Nanostructures and Nonmaterials: Characterization and Properties

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Lecture - 31
Nanomaterials in Nature: bone

In this lecture we will learn about Nanomaterials in nature specifically for a natural bone. We, earlier we were talked about the multitier hierarchy. So, we will see how this hierarchy already present in many of the natural objects. So, in this case we will learn about how these structures developed at nano, at nano level at a molecular level and how do they go about making some ultra structures or finally a bulk structures

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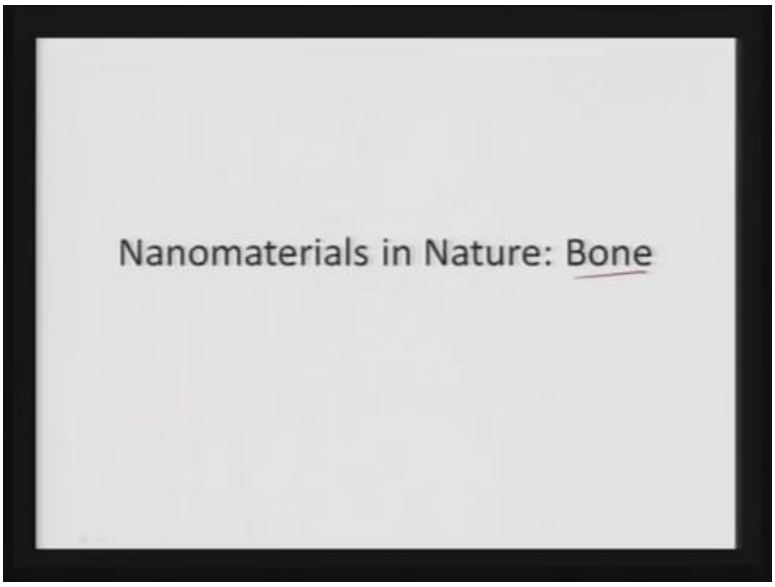

So, in this case, in this particular lecture we will learn how the nano materials in nature, how they devised in terms of forming some basic fundamental units, how do they go on to forming certain structure which are uniform. And then forming a higher level of scale, such as starting from hydroxyapatite or collagen to a fibril, and then to a lamely, and then to a sort of macro structure, and then ultimately form a spongy bone.

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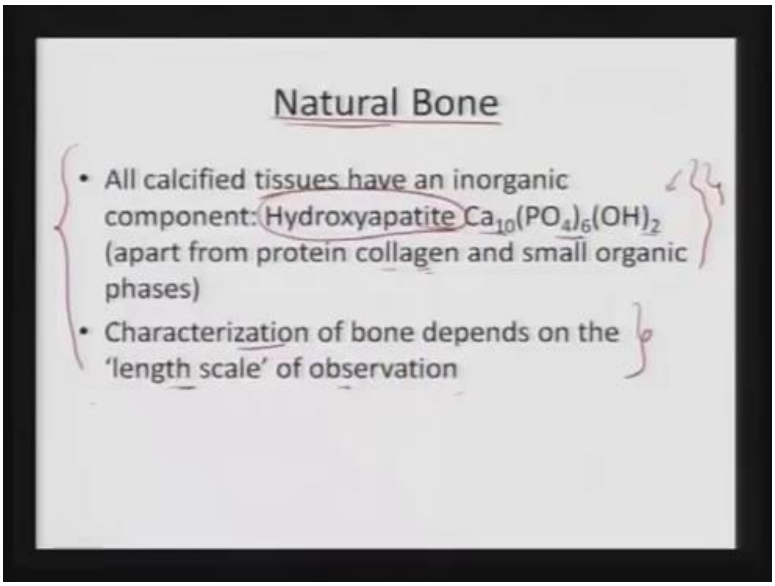

So, talking about natural bone. Generally, all the calcified tissues, they have some inorganic component, that is hydroxyapatite, it is a basic fundamental unit of Ca 5 Po 4 3 OH. An each of those 2 units are occupied in the unit cells, so it gives rise to Ca 10 Po 4 whole 6 OH twice.

Apart from that it also has a protein collagenous content and certain organic phases, which are present on those calcified tissues. And again it is very-very essential to learn how the characterization of bone, how it depends on the lens scale of the observation. Because you are talking about the molecular scale, whether you are talking about the micro structural scale, we are talking about the macro scale, we are talking about the bulk scale on the, on the actual structure of the bone.

So, we can see, we can see how those properties, it can be mechanical, it can be nutritional, it can be biological, it can be chemical. How it is affected by the structure which provides a certain functionality to the bone? So, as you see in natural bone, we have certain components of either some organic components, some inorganic components, in organic components. We have basically a hydroxyapatite, which is present in all the classified tissues apart from collagen. And it is also essential to see how this hydroxyapatite is spread in to collagen, both inter and intra fabulous regions.

So, that will give a very peculiar structure at certain lens scales, and again the characterization of these is also very-very critical. So, we will also learn about how the,

how we can determine the elastic consents of rheological properties of bone, so that when a certain stress is applied on to it, how can it relax or how it can distribute to the stress. So, those things become very-very critical and they depend much on the way, the structure of the particular bone is designed.

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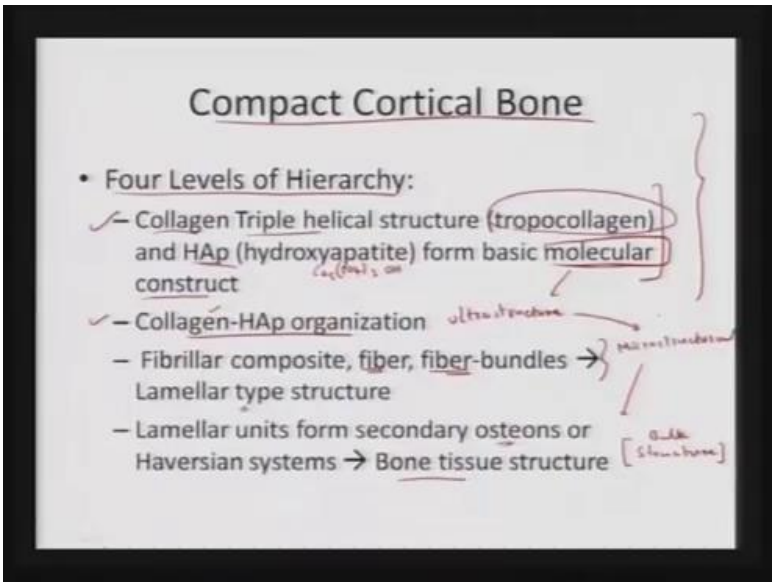

So, learning about the compact cortical bone and as we said earlier there are 4 levels of hierarchy. So, in first case we are talking about a basic molecular construct, and that comprises collagen, triple helical structure which is also called tropocollagen, or the arrangement of hydroxyapatite within it.

So, collagen will have hydroxyapatite they form the basic molecular construct, and this had the hydroxyapatite is been defined as a structure of Ca 5 Po 4 whole thrice OH and 2 such units are there in the unit cell, so it become Ca 10 Ca 4 whole 6 and OH twice. So, collagen and hydroxyapatite that are basic fundamental blocks, to form the basics structure or molecular structure. So, that is the first level of hierarchy then, this HAp starts spreading both in the inter and intra fabulous region of collagen, and that from the second level of construct which is called ultra structural.

So, we molecular structural, molecular structure then, we have ultra structure. And now coming to the third components, all these fibril from fiber or fiber bundles to give rise to a lamellae type of structure and that is again called micro structural. So, starting from molecular, we are gone to ultra structure and that has gone to a micro structure. And then

finally, all these lamellae units, they from secondary osteons. All Haversian systems which are called bone tissue structure which is at a structural level or bulk structure.

So, we can see we have 4 levels of hierarchy, in first level we see a basic display of collagen and hydroxyapatite to give rise to a molecular structure. And how this HAp is being spread on to the collagen fiber that gives rise to ultra structure then, we go on to forming those as fibers, fiber bundles or lamellae, and then that is called a micro structural entity. And how these things go on to evolve a osteon Haversian system to give rise to entire structure which is called a bulk structure or the bone tissue structure.

So, we can see in compact cortical bone, how these 4 levels of hierarchy are defined, and these are inherently present, that is by designed in nature. So, these are inherently present in nature and these all have different way of providing certain property to the bone. So, let us see how these entities are basically been developed, so initially we have the crystals of apatite.

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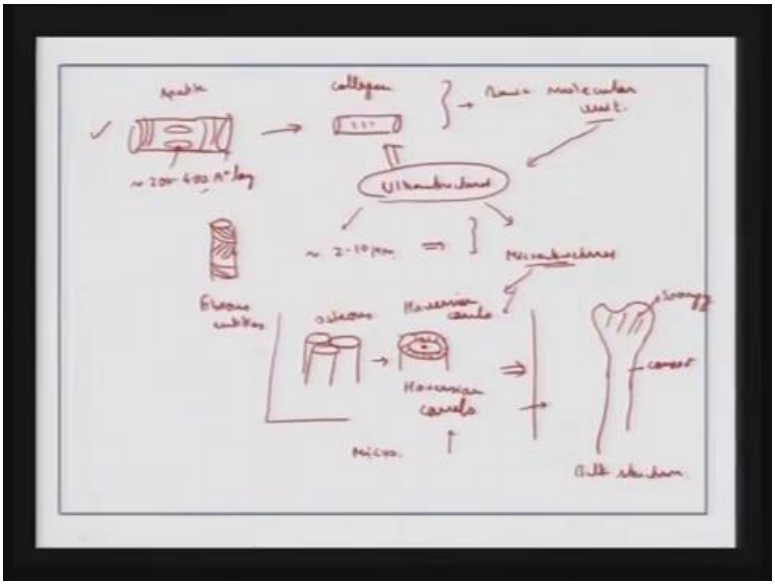

So, we can see there are certain crystals of appetite which are couple of angstroms. So, it start, it is approximately apatite mineral crystals, there we can see certain mineral crystals which are spread intra and inter the collagen fibers. So, we can see this apatite crystals, they are approximately 200 to 400 of angstroms long, and all this are entirely laid on to certain collagen fibers.

These are certain fibers, so they are present in both the inter and intra, so we have apatite and collagen. And these from the basic molecular unit and from that, the arrangement of this gives rise to certain concentrate lamina. So, we can see there are certain concentrate lamina, which is basically generate of this and then these are fibrous entities. And these are approximately couple of microns, may be say 2 to 10 micro meters, and these are nothing but the ultra structural sorry, micro structural.

So, the arrangement of this, arrangement of appetite and collagen is called ultra structural and this goes on to forming this fibers which are micro structural. And again all this fibrous entities go on to forming certain osteons. And eventually they go on to forming Haversian systems, Haversian canals or Haversian systems. So, this is again move back to micro level, micro structural level and then, we see we get finally a spongy bone kind of a structure. So, we have all the cartilages, we have a spongy bone.

So, we can see that as a spongy bone kind of a structure being generated, and we have a compact bone. And in this region, we see the, how the osteons and the Haversian system. So, we have this osteons and this Haversian systems, Haversian canals. So, all these lamellae has been organized in a very nice channels of making Haversian canals and finally, we get entire spongy bone in a compact bone structure with periostrial.

So, we can see that initially we start with apatite and collagenous type of structure which is a basic molecular unit, approximately 200 to 400 angstrom long of apatite crystals. There both present in the intra and inter fabulous region of collagen, and that gives rise to our ultra structural entity, that forms a basic, the basic molecular unit comprised ultra structural units, and this gone to forming certain fibers and lamellae or fibrous kind of entities, which are again at the macro structural level.

And all this fibers go on to forming osteons which eventually form Haversian canals, and this Haversian canals are again at the micro structural regime to finally give a bone. It is a spongy or compact bone which is at the bulk structural level. So, that is how we can see that how the overall hierarchy is basically classified in to four different regimes starting from the fundamental unit of apatite and collagen. Then going on to ultra structural regime of, these arrangements of apatite on to the collagenous fiber.

Then, how these collagenous fiber are properly linked to form fibers or lamellae type of structures. And eventually form osteons or the Haversian systems at micro structural level, and finally give rise to the bone structure.

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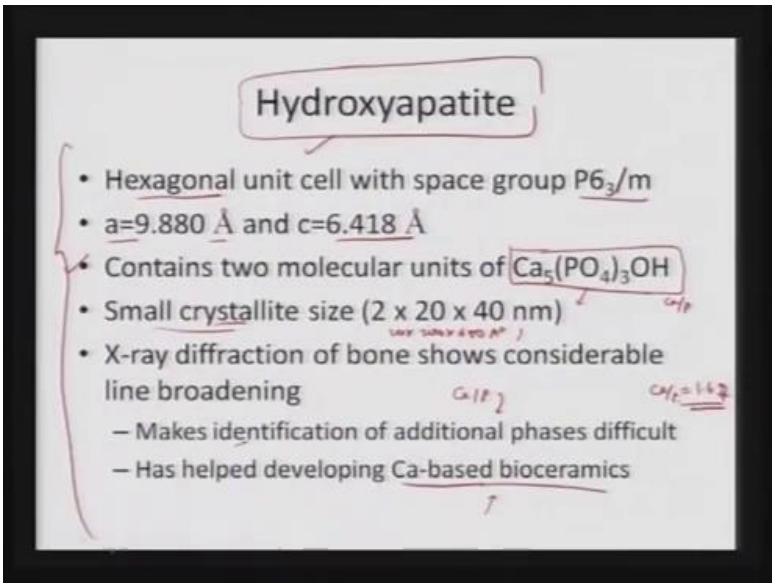

So, basically we can see the fundamental unit of hydroxyapatite. Hydroxyapatite is apatite is a hexagonal unit cell with space group of P6 3 by m. It is a latest parameter of a 9.880 angstrom and C of 6.418 angstrom. So, essentially it has 2 units of Ca 5 PO 4 3 OH and 2 such units are present molecular units are present in a each unit cell. So, that is the reason to become Ca 10 Po 4 6 OH twice and it has a small crystalline size of generate form of small crystalline size of 2 by 20 by 40 nano meter, that is 20 by 200 by 400 angstroms. And it is because it is nano crystalline in nature.

So, the X-ray diffraction of bone shows very-very considerable line broadening, and because of line broadening it is very hard to identify which is other elements are present in this particular structure. So, hydroxyapatite is the basic fundamental structural unit, and again because of the presents of this calcium and phosphate an in this hydroxyapatite which is nothing but the inorganic component of the bone. It is led to the development of certain calcium phosphate based bio ceramics because that is the main mineral block it is Ca 5 Po 4 ratio 1.67.

So, that is the motive behind, that is the basic impedance behind initiating new calcium based bio ceramic as a potential bone implant materials. So we can see hydroxyapatite, it

is a hexagonal unit cell with the space group of P6 3 by m with lattice parameters of 9.88 and C of 6.418 angstrom and it contains 2 molecular units of Ca 5 PO 4 of whole thrice OH, and it is a very small crystallite size to the order of 2 by 20 by 40 nano meter. So, it is a very forms, very nano meter regime apatite crystals, and because of that the X-ray diffraction of the bone it shows very-very high line broadening because of the nano crystallites of this inorganic component of the bone, and that makes the identification very-very difficult because there is so much line broadening in the background is very-very high for this particular ceramic component.

And then, but this, but because of presence of calcium and phosphate, those have led to the development of calcium based bio ceramics which is now the major field of research in the bio medical industry. So, that is the basic fundamental unit.

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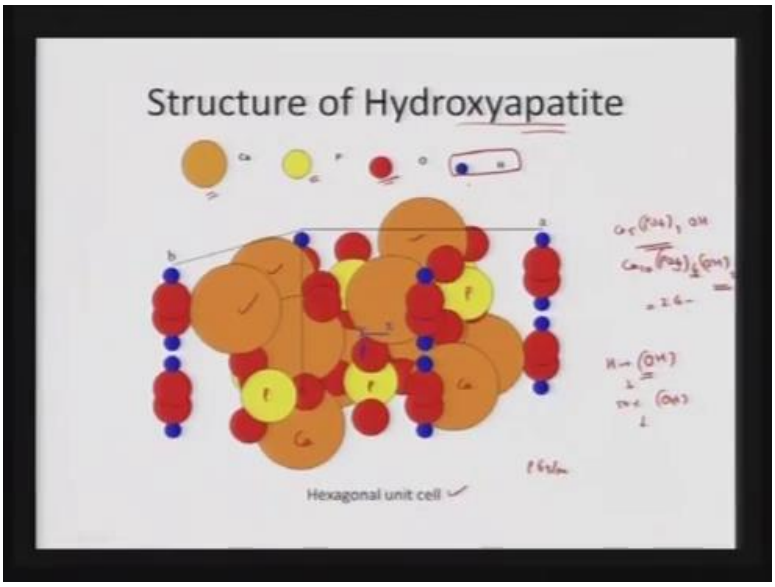

And we can see the structure of hydroxyapatite more looks like this. So, there are 2 blocks of Ca 5 PO 4 thrice OH, so in a unit cell will get Ca 10 PO 4 6 OH twice. So, we see that the total of 10 Ca atom, so this orange 1 is the calcium, that is what we are seeing here. So, we have 10 of such calcium atoms in a unit cell, and there are 6 of phosphorous those are the nothing but yellow atoms which you see here, those are the phosphorous and then, we have oxygen.

So, we can see that there are total of 26 oxygen O 4, so 24 plus 2, 26 as oxygen which are present in a unit cell and then, we have hydrogen which is at the corners. Apparently

that the hydrogen is present as OH and the total of, out of total number of sites only half of them, only 50 percent of sites are being occupied by the OH. So, in this particular case we have OH twice, so only 2 of the OH components are present in this case, and that is occupying only the 50 percent of the available sites for the OH.

So, we can see that the hexagonal unit cell, it is P 6 3 by m. So, that is the basic space group for the hydroxyapatite and the total of 10 calcium atoms, total of 6 phosphoresces, and there are total of 26 oxygen and 2 hydrogen which are present in unit cell of hydroxyapatite.

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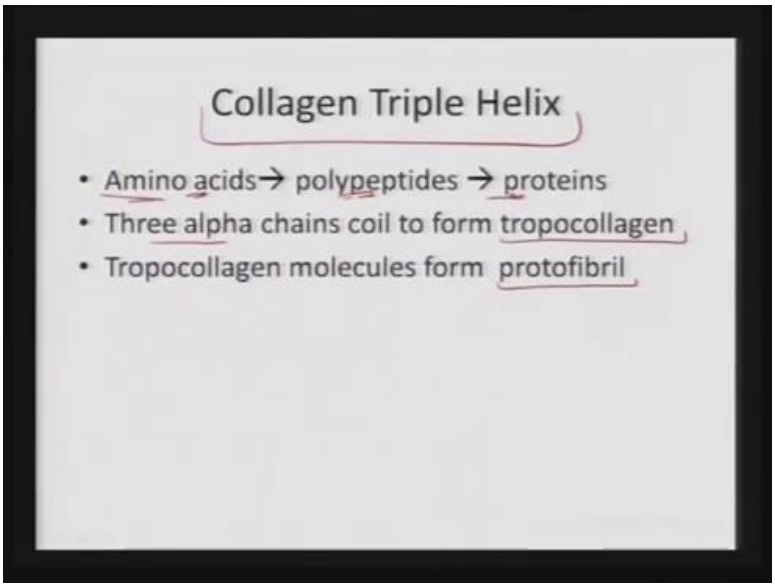

And to understand how the collagen of triple helix is basically formed, we need to learn about how the amino acids go on to form polypeptides, and how they eventually turn out to be proteins. And in the case of collagen triple helix, we have 3 alpha chains which are at the left handed screw they coil to form tropocollagen, which is a triple helix structure and these tropocollagen eventually form protofibrils.

So, for the tropocollagen triple helix we have to start with the fundamental amino acid, how the polypeptide bond, the hydrogen and the nitrogen bond, how do they basically emerge to form finally proteins and how this alpha chains coil to form tropocollagen and this tropocollagen eventually form protofibrils in the bone structure. So, let us see how the collagen structure is basically developed, as starting from the chains of this alpha helix structure. So, we can see that the alpha helix is a left handed helix.

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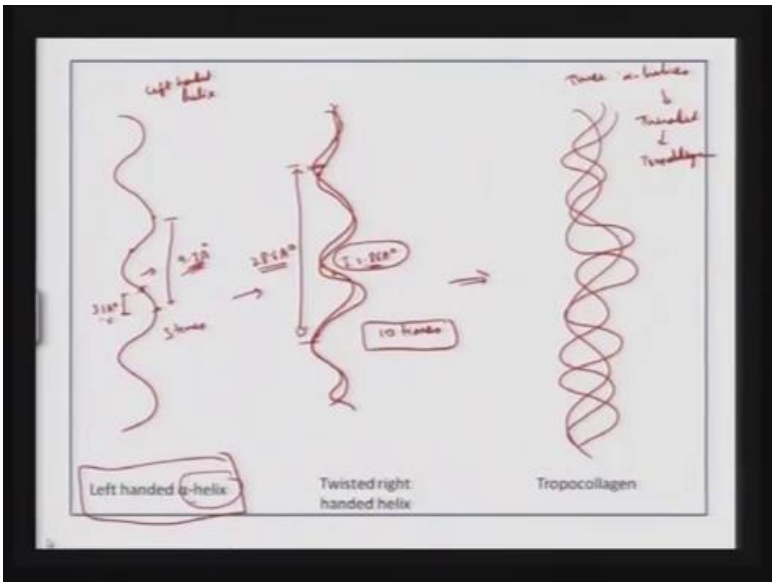

So, we can see it has a, so it has a certain repeat unit. So, it has a repeat unit of approximately 9.3 angstroms. So, we can see it has certain structure of. So, it has a residue of around 3.1 angstrom. And it has a sorry, it has a repeat length of 3.1 angstrom and again it has a residue, which is of length around 3.1 angstrom. And it basically comes as a residue, residue is again a repeat point where the same point of the appears again.

So, that is approximately 9. 3 angstroms, so 3 such units are there in a repeat unit. So, this is for the alpha helix structure, alpha helix left handed structure and after that once we start. This is the alpha left handed helix, and once it is been opened up and coiled with the right handed helix. So, we have 1 left hand side helix and then 1 right handed helix. So, they basically, so because of its opening the overall residue reduces from 3.1 to around 2.86.

So, the overall residues is approximately 2,86 angstroms, but the repeat length, the repeat length because of the presence of 2 types of structure, repeat length is now the 10 times becomes instead of here it was 3 times. So, the repeat length is approximately 3 times in the alpha helix, which increases to 10 times. So, in this case, we have overall repeat length is from 3.1 to 2.86, but the overall repeat length, overall repeat length is basically increase by 10 times.

So, it is the residue which is decreasing from 3.1to 2.86, but the repeat length is now increased to around 10 times and becomes 28.6 angstrom in the crystal right handed helix. So, we start with alpha helix we try to open it and then the residue is decreased by 2.86. But the overall repeat length is now increased from 9.3 angstrom to 28.6 angstroms in the twisted the right handed helix. And then these are threaded to form, so 3 such units comes together and then, they form this tropocollagen.

So, there are 3 such units, which go on to form this particular tropocollagen which is very-very complicated. So, 3 alpha helixes, they form a threaded, so 3 such alpha helixes they get threaded to form his tropocollagen structure. So, initially we started with alpha helix which has a left handed screw, which has a residue of around 3.1 and repeat length of 9.3 angstrom. And then because of it is uncoiling, the residue basically decreased to 2.86 angstrom. With the repeat length of around 28. 6 and this is approximately 10 times that of earlier case, so 10 times of this residue.

So, in this case it is gone from 9.8 angstrom to 28.6 angstrom and 3 such alpha helixes, they are now threaded to form this tropocollagen structure. So, that is what we see at the basic fundamental unit. So, this we have now hydroxyapatite which is P 6 3 by m. And now we have this tropocollagen, and now these chains, the chain of tropocollagen and the crystals of apatite, they are present in both intra and the inter collagenous region to form the ultra structural units.

So, we have the fundamental block of a hydroxyapatite and this tropocollagen and dispersion of hydroxyapatite in this particular tropocollagen is basically giving rise to the second level of hierarchy that is the ultra structure.

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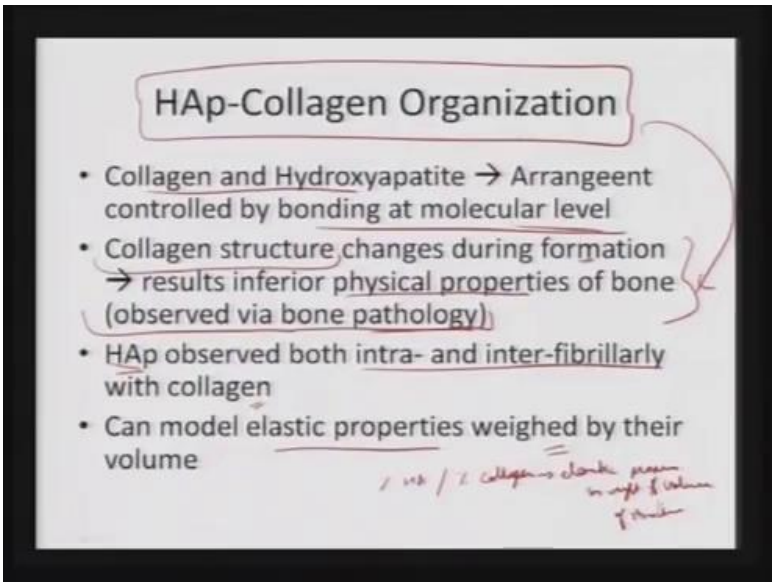

So, this HAp collagen organization, so it is controlled by bonding at the molecular level. So, we can see the basic unit of collagen of hydrogen and hydroxyapatite, their arrangement is getting controlled by the bonding at the molecular level. And now here in this what is happening is, the collagen structure can also change during the formation because the collagen is getting replicated from the alpha helixes.

So, during the initial stage of its formation, its structure can be very-very different. And again when it is just forming, it is physical properties of the mechanical properties are very-very inferior. So, that is been observed by the bone pathology and that can be a very weak mechanical properties as well. So, those inferior physical properties relates directly to the mechanical properties, and it may take a long time to heal if certain stresses are applied to it. So, that structure is very-very important in terms of dictating the overall properties of the bone.

So, fundamental units itself is very-very feeble or very-very weak, it will lead to such changes in the bulk property as well. So, that is also very-very critical at this stage that HAp collegial organization is completed, so we get a proper fundamental block for exhibit to form micro structure or the final bone structure. And HAp is been observed both in the intra and the inter fiberlary regions with collagen. And now what is happening in this particular case now we have proper mix of HAp and collagen.

So, here what we can do, we can model the elastic properties based on the weight of each component. So, we know that certain content of hydroxyapatite and certain content of collagen. Now, we can identify what can be the elastic properties of the structure. Elastic properties by weight of or volume of this structure. So, till now, once we had only Hap and once we had only collagen and the dispersion was still under progress. So, in this case once they have organized. Now, we know exact content of hydroxyapatite and exact content of collagen. And from here we can really model what will be the elastic properties of this particular organizational at the macro structural level.

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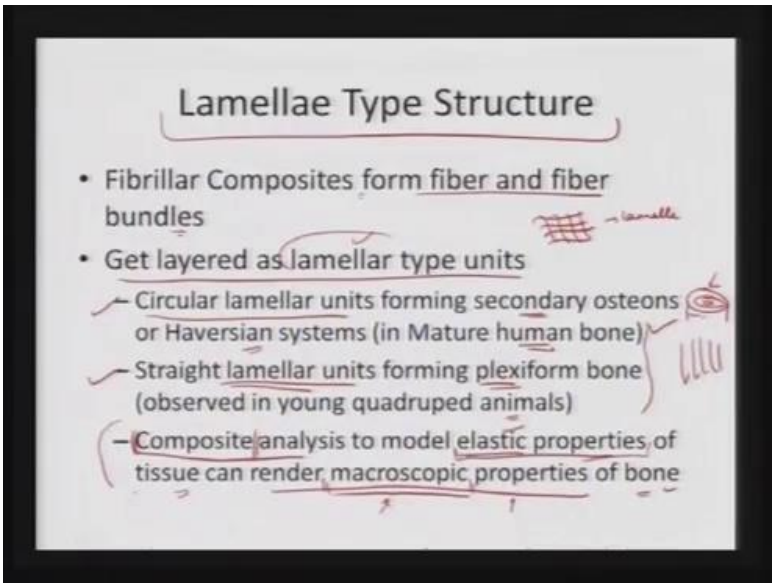

And from there on, we go on to forming lamely type of a structure. So, we know that, this generation of this apatite on the collagen is r fibers structures fibular type of composite, and these eventually form fiber bundles and these fiber bundles can be layered. So, these fiber bundles can get layered to form certain lamellar. We can see that all the fiber components that are forming certain lamely.

So, these lamellas structures can neither go as circular lamella units, so it will, it can form circular lamellar units, which forms secondary osteons or Haversian system. And this is present mainly in the nature human bone. So, this circular lamellar units can go on to forming on osteons and Haversian systems, which are predominant in the nature human bone. These are also go on to forming straight lamellar units, so it can also from

straight lamellar units, and which forms plexiform bones and this are observed in quadruped in animals such as cats or rabbits.

So, we can see that the lamely can be distinguished into 2 parts, circular lamely units which are gone to form Haversian system of osteons, which are predominant in the nature human bone. And these are also, these kind of also gone to forming straight lamellar units which forms plexiform bone in the quadruped in the animals such as cats or rabbits or higher than that. And now in this case, we have developed the entire structure.

So, we have formed the fabulous units these have finally form the lamely units, along with lamely, we can identify what is the overall mechanical performance of the, what is mechanical response of this particular unit or that particular structure. So, now we have the composite available to us, and we can analyze this particular composite of how it is responsible to a certain external stimuli. It can be elastic properties, it can also be the rheological properties in terms.

So, we can identify the happening at the macroscopic level. In the previous case, we know the, we knew the micro structural arrangement of it. So, we could weights the properties, the elastic properties by the composition of hydroxyapatite and collagen. In this case, we know exactly how these units are been circulated and what is the overall system or the overall structure, which is being developed either a circular lamely or a straight lamely.

So, now we have the entire composite available to us, and now we can model its elastic properties. That is the beauty of this structural or generation or the development of this structural units. So, now we can model the elastic properties of the tissue, which will render macroscopic properties to the both. So, that is very-very nice flow of properties that we start from basic structural units, those forms to ultra structural units and in ultra structural units, we know what is the distinguishing.

So, we can identify certain properties at that level, but in this case, we can identify how these layers are now arranged as lamely units, and now because it is lamely, we know how is the overall arrangement of these osteons and Haversian systems or may be as plexiform. So, now we have a composite available to us and then we can model the

elastic properties of tissue. So, it can mimic or it can tell us the macroscopic properties of the bone because this is the unit which is eventually forming the bone.

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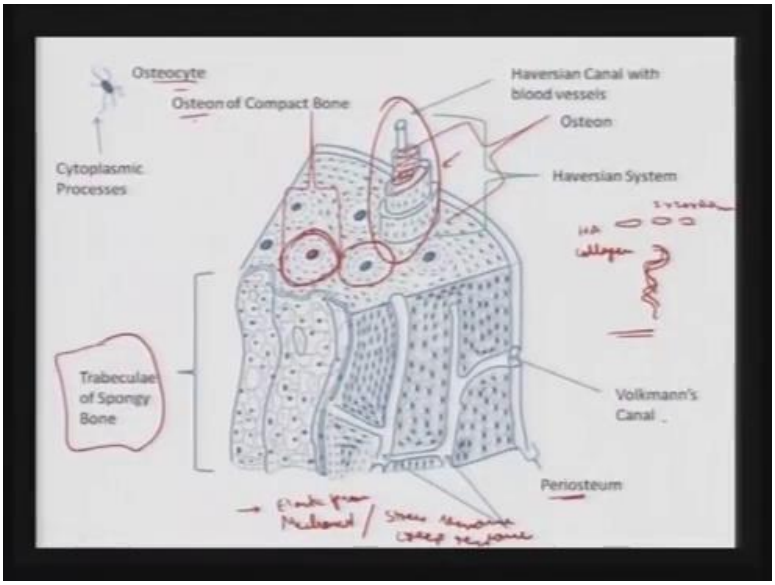

So, this is the complexity which is associated with the bone hierarchy. So, we start with the basic fundamental blocks of hydroxyapatite and collagen. So, we know, we have certain crystals of hydroxyapatite 2 by 20 by 40 nano meter. We have collagenous fiber, tropocollagen and these going to following certain fibrous or lamellar kind of structure. And these eventually form osteons.

So, we can see the osteon construction like this. So, we have Haversian canal out here and the osteons how do they form the circular units, circular Haversian of osteons. So, we can see that part out here, these are nothing but the osteons of compact bone. So, we can see how these units are now arranged, how these lamellas are, this circular lamellas are now arranged to form this entire construct of structure of bone.

And now in this case when we have everything available to us, we can eventually form get the elastic properties as well as the mechanical properties it can, it can be either the stress response or the creep response we can also be observed. So, we can see we have periosteum, Volkmann's canal, we have Haversian canals, we have osteons, osteocyte, so we have osteocytes, osteons even the entire Haversian system is. Now, Haversian canals, and Haversian system is now is available to us to completely form the spongy bone.

So, once we have this entire construct ready, we can now play with it and find the mechanical response of this entire structure. So, that is the very nice thing about the difference in hierarchy. So, the properties of the hydroxyapatite with the collagen will be very-very different once they go on to forming a fabulous kind of a structure or lamely kind of a structure. Then the construct will be very-very different and find the properties of the dead level.

Because we know the percentages of the HAp and the collagen and once they come together to form osteons the overall out lay of the osteons either a circular or a straight lamely. We can identify what will be the response of the bone because now these are the units the way they are arranged. They will, they will give rise to certain give and takes at interfaces as well as the properties, the individual properties and how they are arranged at that level they make the nature of the bones. So, now we can get the bulk properties of the bone while this construct

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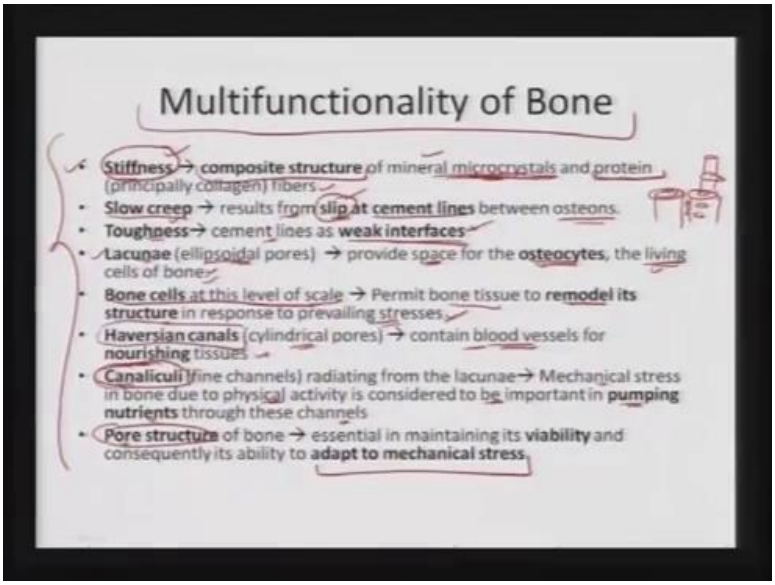

And apparently the way all the individual components are present, we know that bone is a multi functional entity, we are running with jog a lot, so bone undergoes much more mechanical stress, it under goes fatigue, it also rise to give some yielding, so that the some stress can be easily dispersed. At the same time all the blood cell have to be supplied certain nutrients.

So, now we can see the different complexity in terms of supplying the neutrinos, supplying the gasses to those cells, also being able to accommodate all the cells without getting them die. So, incorporating certain stress distribution, having some porosity to absorb some shock. So, these are the multi functionality which is been incurred by the bone on a daily basis. So, we can see the stiffness, it arises because of the composite structure of the mineral part.

So, we have micro crystals, which are present in the bone, and again the proteins which are the also absorb certain shock. So, we have stiffness which is comprising out of the loading. So, loading is been taken by the micro crystals of the hydroxyapatite and protein takes the shock. So, the entirety we get a stiffness arising because of the composite structure of the minerals micro crystals of hydroxyapatite and collagen is protein fibers.

So, that is 1 component of the bone functionality, other than that it can also undergo certain slow creep. So, for allowing the creep so that the stress can be distributed easily, we need to allow slipping, so the slip can also occur at the slip lines between the osteons. So, we have certain osteons, so slip can occur between those osteons so slip can easily occur between the osteons and within the osteons as well to give rise to certain slips that can also accommodate the certain stress.

And again the toughness can also come as because of the weak interfaces, interfaces are very-very strong then, it can even crack the bone. That part we do not want because we do not want to damage the bone. So, the nature is devised or nature is designed the bone in a manner that it can also incorporate certain slipping at the cement lines and that occurs because of the week interfaces and in the process we can also absorb some, absorb some shock.

And again the lacunae or ellipsoidal pores are present to provide space for the osteocytes, if there is no place for the osteocytes then basically there will not be living entity in the bone. So, there are certain osteocytes, they have to be supplied certain nutrient, they have to be supplied certain gasses or some oxidizing atmosphere, so that they can absorb the nutrients and they can survive. And they can reconstruct the bone as and when required. We do not have any space available for them, there eventually the bone will start getting dead and that part will again hamper the functionality of the bone.

So, the way that has been designed that there are certain lacunae and ellipsoid pores which will provide space for this osteocytes, and make the life, living for the bone cells. Again bone cells at this level of scales, they also permit bone tissue to remodel its structure. So, in order to remodel we also need to have some space, we need to have some regime to allow its re construction, it is remodeling, at the same time should also access to getting certain nutrients.

So, all those things are allowed by the bone cells at this level of scale to permit the remodeling of the structure and in response to the stresses. So certain stresses are being applied, it should be able to remodel to itself like, by slipping at certain regimes, by allowing the collagen to stretch, by allowing the protein to impart certain toughness to it. So, all these things require remodeling and that is again permitted because of the complex structure of the bone and then we have a Haversian canal of cylindrical force which are present to contain blood vessels because the all are tissues in the bone, they also need nourishments.

So, nourishment is being provided by the Haversian canal, which are nothing but the cylindrical pores which contain the blood vessels. Then we also have fine channels of canaliculi, they also assist by pumping the nutrients. So, once a certain mechanical stresses are been applied because of certain physical activity, it can be running, jogging or an impact or even of walking. So, they basically get nutrition by the pumping of this mechanical stress through this channels and that is being incurred by the canaliculi. And again the pore structure is designed in such a manner, that it is able to adapt to the mechanical stresses.

So, we can see this so many components of the bone how complex, and how they can be organized together to give a multi functionality to a bone. So, stiffness we can see stiffness is arising because of the composite structure of the hydroxyapatite crystals and the protein, creep also can be accommodated by slipping edge the cement lines. Toughness is also been incurred by the cement lines at the weak interfaces then, we have lacunae which will provide space for osteocytes that it can provide the nutrients and it can allow the living of all those bone cells.

And then bone cells, they are required because they want to re-model the structure in case of any stresses are applied to it. Then we have a Haversian canal, it also contain

blood vassals to providing the nourishment to the cells. We have canaliculi with fine channels which allow the pumping of the nutrients through this channels, so it can be reach to the cells. Then we have a particularly designed pores structure to allow the adaptation to the mechanical stresses.

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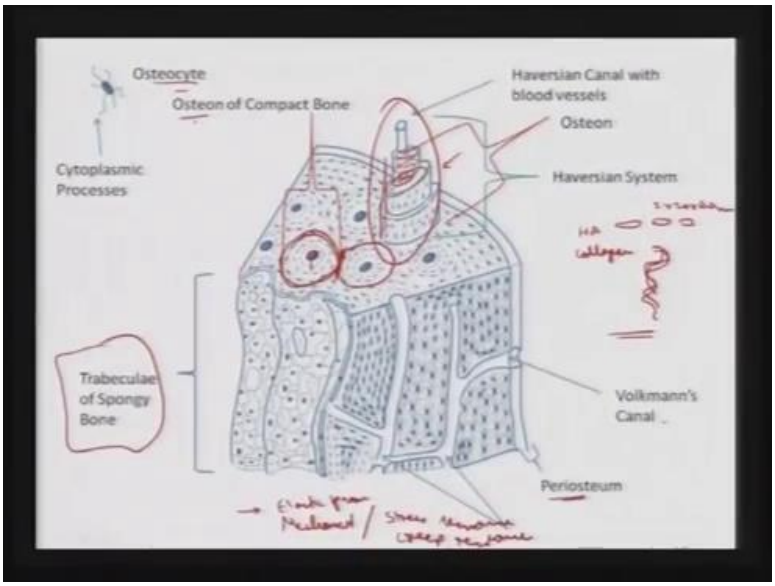

And that is why we see, we have all those lacunae or the slip lines between those osteons and how we can supply the nutrients. We have canaliculi or the pore structure and then, we have blood vessels which can provide the nutrients. So, all these things are so complicated and well so connected at the, at this level to allow the multi functionality of the bone.

So, that is what makes the structure very important in different bone scale. Unless we have a smaller entity, smaller pore, we cannot generate a bigger pore and how these canals or how these lamellas are devised. So, that they can yield as it when required and response to the mechanical forces or in response to the slipping, in response to certain other shock.

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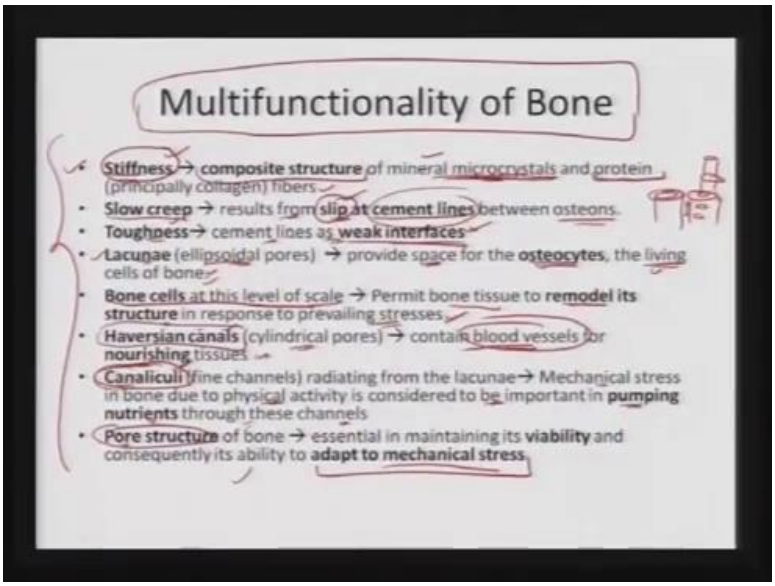

So, that is what we see that multi functionality of the bone is highly depended on the structure, which is predominant in different lens scale. It can be very-very fine like canaliculi to pump the nutrients, it can be much bigger so Haversian canal system to contain the blood vessels. So, the same porosity but with different lens scale, it can, it can render different properties.

So, we can see canaliculi can pump nutrients, Haversian canal can continue blood vessels for providing the nourishment to the tissues. And again the pore structure itself can allow repetition to mechanical stress. At the same time the cement line which are nothing but the porosity, they can also yield slipping as an when a mechanical stress is applied by acting as a weak interface. So, that is the overall functionality of the bone which is so very essential for devising the multi functionality to the bone.

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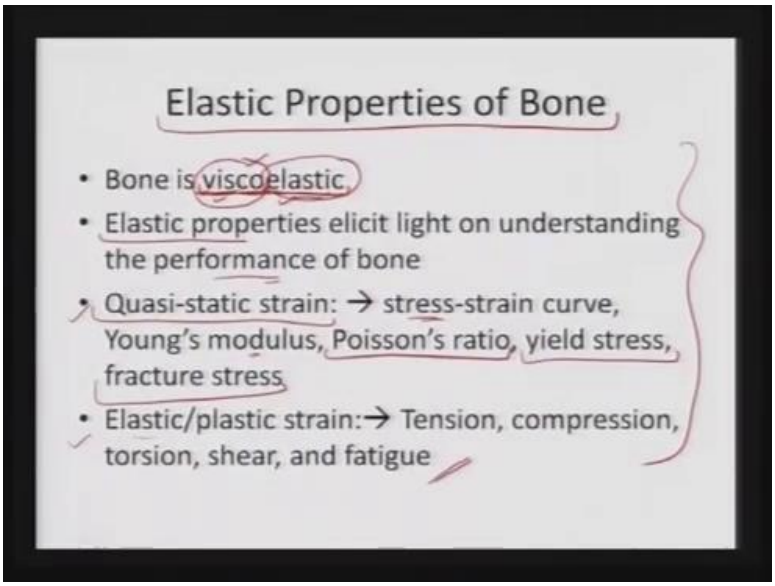

The elastic property of the bone is restricted by its components, and bone is viscoelastic in nature, it means that the bone gives response because of the bonding between the atoms or the molecule. There is a elasticity part, viscosity or the visco elastic becomes because of the diffusion of atoms at particular level. So, diffusion of atoms or molecules gives rise to viscous in nature of the bone and elasticity comes because of the strong and the mineral part of the bone.

So, once we have the mineral components that gives the elasticity and some molecular, or amorphous nature, or liquid type nature gives to rise to some viscous type of response. That is because of the diffusion of atoms and elasticity is because of the immediate response because of the bonding between the atoms and bone is a visco elastic entity.

So, learning that elastic response or the visco elastic response will tell us, how the bone will perform when certain stresses are been incorporated, or how it will, it will respond to certain external stimuli. The many-many properties of bone, which have been studied because by doing certain experimentation.

So, Quasi-static strain gives rise to stress and curve, it can give rise to the evaluation of the young's modulus. We can also identify the Poisson's ratio by the response of the transverse components with respect to the longitudinal components. And then we can also identify the yield strength, yield stress, yield strength, fracture stress of fracture strength, and other than that if we apply certain elastic or plastic strain in tension,

compression, or torsion, shear, and fatigue. We can again identify certain properties of the bone.

So bone is a very complicated structure because of its visco elastic in nature, and elastic properties will tell about the overall performance or understanding how it will behave when any external stress or external stimuli is being applied on to it. So, we can either have Quasi-static strain to identify certain static properties or elastic plastic strain to identify its visco elastic properties. So, that will make the structure very-very complicated.

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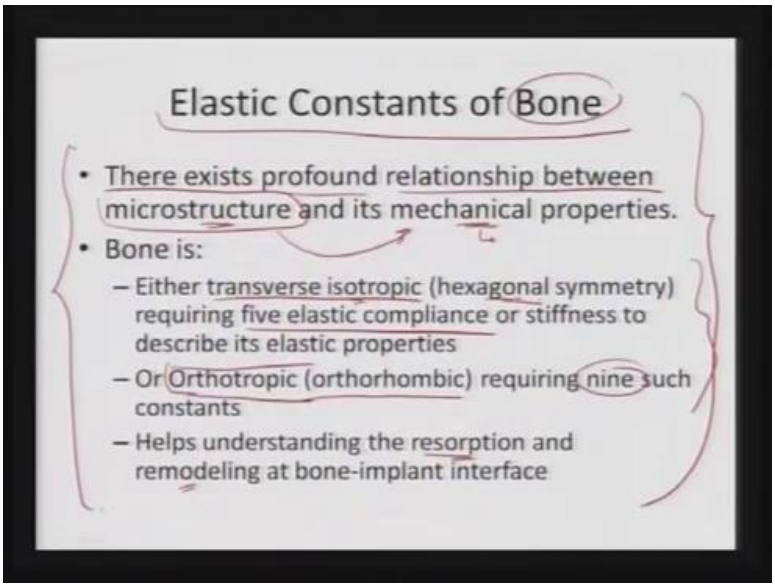

So, there are certain ways which we are relating the bone to, so basically it is the hydroxyapatite, which will give rise to elastic components, elastic part of the bone. So, again we can, bone can be considered as either as a transversely isotropic or orthotropic because of the hexagonal symmetry of the apatite which is the basic load bearing components of the bone.

So, there is much relation or much more profound relation between the micro structure and the mechanical properties. So, the manner in which we have the micro structure or how this apatite and collagen are arranged at a micro structural level, that will dictate how the mechanical properties will basically evolve. So, bone is can be considered either as transversely isotropic because of its hexagonal symmetry and when it is considered as

hexagonal, it will require only 5 elastic complaints and stiffness, to describe its elastic properties.

But in cases when it is not, so when it is orthotropic because of its orthorhombic symmetry will require nine such components and by devising them in that way, it will help us to understand the resorption and remodeling because that is very-very long that when stress is applied to a bone it will resorp or it will try to generate itself or remodel itself so that, it can take stress in a better manner, or in a better fashion. And where there is no stress is being incorporated by the bone then, that part of the bone will get dissolving itself.

So, that is the beauty of the bone that it can remodel itself or it can take the stress and it can regenerate itself. So, for that it is very-very essential that we learn how this elastic constraints or how this elastic or the mechanical properties of the elastic properties are very much essential for the development of the bone.

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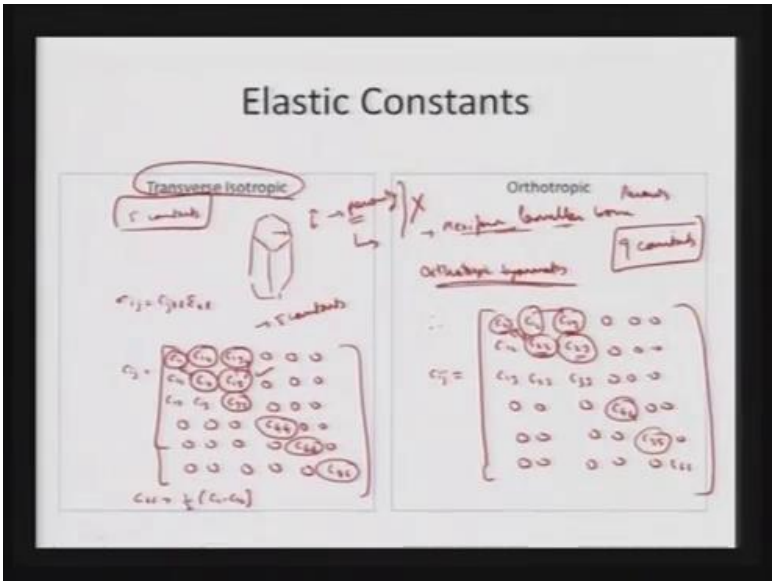

So, when we consider it, consider it transversely isotropic, we can define it by using 5 constants and that arises because of the hexagonal symmetry of the bone. So, we can see the properties along 1 and 2, they turn out to be the same. So, in that particular case, we can see that the overall compliance matrix can be given, first of all the dependence of ij. So, the overall compliance matrix can be given as C 11, C 12, C 13, 0, 0, 0, and we have C 12, and C 22 is now similar as C 11 and C 23 is also now similar as C 13.

So, that is the direction of the elastic constants, out here compliance constants consent out here. Now, we get C 44 now again C 22 is this C 55 is similar to C 44, so in that case we get C 11, C 12. Now, C 13 and C 23 are the same and so we can get the similar entity C 22 is also similar to C 11 that is the dependence we get then C 12, C 13, C 33, C 44, and C 55 is similar to C 44 and C 66. So, here we can see total of six constants, but C 66 can be given as a dependence of half of C 11 minus C 12.

So, in totality we have now five constants which are required for defining the transversely isotropic crystals because of the hexagonal symmetry of the hexagonal symmetry, we can define them only via five constants. So, that is how, that is how we can see out here. But what happens once we are, once we are stretching it, it might lead to certain porosity and once it is leading to certain porosity then, obviously the bone can be defined via transversely isotropic or via hexagonal symmetry.

So, in that case it can also change the properties along the radial of the initial direction. So, because of that in such as elastic in flaxy form lamely bone as flaxy form lamely bone or because of porosity. This dependence are no more ((Refer Time: 42:51)) So, in that case we have to define them via orthotropic symmetry. So, in that case we do not have dependences of C 13 been equal to C 23. Now, these additionally becomes arise.

So, C ij now become C 11, C 12, C 13. Now, C 22 is not equal to C 23 or C 11, so C 22 is different and C 11 is different, and then our C 23 is also different from C 13 which was not so in the earlier case. So, we can see, now our C 44 is also different from C 55, that is the dependence what we get in this particular case. So, the C 23, C 13 they are not similar and C 11 and C 22 they are again not similar and C 44 and C 55 are also not similar.

So, in that case once we have a non transversely isotropic property because of generation of porosity or because of plexi form lamely kind of a structure, these are no more uniform along the 1 and 2 direction. So, now we need to also provide the values of properties along those directions, so in that case C 13 and C 23, they are not the same, and C 44 and C 55 also are not the same. C 11 and C 22 are also not the same.

So, now we need the total of nine constants to define the overall elastic properties of this orthotropic structure and so bone is generally orthotropic in both the direction and that is how we can define the mechanical properties along these two directions.

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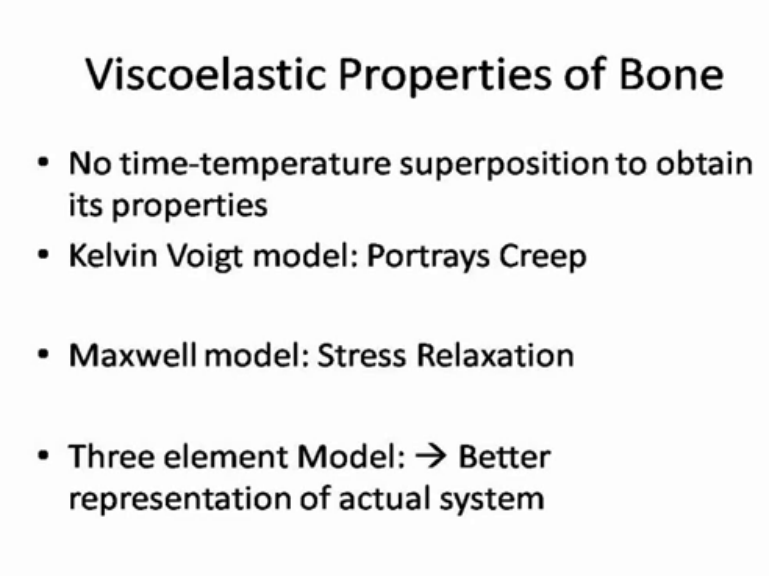

Now, coming to the visco elastic property of the bone. So, basically there is no time temperature superposition to obtain its properties because the way in which the time and the temperature will behave, it is very-very different. So, we cannot impose by increase in temperature to that will be the time response of the bone that is not so. So, we need to define it via Kelvin Voigt model that can portray the creep properties, we can also define them via Maxwell model, that will provide the stress relaxation of the bone.

So, when we are applying certain stress, how that stress is getting reduced, that can be defined via these two models. And again these are only two element model, so in Kelvin Voigt model or the Maxwell model we only have one, one of each resistance and the capacitance part. So, that is how we define them, so in Kelvin Voigt model we have everything in, everything in parallel. So, we have this resistance and then this capacitance in parallel whereas in Maxwell model we have both of them in series.

So, we have resistance and capacitance in series from there we apply the stress. But these models some times are not enough to define the properties of the bone. So, three elements or more elements or models will be representing the bone response in a much better manner and it will be nearer to the actual system. So, let us no see how the response will occur for the Maxwell and the Kelvin Voigt model and the Kelvin Voigt model.

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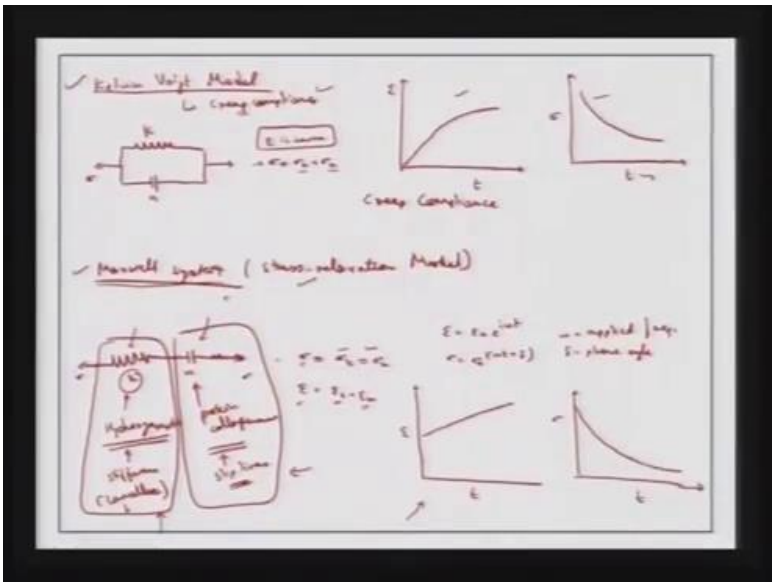

What we are doing, we are defining the creep compliance to it and we have these entities in parallel. So, we can see we have a resisters and capacitance with certain stress has been applied to it. So, in this case we can see the stress the we can the resistance part can be k and this capacitance part can be n, so in this case what we are seeing is, the stress is now been shared between these two components of the stain is same, and sigma is nothing but sigma of k components plus sigma of n components.

So, that is what we are able to see here in the creep, in the Kelvin Voigt model. So, eventually we can see is the strain, how the strain developed with the, how the increase in time we are getting strain in increase the stresses, or how the stress is being released with the time. So, we have sigma n t, this is also called creep compliance model. So, once we are applied certain constraint load, how the stress or stain basically start increasing, how the stress start decreasing with time. And again we have one more model, so we can see once we, so once we have this other model of Maxwell system or Maxwell model is also called the stress relaxation model.

So, in this case what we have, we have this system in series, so we have this k component and this capacitance component in series. So, we have stress k component and n component, so in this case what is happening is the overall stress is being shared, so sigma, so the stress is similar, the strain is being shared, so sigma is equal to and this

is being equal, so sigma equal sigma k, this is sigma n in the Maxwell model, and again approximately it is overall it can also be represented by…

So, if we apply some frequency that is the omega is applied frequency and delta is the phase angle that is the phase line between the stress and strain. So, with these we can see the overall, the overall strain response with respect to time will appear out to be a linear dependence. And then, with respect to the time or stress we get a decreased, so that is sigma eventually dies out with, dies out with time. So, Maxwell model is very good for showing the stress relaxation and Kelvin Voigt model is very good for the creep compliance.

So, we can see that in the Kelvin Voigt model, we have the resistance and the capacitance in parallel. So, in this case the strain is similar in both the components and that may not be same in the real cases, but the strain is now being shared between those two components it is being k and n. Whereas in Maxwell model, we have stress is the similar in all the components whereas stain is the combination of the resistance and the capacitance.

And that is what we are seeing here and both the cases. These are nothing but the rheological response of the bone, and that can arise because the resistance can be given mainly from the hydroxyapatite. This is the mineral part and then n can be come mainly from the protein or the collagenous component. Apart from that the overall construct and mechanical structure can also lead to much more stiffening, so this stiffness part and the compliance part which can also come because of this slip lines.

So, it can be again from lamely, so lamely the overall stiffening part can come out as a resistance whereas the compliant part can come out, or the capacitance part can come out from the slip lines between the osteons and porosity of the protein collagenous type of the structure. So, we can see that the bone structure can be easily represented by these two components of resistance and capacitance to give out a final remodeling or the final reconstruct of the structure to yield the rheological response with respect to certain stress.

So, when you apply certain stress, how the stain develops or how the reconstruction or the re modeling of the bone occurs with respect to time can easily represented by the Kelvin Voigt model where we see the creep compliance or it can also be represented by

the Maxwell model where we can see how the stress relaxation can occur in that particular case.

That tells the hierarchy part, but that is the multitier hierarchy which is inherit in the bone, that how the hydroxyapatite and collagen come together to give of certain properties, the elastic properties. And how those elastic properties are been utilized when a more lamely structure or lamely or osteon structure is formed to give out the bulk properties, or the bulk property to the bone structure.

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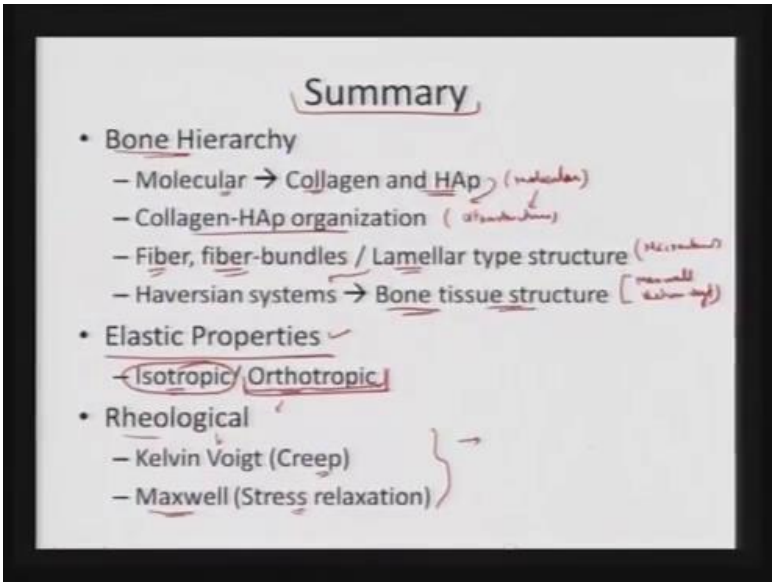

So, in summary we can see that the bone hierarchy is very-very complicated. At molecular level we can see the construct of collagen and hydroxyapatite. Eventually this collagen and hydroxyapatite is organized to form ultra structure. So, from molecular structure, we go to ultra structure then these going to form the fiber, fiber bundles or lamely type of structure. There is nothing but the micro structure and now these going to forming osteon and Haversian systems to finally yield the bone tissue structure.

And at this level we can identify the rheological response via Maxwell model or via Kelvin Voigt model, Voigt model and also we can also identify the mechanical properties via making them transversely isotropic or orthotropic in nature. In that particular manner, so that is what we see the elastic properties either be isotropic or those can again be orthotropic. And once it is hexagonal symmetry we can reduce the number of constants and because of the presence of this lamely type of structure, linear type of a

structure that can, the presence of porosity, that can basically make the structure orthotropic.

And further we can define the overall rheological response via Kelvin Voigt model where we can define the creep relaxation or the creep compliance, or it can also be represented by the Maxwell model, where we can learn about the stress relaxation in a much nicer fashion. And these are the two element models, but we can always increase the number of elements to more than 2 an learn about the overall rheology of the bone. So, we can learn about the response mechanical response of these structures with respect to certain stress or loading. With this, I end my lecture here.

Thank you.