Biomechanics of Joints and Orthopaedic Implants
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Lecture No. 26
Bone Structure and Mechanical Behaviour

Good morning everybody. In this lecture, we will be discussing about the bone structure and mechanical behaviour.

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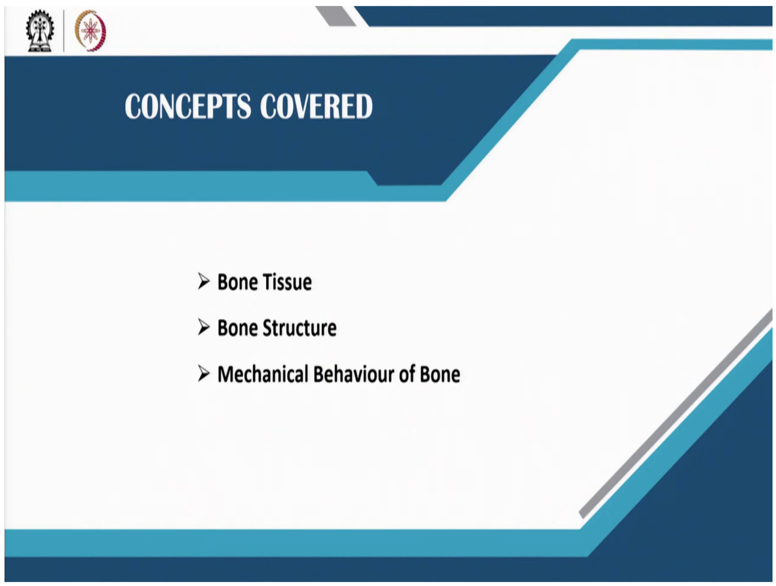

The concepts covered in this lecture are bone tissue, bone structure and mechanical behaviour of bone.

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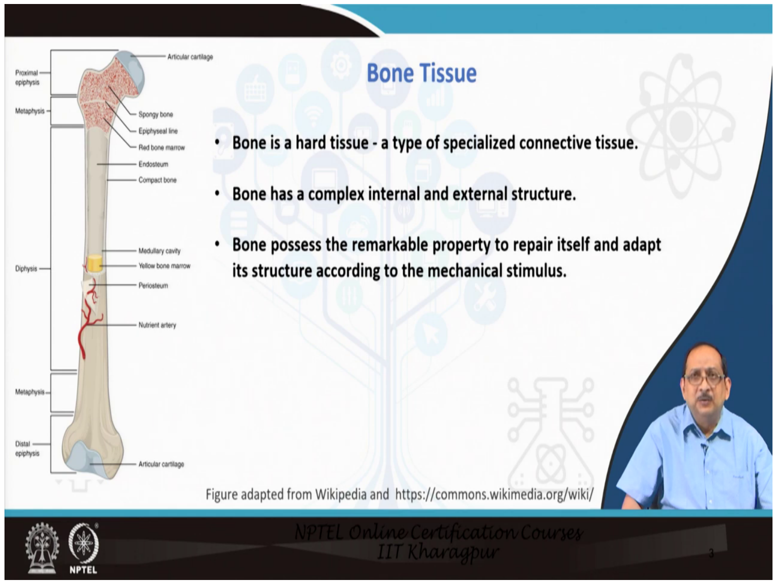

Now, bone is a hard tissue and it is a specialized type of connective tissue. It has a very complex internal and external structure. It possesses the remarkable property to repair itself and adapt its structure according to the mechanical loading or stimulus it receives.

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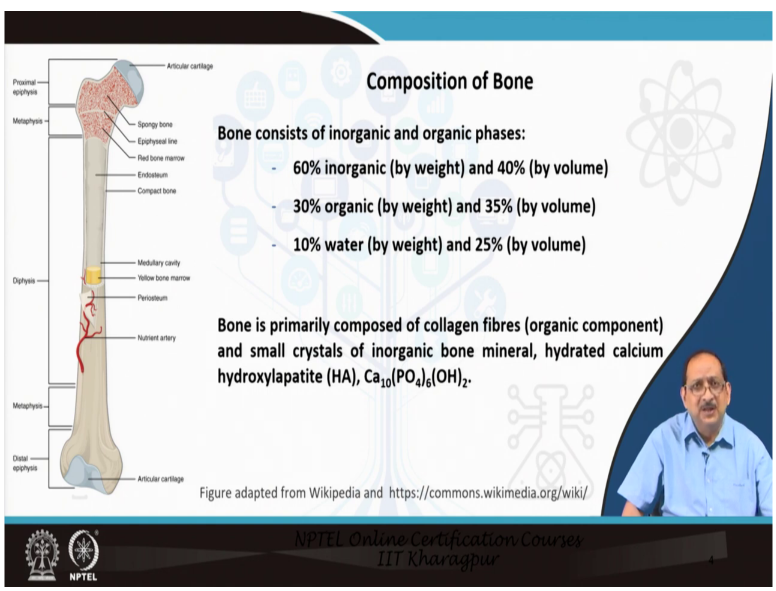

Now, let us come to bone composition. Bone consists of inorganic and organic phases: 60 percent inorganic by weight and 40 percent by volume, 30 percent of bone is organic by weight and 35 percent by volume, the rest 10 percent is water by weight and it consists of 25 percent of the volume. Bone is primarily composed of collagen fibre, which is organic component and small crystals of inorganic bone material, which is hydrated calcium hydroxyapatite.

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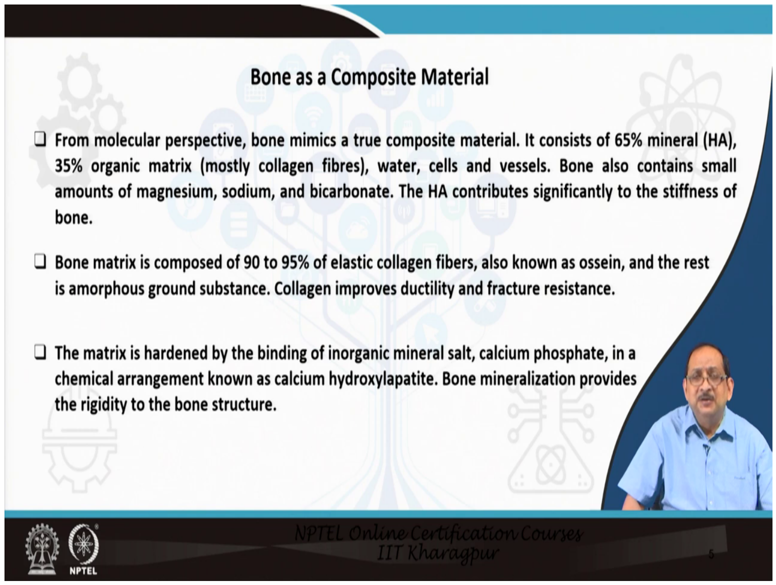

Now, bone can be regarded as a composite material. So, from molecular perspective bone mimics a true composite material. It consists of 65 percent mineral (hydroxyapatite) and 35 percent organic (matrix mostly collagen fibre). Apart from that, it consists of water, cells and vessels. Bone also contains small amounts of magnesium, sodium and bicarbonate.

The hydroxyapatite contributes significantly to the stiffness of the bone. The bone matrix is composed of 90 to 95 percent elastic collagen fibre also known as ossein and the rest is amorphous ground substance. The collagen contributes towards the ductility and fracture resistance. The Matrix is hardened by the binding of inorganic mineral salt, calcium phosphate, in a chemical arrangement known as calcium hydroxyapatite. Bone mineralization actually provides rigidity to the bone structure.

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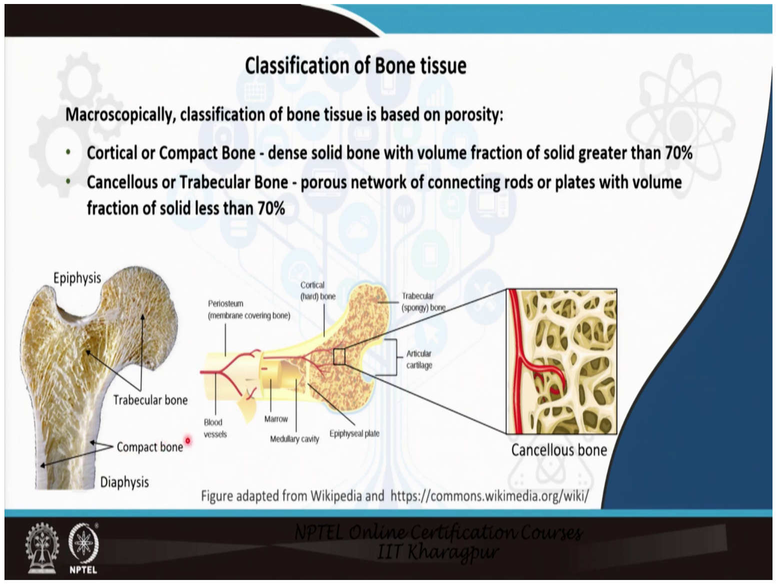

Now, how is the bone tissue classified ? Macroscopically, bone tissue is classified based on density or porosity. Now, we have broadly two classification: one is cortical or compact bone, the other is cancellous or trabecular bone. The cortical bone or the compact bone is the dense solid bone with volume fraction of solid greater than 70 percent. In case of cancellous bone, it consists of a porous network of rods and plates with volume fraction of solid less than 70 percent.

The cancellous bone structure is clearly shown here. The porous network of interconnection of rods and plates and the cortical bone or compact bone is shown here, which is a dense solid bone.

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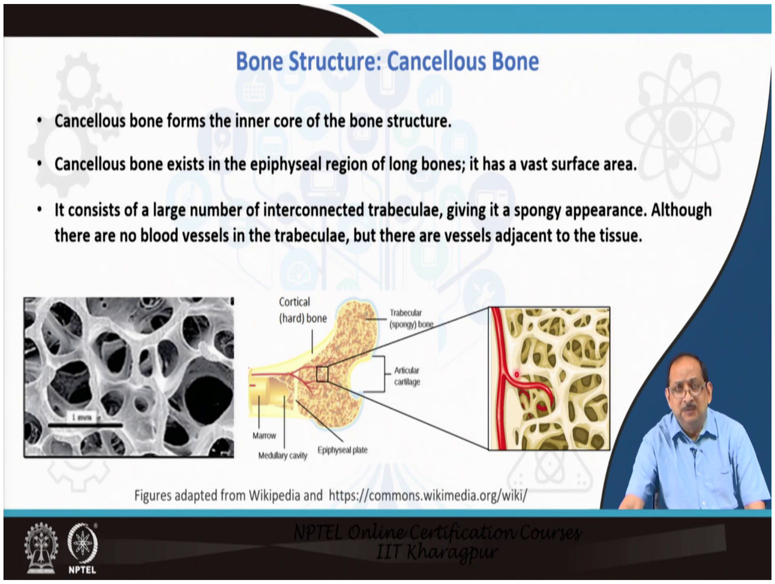

Now, cancellous bone forms the inner core of the bone's structure. It exists in the epiphyseal region of long bones and basically has a vast surface area. It consists of a large number of interconnected trabeculae, giving it a spongy appearance; that is the reason it is also called spongy bone. Although there are no blood vessels in the trabeculae usually, the vessels are adjacent to the tissue.

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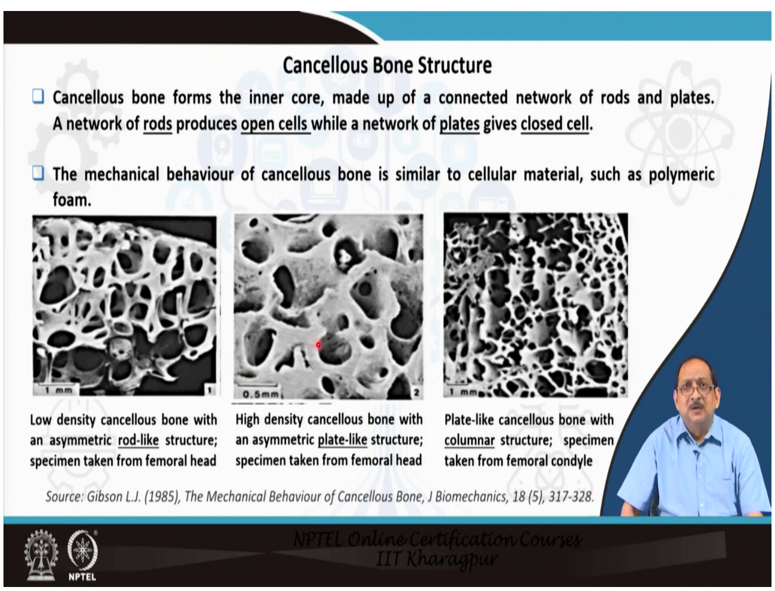

Now, let us move into the cancellous bone structure. Cancellous bone actually formed the inner core of the bone structure made up of a connected network of rods and plates. A network of rods actually produces open cell structure whereas, a network of plates gives rise to a closed-cell structure. Basically, the mechanical behaviour of cancellous bone is similar to cellular material such as polymeric foam.

So, in this slide, we can see low density cancellous bone with an asymmetric rod-like structure. The specimen was taken from the femoral head. It is a scanning electron micrograph image, SEM image. Then we have the relatively higher density cancellous bone with plate-like structure; the specimen was also taken from femoral head. And finally, the plate-like cancellous bone with columnar structure is the specimen taken from femoral condyle. So, you can see from rod-like to plate-like transformation, that is, open cell to close cell type structure.

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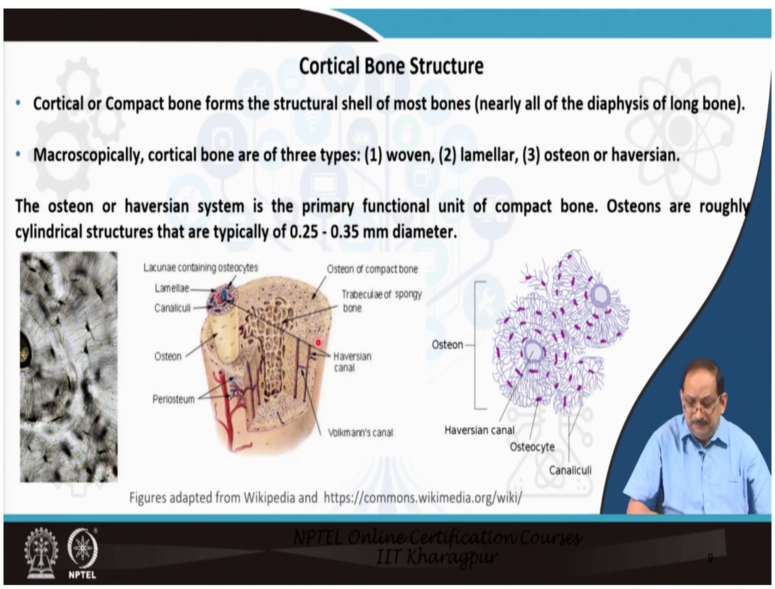

Let us now discuss about the structure of cortical bone. The cortical or compact bone forms the structural shell, basically the outer structural shell of most bones (nearly all of the diaphysis of long bones). Macroscopically, cortical bone are of three types: it is woven, lamellar and the third one is osteon or haversian. The osteon or Haversian system is the primary functional unit of the compact bone. Osteons are roughly cylindrical structures that are typically 0.25 to 0.35 millimetre diameter. The structure of the cortical bone is shown in the figure.

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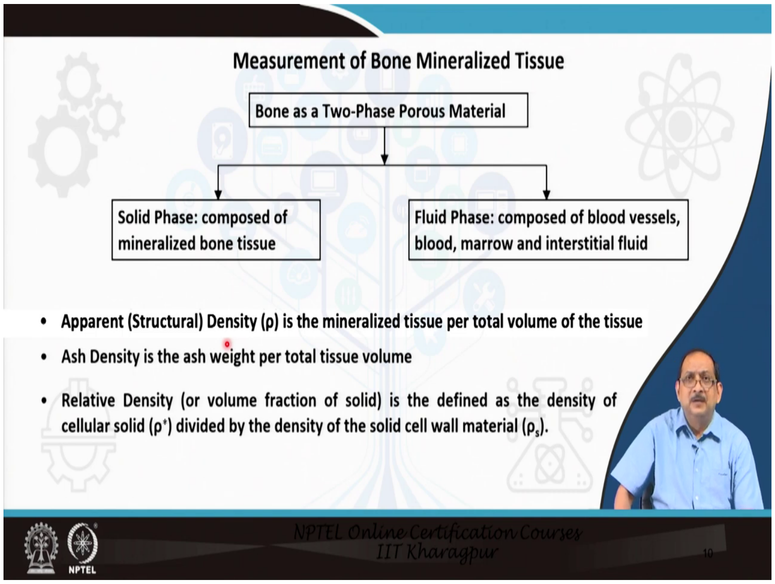

Now, how is born mineralized tissue measured? As you can feel that bone actually exists as a two-phase porous material. It has a solid phase which is composed of bone mineralized tissue, and a fluid phase which is composed of blood vessels, blood, marrow, and interstitial fluid. Now, the most important measurement of bone mineralized tissue is in the form of apparent density or structural density, which is defined as the mineralized tissue per unit or per total volume of the tissue.

So, it is defined as the mineralized tissue per total volume of the tissue. It can also be defined by ash density. It is defined as the ash weight per total tissue volume. Sometimes, the relative density has also been used to define bone mineralized tissue. The relative density is also regarded as the volume fraction of solid and is defined as the density of cellular solid divided by the density of solid cell wall material. But most popular is the apparent density or the structural density, which is basically the mass of the mineralized bone tissue divided by the total volume of the bone tissue.

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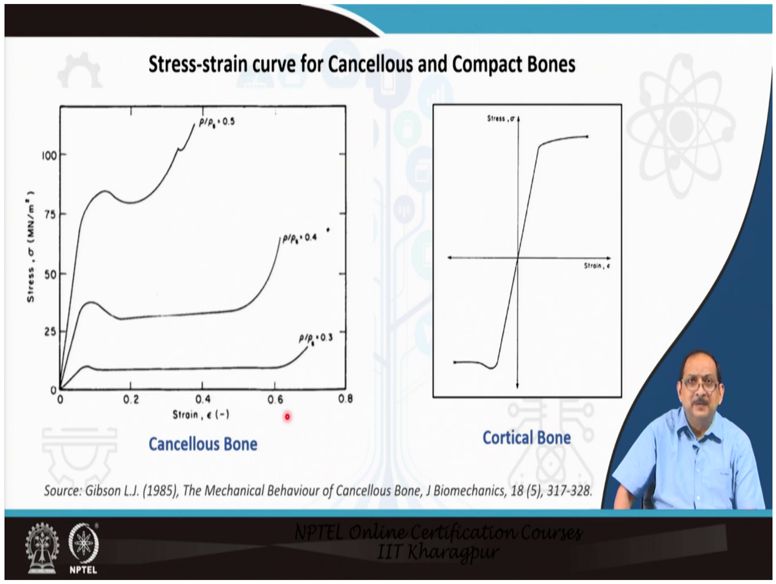

Now, let us consider the stress-strain behaviour of cancellous and compact bones. On the left, we have the cancellous bone and you can see for different relative densities, the behaviour of the stress-strain curve, the nature of the stress-strain curve is changing. For cortical bone on the right, this stress-strain behaviour somewhat resemble brittle type of material behaviour whereas, cancellous bone, as you can see, has a more ductile type of behaviour.

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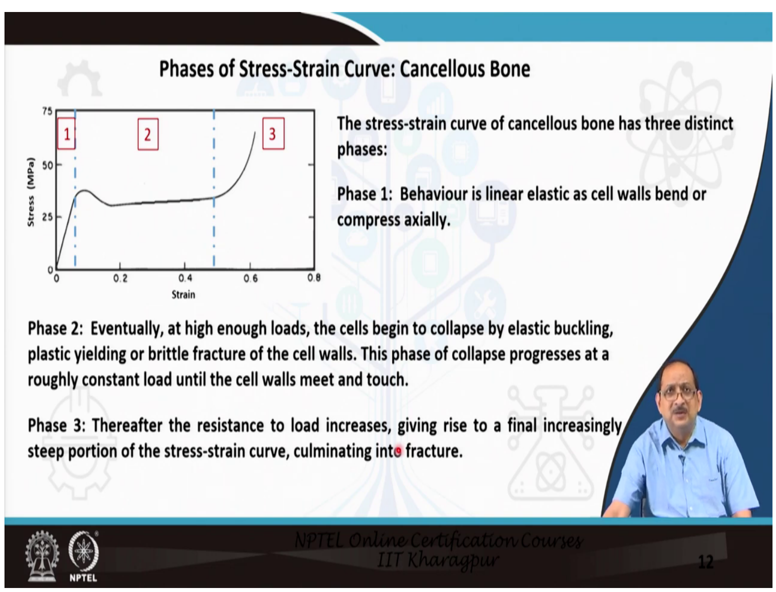

Now, let us discuss more in detail about the phases of the stress strain curve, the stress strain curve of cancellous bone has three distinct phases. The first phase in which the behaviour is linear elastic as the cell walls bend and compress axially. So, the phase 1 is linear elastic behaviour of the cell walls.

When it enters phase 2, which is eventually at high enough loads, these cells begin to collapse by elastic buckling, plastic yielding or brittle fracture of the cell walls. So, this phase of collapse progresses roughly at a constant load until the cell walls meet and touch each other. Therefore, the second phase of the stress-strain curve resemble a plateau region of the whole mechanical behaviour.

In the final third phase, the resistance to load increases in a steep manner. So, it is giving rise to a final increasingly steep portion of the stress-strain curve culminating into a fracture. So, after the second phase that is the collapse of the cell walls, the resistance to load actually increases, giving rise to a steep portion of the stress-strain curve in the third phase.

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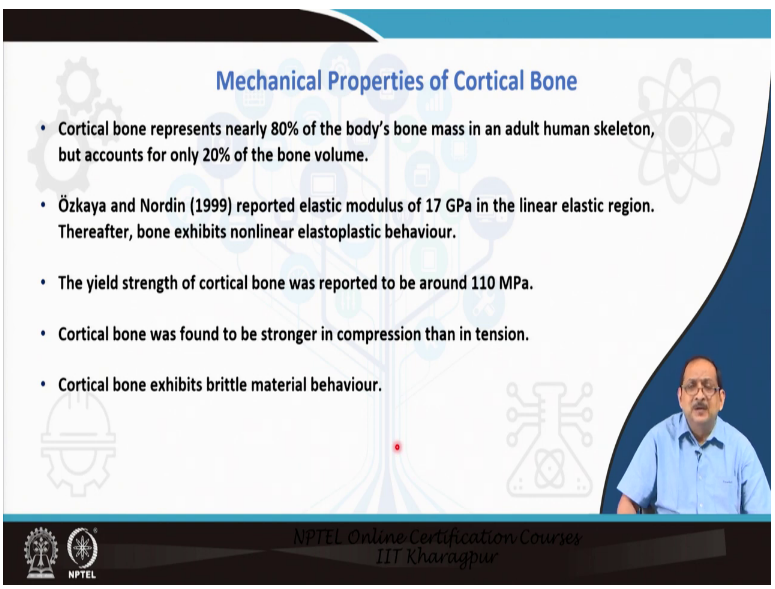

Let us, now discuss about the mechanical properties of cortical bone. Cortical bone represents nearly 80 percent of bone mass in an adult human skeleton, but accounts for only 20 percent of the bone volume. Various researchers over decades have investigated the elastic modulus of cortical bone and reported values in the range of 15 to 20 GPa, but then elastic models value of 17 GPa in the linear elastic region has been recognised as quite popular.

Thereafter, bone exhibits nonlinear elastoplastic behaviour. The yield strength of cortical bone was reported to be around 110 MPa. Cortical bone was found to be stronger in compression than in tension, and we can, looking at the stress strain behaviour shown earlier, we can conclude that cortical bone exhibits brittle material behaviour.

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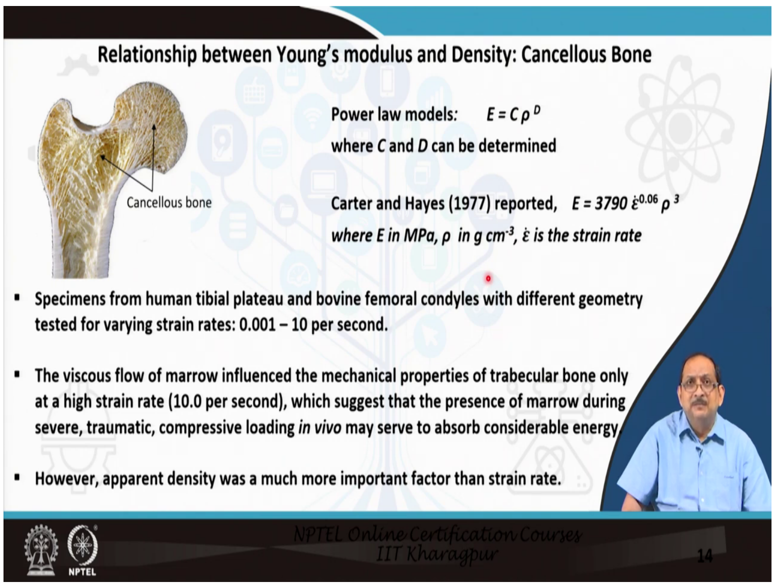

Let us concentrate on the relationship between Young's modulus and density of cancellous bone. Now, over decades there has been a lot of work on defining the mathematical relationship between Young's modulus and density of cancellous bone, and it has evolved that power-law models in the form of E, which is the Young's modulus and rho, which is the apparent density is connected with each other through power-law relationship where C and D are constants.

The first pioneering work by Carter and Hayes in 1977 reported a very important relation, E is equal to 3790 strain rate to the power 0.06 and rho cube, where E is in MPa and rho is in grams per centimetre cube and epsilon dot is the strain rate.

$$E = 3790\epsilon^{0.06}\rho^3$$

Now, specimens were taken from the tibial plateau for this particular experiment by Carter and Hayes and also bovine bone, bovine femoral condyles of different geometry tested with varying strain rates varying from 0.001 to 10 per second.

It was observed that the viscous flow of marrow influence the mechanical property of trabecular bone only at high strain rate, which suggests that the presence of marrow during severe traumatic compressive loading, say for instance, an impact load, an accident case in vivo may serve to absorb considerable energy. But, overall, it was concluded by Carter and Hayes that apparent density was a much more important factor than the strain rate to define the relationship between Young's modulus and apparent density.

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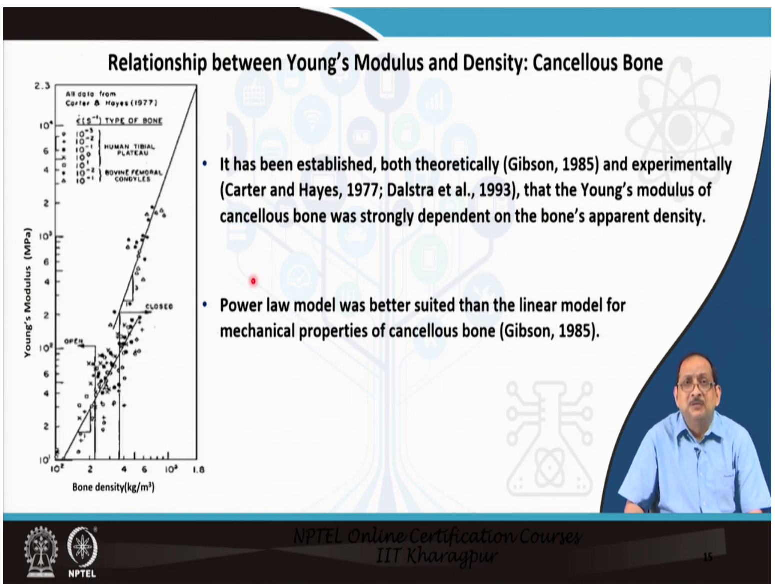

We continue with the relationship. As you can see on the left, all the data tested by Carter and Hayes has been plotted. Later, Gibson L J Gibson from MIT actually fitted relationship based on this experiment data. So, it has been established both theoretically by Gibson and experimentally by Carter and Hayes as well as the Dalstra that Young's modulus of cancellous bone was strongly dependent on bone apparent density. Power law models was definitely better suited than linear models, which were suggested over years earlier for mechanical properties of cancellous bone.

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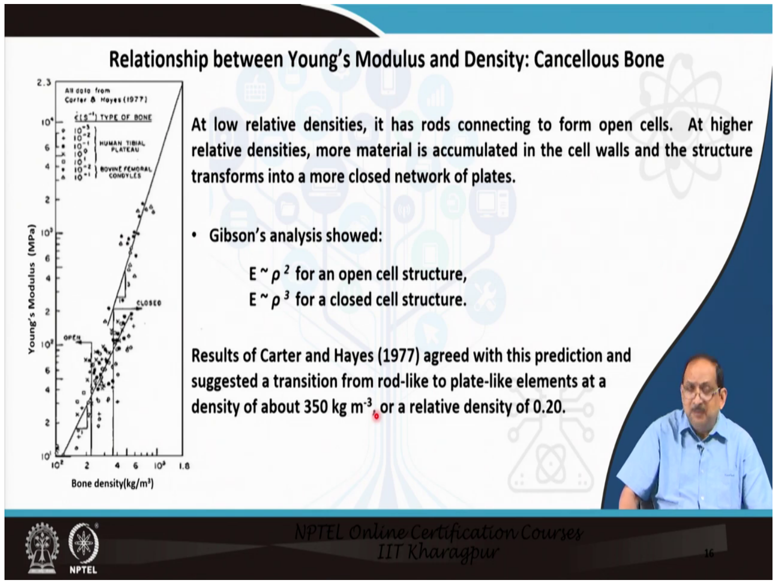

Now, at low relative densities or low apparent densities, the cancellous bone has rods connecting to form an open cell structure. At higher relative density, more material actually is accumulated in the cell walls and the structure transforms from a more into a more closed network of plates. So, with accumulation of more material the in the cell walls, the structure transforms into a more closed network of plates.

So, the Gibson analysis actually predicted two power-law relations with exponents 2 and 3, as you can see, E is related to rho square and rho cube. So, the square relationship stands for open cell structure and the cubic relationship for a closed-cell structure. So the experimental results of Carter and Hayes agreed with this prediction and suggested a transition from rod-like structure to plate-like structure at a density, apparent density of about 350 kg per metre cube or relative density of point 0.2.

$$E \sim \rho^2, \textit{open cell structure}$$

$$E \sim \rho^3, \textit{closed cell structure}$$

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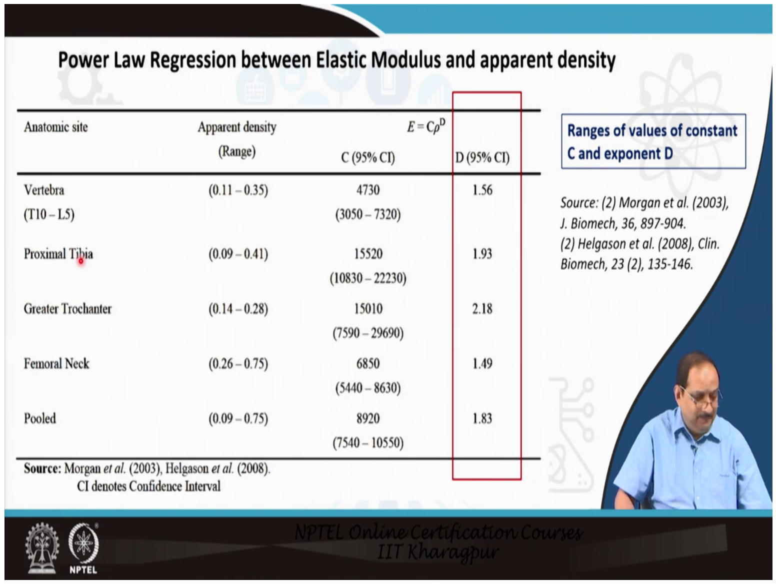

Now, let us consider the power-law models, which basically quantifies the relationship between elastic modulus and apparent density of different anatomic sites. So, you can see that the anatomic sites vary from vertebra, proximal tibia, greater trochanter femoral neck and a pooled data set and the range of values of the constant C and the exponent D is presented here in this slide. The the variation of exponent D is very clearly presented and it clearly shows that the relationship actually will vary with the anatomic sites. So, there is no single E to row relationship it varies from one anatomic site to the other, one bone to the other.

Now, there has been a lot of work in establishing power-law relationships over the years and similar to the elastic modulus and apparent density relationship, the local static strengths of cancellous bone were also can be related to the local apparent density of bone through similar power-law relationships and that has been investigated by a group of researchers as well. So, the elastic modulus as well as strength of cancellous bone is related to apparent density through the power-law relationship.

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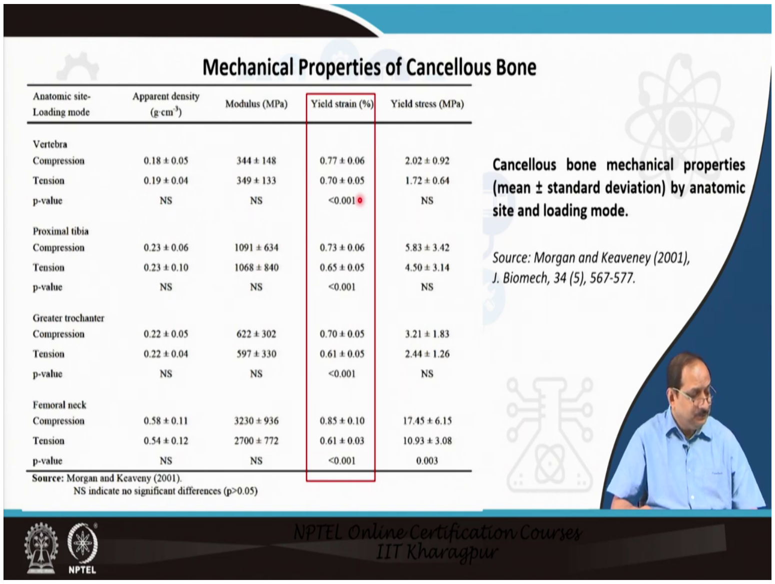

The next table that I am presenting is on the yield strain behaviour which has been highlighted. So, here also the anatomic sites are different. So, you can see vertebra, proximal tibia, greater trochanter femoral neck. An important aspect of presenting this data is that mostly load transfer and strength of bone has been expressed in the form of stresses.

But it has been found for cancellous bone, the yield strain or strain-based criteria has been found to be mathematically more simple and statistically powerful, particularly for the human trabecular bone. If we have a closer look, we see that there is variation of the yield strain from one anatomic site to the other.

But within a single anatomic site, the variation is very less in the yield strain behaviour which means, that the yield strain within each site is more or less uniform within the site providing a strong argument for the utility of strain-based description for describing failure of trabecular bone.

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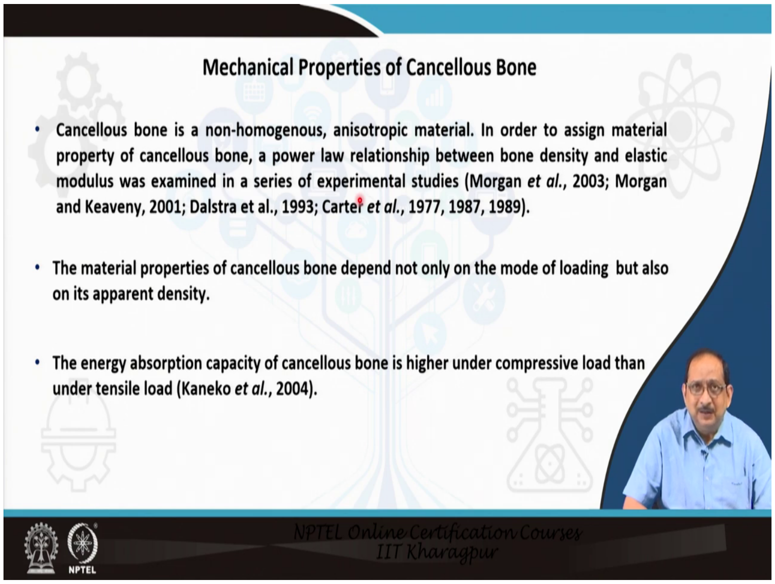

Let us now summarise the mechanical properties of cancellous bone that has been presented in the lecture. Cancellous bone is a non-homogeneous or heterogeneous, anisotropic material. In order to assign material properties of cancellous bone, a power-law relationship between bone density and elastic modulus was examined in a series of experimental studies over more than 2-3 decades.

The material properties of cancellous bone depend not only on the mode of loading, but also on its apparent density. The energy absorption capacity of cancellers bone is higher under compressive load than under tensile load.

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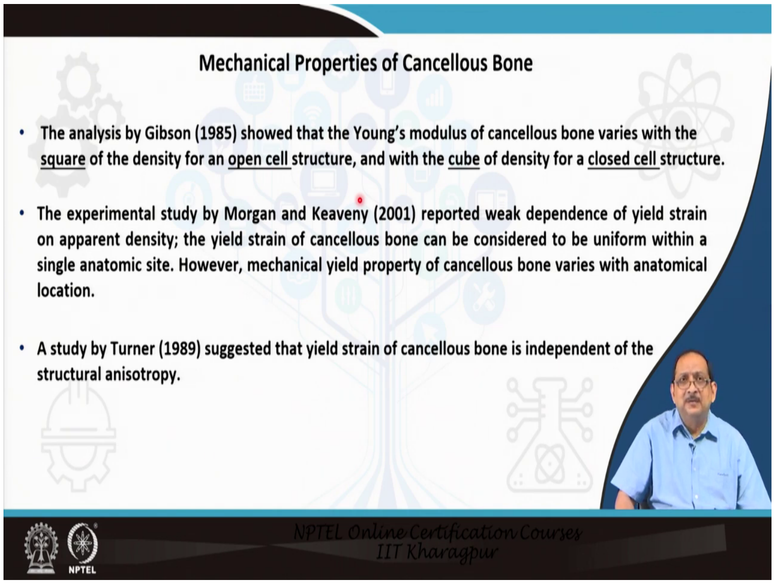

The analysis of Gibson (1985) showed that Young's modulus of cancellous bone varies with the square of the density for an open cell structure and cube of the density for a closed-cell structure. The experimental study by Morgan reported weak dependence of yield strain on apparent density.

The yield strain of cancellous bone can be considered uniform within a single anatomic site. But, the mechanical yield property of cancellous bone can vary with anatomic location. But, a study by Turner also suggested that yield strain of cancellous bone is independent of the structural anisotropy.

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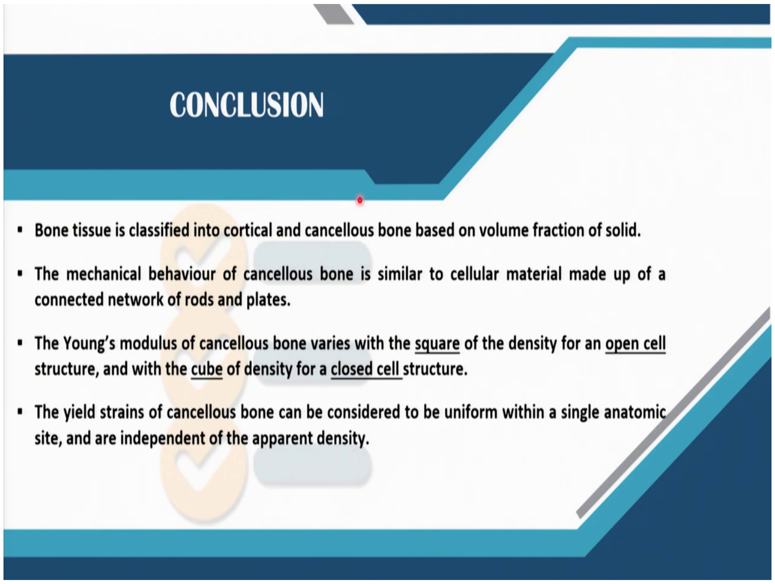

Let us now summarise the conclusions for this lecture. Bone tissue is classified into cortical and cancellous bone based on volume fraction of solid. The mechanical behaviour of cancellous bone is similar to cellular material made up of a connected network of rods and plates. The Young's modulus of cancellous bone varies with the square of density for open cell structure and with the cube of density for a closed-cell structure. The yield strain of cancellous bone can be considered uniform within a single anatomic site and are independent of the apparent density.

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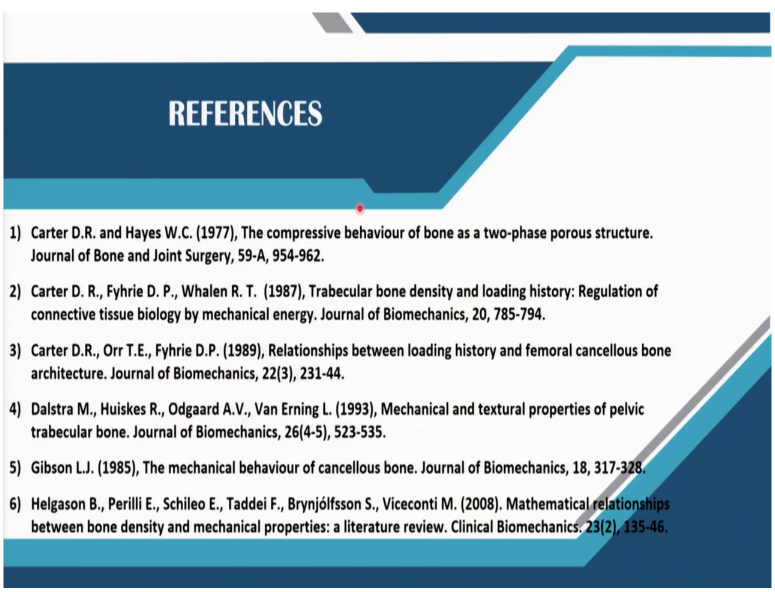

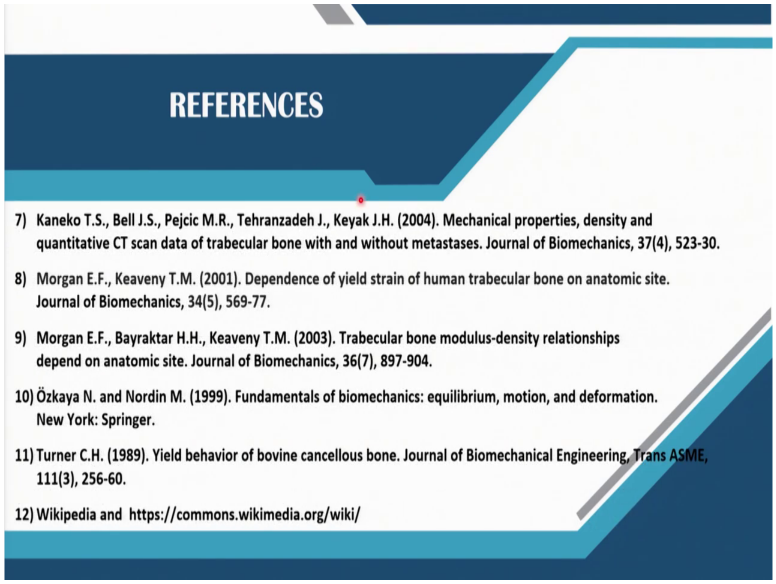

The references are mentioned here. Thank you for listening.