 2 loading and under mode 3 loading. So, these are like three different kind of loading configuration, I have shown in this slide. So, depending on what kind of loading configuration, you can define what is the stress intensity factor under three different mode of loading.

And the criticality condition essentially means that, when the external the K1 value is equal or greater than K1C, then K1C is the intrinsic property of a material. Like every material has this fracture toughness values which is independent of the testing conditions. So, that is the critical stress intensity factor.

Now, suppose you are applying some sigma value here, now compared to sigma values, you have to calculate the applied stress intensity factor or in other word the stress intensity factor due to the application of stress, externally applied stress sigma. Now, once this K1 value is greater than the materials intrinsic property K1C. So, then the material actually fractures into pieces.

So, having said this, I have given some ideas, about what is meant by fracture toughness. I repeat. Fracture toughness is essentially is the resistance to crack propagation. So, therefore you have to first introduce certain cracks in a material and we see how this crack propagates along this particular direction. Once the crack propagates through and through into the material, the material is then broken into two pieces.

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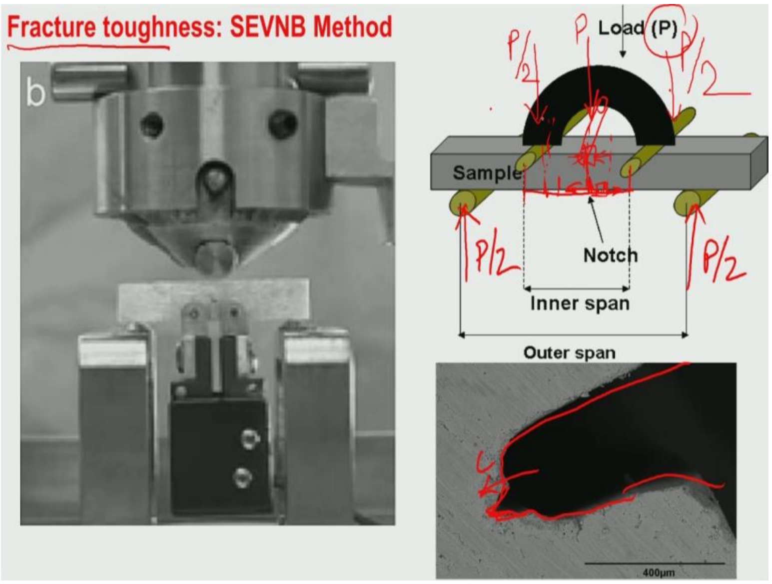

This is something we can measure, experimentally. How we can measure the fracture toughness? We can measure the fracture toughness by ACBMB. ACBMB stands for single H, V notch P. As the name suggests, it means we have to introduce V notch in one of the ages and that age is to be placed on the tensile surface. Now, once you produce the P notch on the tensile surface, then you have to break them into Flexural mode. This is 4 point Flexural mode.

Instead of this 4 point, we can also keep on single ruler here and you can apply the inter node P here. So, this is called 3 point loading. So, we can use either 3 point loading or 4 point loading. But 4 point loading is by far more preferred because here this much region would be under uniform tensile stress. In case of 3 point loading, only very limited features will be under uniform tension.

So, therefore any crack which is present in this uniform stress region, can simply propagate leading to failure of the entire sample. So, this is how the fracture takes place in brittle materials and that is how experimentally one can measure the fracture toughness of a brittle material like ceramics.

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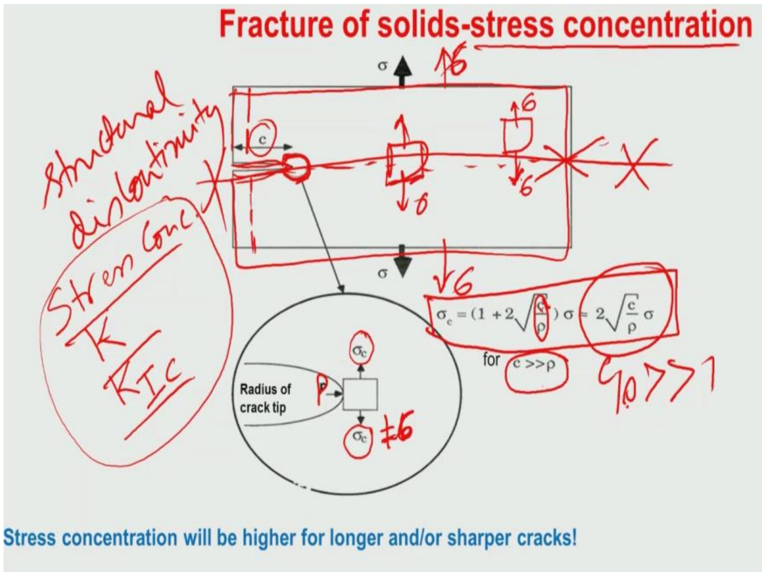

So, the three things that is important for one to remember. One is the stress concentration. Second one is the K factor that is the stress intensity factor. Third one is K1C that is the critical stress intensity factor, under mode 1 loading. So, this is more than enough just to understand many things which is required to know about the fracture of the brittle solid like bone and fracture of the brittle solids like ceramic best materials.