Medical Biomaterials
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Lecture – 38
Ceramics

Hello everyone welcome to the course on medical biomaterials. Now we will start a new topic that is called ceramics. Ceramics is also a medical biomaterial, just like a metals, polymers both synthetic and natural. Ceramics are finding lot of applications, because they have a very useful property like a osteo integration, bio reorganization and so on actually, as you know bone contains lot of ceramics. In fact, as a martial a bone is made up of a hydroxy apatite, hence ceramics oxides, different types of oxides, like alumina, zirconia they are all finding applications in the area of medical biomaterial as spacer, as a filler, as a coating material and so on actually.

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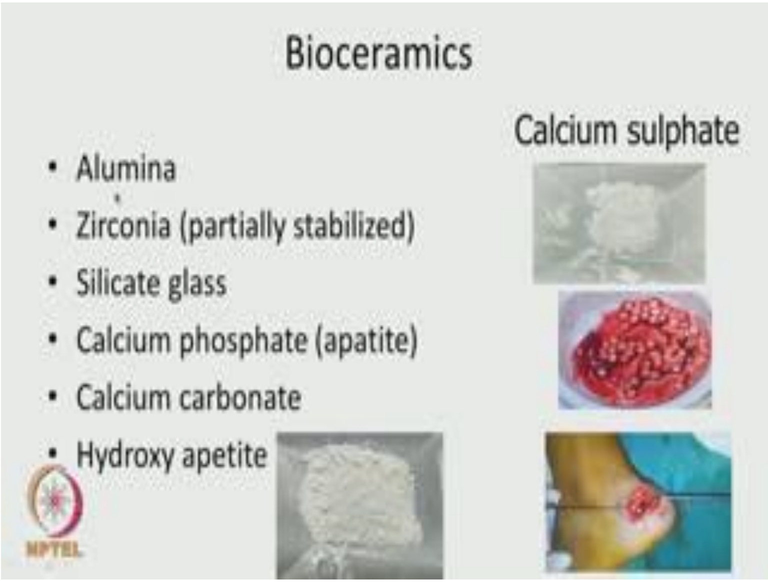

If you look at bio ceramics, alumina; that is aluminium oxide is a ceramic material which finds lot of applications, zirconia for example, zirconium oxide silicate glass; that means, SiO2. So, they are different types then calcium phosphate; that is the apatite. In fact, our bone contains lot of this calcium carbonate, hydroxy apatite. So, all these or ceramics which are finding lot of applications in fact, in this picture is of hydroxy apatite. Calcium sulphate it is used quite a lot in a orthopaedic for filling. For example, this picture if you can see there is filling which needs to be done. So, they use calcium sulphate, and some of the bone, ground bone material and they fill it up here. So, not only it gets integrated, it is highly bio compatible, it prevents bacterial infection and so on actually.

So, these biomaterials, these bio ceramics or extremely bio compatible and they can be nicely integrated especially in dental applications in orthopaedic applications. Of course, they have certain short comings, especially they cannot take a tensile force, and they do not have a crack propagation resistance. So, these are some problems of these type of material, but then they have quite a lot of advantages which are now being exploited in the area of our biomaterial. So, we will look at some of these in this particular class. So, lot of advantages. They have high compression strength; they have good wear and corrosion resistance.

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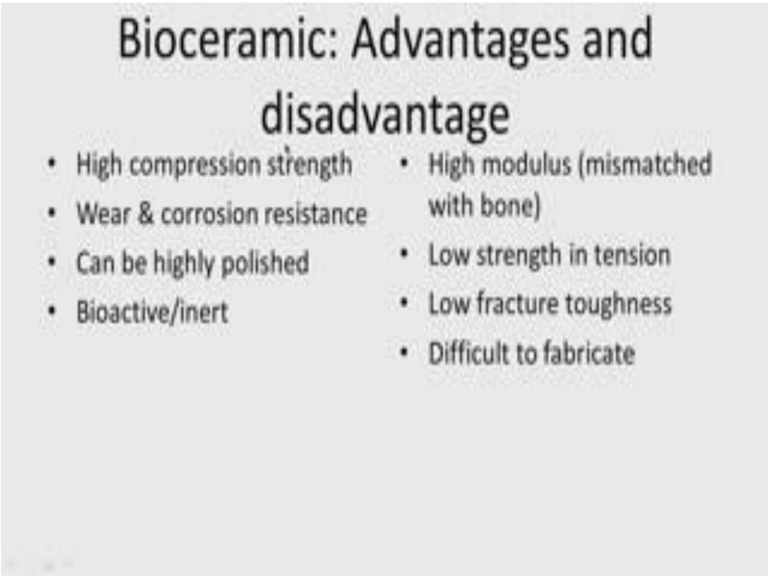

So, now for example, if you take metal stances are either they could be oxide corrosion, or by metallic corrosion, or wear corrosion; whereas these materials do not wear so easily. They can be highly polished, they are bioactive, bio inert and osteo integration properties. All these are advantages of a bio ceramics. Now of course, it has some disadvantages, high modulus, so mismatched with the bone. The modulus has to match with the bone, otherwise you end up having stress shielding, that is why nowadays titanium based material alloys are coming where the modulus is coming closer and closer to the bone. Low strength in tension, it just cannot take tension it will just nap, low fracture toughness; that means, if there is a crack, propagates very fast and the material break; whereas if there is a crack in metal, that it has got very high fracture toughness, metal will still survive for a very long time. Difficult to fabricate: so materials polymers can be fabricated to any shape, size, dimension, but these are little bit more difficult fabricate. So, these are some disadvantages of that.

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They are bioactive, they integrate very well, as the name implies Osteo so; that means, with the bone, they integrate very well. So, the form a good bonding between bone and material will be formed, a chemical bonding. Whereas if you put inert material, then it will be separate, the material and the bone will be separate; that is how they do not integrate. Whereas, ceramic material integrates very well, they are bioactive like hydroxyapatite. There is a good contact between bone and the implant, so osteo integrate especially like titanium.

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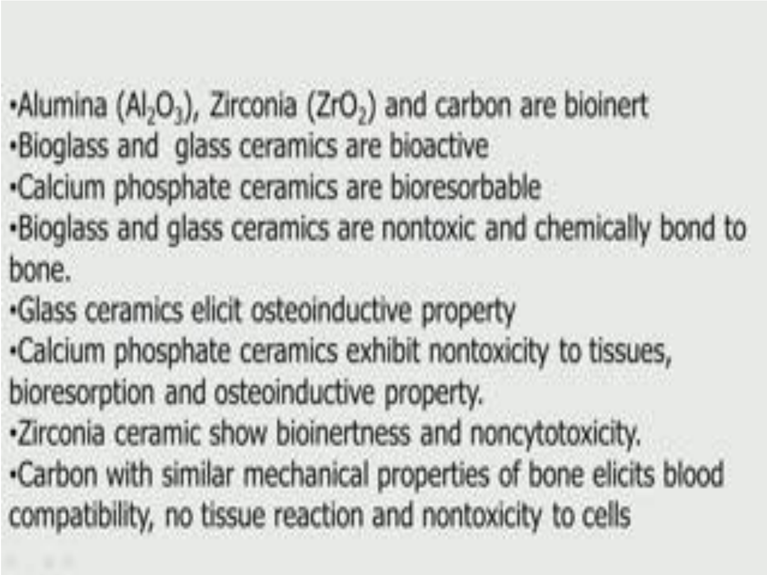

So, ceramics have all these good properties. If we take alumina; that is Al2O3, zirconia, it is a zirconium oxide and carbon are bio inert. So, they do not cause any adverse reaction to the whole system. If you take bio glass or glass ceramics bio glass; that means, SiO2 silicon type of material, they are bioactive; that means, they take part in the integration process.

If you take calcium phosphate ceramic, they are bioresorbable; that means, they will completely disappear over appear of time. So, if I am going to use it for filling, bone filling, when the bone starts growing this will completely get resorbed, or if I am using it for stuff holds you will get completely resorbed. So, that is beauty of a calcium phosphate bio glass and glass ceramics, they are nontoxic, they chemically bond to the bone. So, they do have good advantages. If you take glass ceramics they good have osteo inductive property, so; that means, they will allow cells flurry freed. And calcium phosphate ceramics like I mentioned exhibit nontoxicity in tissues, they get bio resorbed and they also have osteo inductive property. Zirconia ceramics, they are bio inert and they are noncytotoxicity.

Carbon; carbon is also used now a days, they have good mechanical properties of the bone, they elicits blood compatibility, no tissue reaction and nontoxicity to cells. So, carbon is also very good which can be used in some biomedical applications. So, you see lot of these properties coming to picture, bio inert if you are interested, or if you want bio, if you want to have a osteo inductive property, or if you want to osteo integrative property, if you want bio resorb able property, then we can have different types of ceramics. This particular table I showed long time back comparing ceramics metals and polymers.

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	Ceramic	Metal	Polymer
Hardness	VH	L	VL
Elastic modulus	VH	H	L
High temperature strength	H	L	VL
Thermal expansion	L	H	H
Ductility	L	H	H
Corrosion resistance	H	L	L
Resistance to wear	H	L	L
Electrical conductivity	B	H	L
Density	L	H	VL
Thermal conductivity	B	H	L

As you can see hardness, ceramics have very high, metal have low, a polymers are very low. Elastic modulus very high, polymers are low high, temperature strength high low very low, thermal expansion, it does not expand at all. Whereas, metal will have very high thermal expansion, polymers also can have. Ductility it is very low, because we cannot make shapes out of it ductile. Corrosion resistance, ceramics have very high corrosion resistance, when compare to metal or polymer resistance to wear, again it is very high. Electrical conductivity, it may, because you can have ceramics with conductive or non conductive properties metals high and of course, polymers low. Density, it is very low, metals will be high, polymers will be very low, thermal conductivity, it can have thermal conductivity, just like electrical up or down, metals will be high polymers will be low. So, this table gives a very nice comparison between all these 3 major classes of biomaterials.

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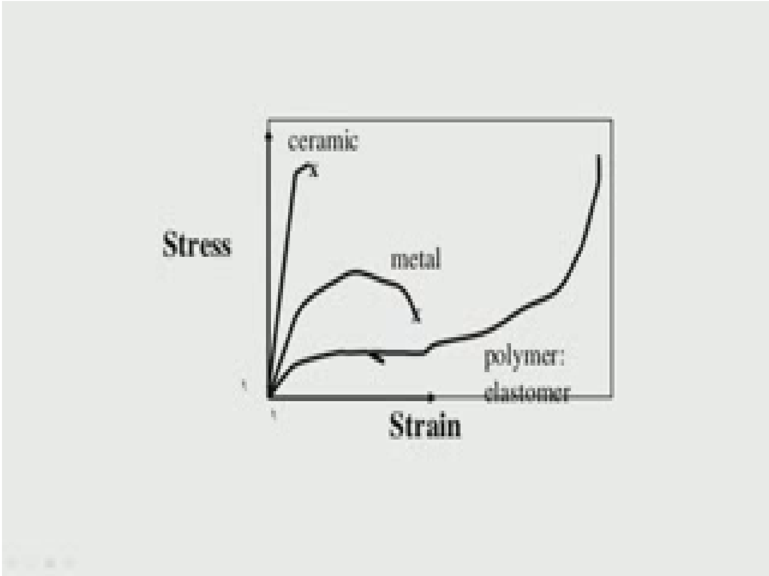

So, this picture if you see stress strain diagram, metal you will have the elastic region than the plastic region, polymer as you can see it can go like this, ceramics where as it will have high modulus, it will have very poor crack proper, I mean it will have very high crack propagation. So, it does not, it is not tough, so it does not take a tension. So, it cannot be used in such applications, it will just snap here. You know what see a plastic region at all and like metals, it just a stress strain diagram.

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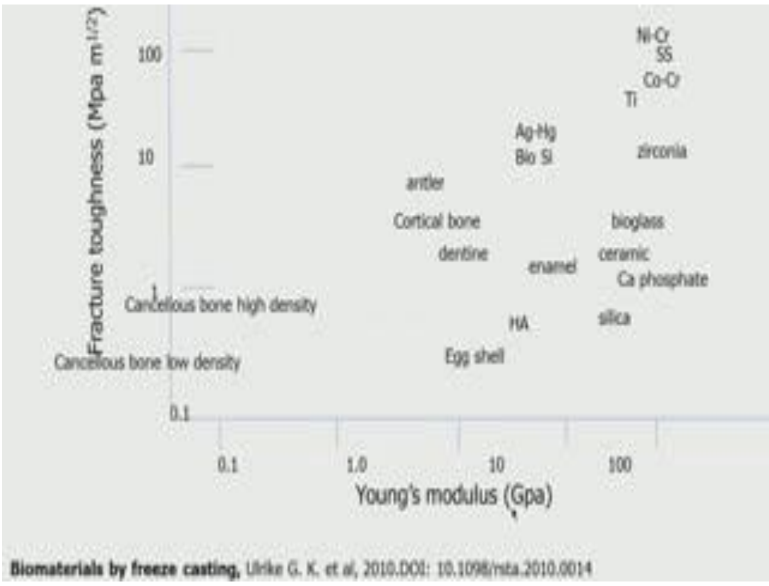

This also a very interesting picture taken from this reference, if compare the young's modulus fracture toughness. As I say mention what is fracture toughness, if there is a crack that developed how long can the material lasts, or the cracks starts propagating very fast and material fails; that is called crack fracture toughness. It is got this particular units Mega Pascal meter per half, as you know young's modulus has Giga Pascal. So, if you look at materials like egg shell, hydroxyapatite, silica, ceramic they do have good Young's modulus, compressive Young's modulus, but their fracture toughness will be very low; that means, if there is a defect or a crack that is formed, the material will fail immediately, mean comparable to your bone or dental material; whereas, if you take metals like chemical chromium, stainless still, they have very high Young's modulus, very high fracture toughness. Zirconia of course, not bad, it is coming up in fracture toughness, but these are the metal area, you have amalgam, then we have titaniums. So, if look at zirconia or bio silica based material or bio glass they have quite high fracture toughness when compare to the remaining ceramics material, like bio glass ceramic, calcium phosphate, silica hydroxyapatite. So, egg shell you can see it is got very low fracture toughness; we have use to that right, if there is a crack immediately it fails. Some of your bone material high density low density chanceless bone, have very low Young's modulus as well as very low fracture toughness. So, the fracture toughness of most of the ceramics are low whereas, the compressive Young's module for strength is high hm.

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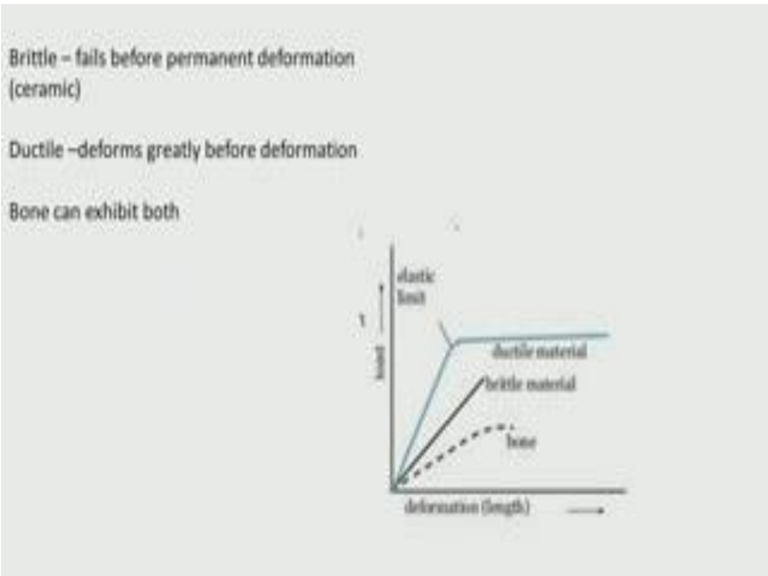

Once again this picture you can see, this is material, ductile material, this brittle material, this is the bone, brittle fails before permanent deformation like ceramic, ductile deforms greatly before deformation, bone can exhibit both. So, brittle material will not show any ductility, it will fail.

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Material	Tensile strength (MPa)	Compressive strength (MPa)	Elastic modulus (GPa)	Fracture toughness (MPa. $m^{1/2}$)
Bioglass	42	500	35	2
Cortical Bone	50-151	100-230	7-30	2-12
Titanium	345	250-600	102.7	58-66
Stainless steel	465-950	1000	200	55-95
Ti-Alloys	596-1100	450-1850	55-114	40-92
Alumina	270-500	3000-5000	380-410	5-6
Hydroxyapatites	40-300	500-1000	80-120	0.6-1

https://en.wikipedia.org/wiki/Mechanical_properties_of_biomaterials

This is an interesting table again, because we are comparing different materials with your bone as you can see bio glass, tensile strength is comparable to the bone, elastic modulus is also poor fracture toughness, compressive force strength is very high. Hydroxyapatite, if you look at it is also comparable to cortical bone compressive strength is very high, elastic modulus is also high, fracture toughness is extremely low. Alumina you can see here, stainless steel if you see the fracture toughness is high, elastic modulus is very high. When compare to your bone titanium of course, is much less than your stainless steel. But still even that has very high elastic modulus when compare to your cortical bone. So, this table compares different metals as well as the ceramics, like hydroxyapatite, alumina bio glass with the bone.

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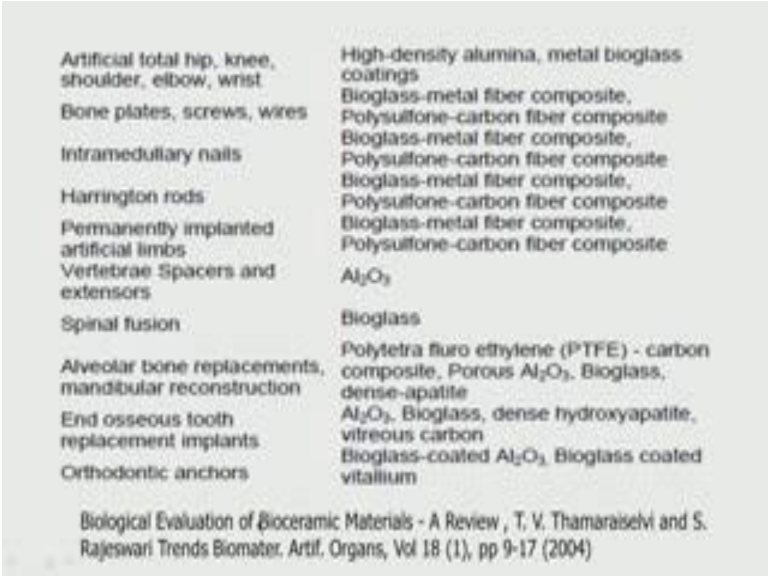

Artificial total hip, knee, shoulder, elbow, wrist	High-density alumina, metal bioglass coatings
Bone plates, screws, wires	Bioglass-metal fiber composite, Polysulfone-carbon fiber composite
Intramedullary nails	Bioglass-metal fiber composite, Polysulfone-carbon fiber composite
Harrington rods	Bioglass-metal fiber composite, Polysulfone-carbon fiber composite
Permanently implanted artificial limbs	Bioglass-metal fiber composite, Polysulfone-carbon fiber composite
Vertebrae Spacers and extensors	Al_2O_3
Spinal fusion	Bioglass
Alveolar bone replacements, mandibular reconstruction	Polytetra fluro ethylene (PTFE) - carbon composite, Porous Al_2O_3, Bioglass, dense-apatite
End osseous tooth replacement implants	Al_2O_3, Bioglass, dense hydroxyapatite, vitreous carbon
Orthodontic anchors	Bioglass-coated Al_2O_3, Bioglass coated vitallium

Biological Evaluation of Bioceramic Materials - A Review , T. V. Thamaraiselvi and S. Rajeswari Trends Biomater. Artif. Organs, Vol 18 (1), pp 9-17 (2004)

This was taken from this particular reference. So, these biomaterials ceramics are widely used mostly in dental and in orthopaedic applications; like total hip, artificial total hip, knee high density alumina metal bio glass coatings, physically they are coated. So, that the metal on metal interaction does not take place, which may lead to derby formation metal leaching and so on. Bone plates screws; they are all coated with bio glass, polysulfone carbon fiber composite, if you look at intramedullary nails. Again this an orthopaedic, it should came long time back, we can have bio glass coating rods, permanently implanted artificial limbs, again you have bio glass carbon fiber composite vertebrae spaces alumina, spinal fusion bio glass, alveolar bone replacements, mandibular reconstruction, we have PTFE porous alumina, bio glass, dense apatite, end osseous tooth, this is teeth related alumina bio glass dense hydroxyapatite, orthodontic anchors, bio glass coated alumina. Again see as you can see generally bone related pleasures, fillers, coating and then some teeth related tooth an orthodontic anchors and so on. This information is got form this particular reference.

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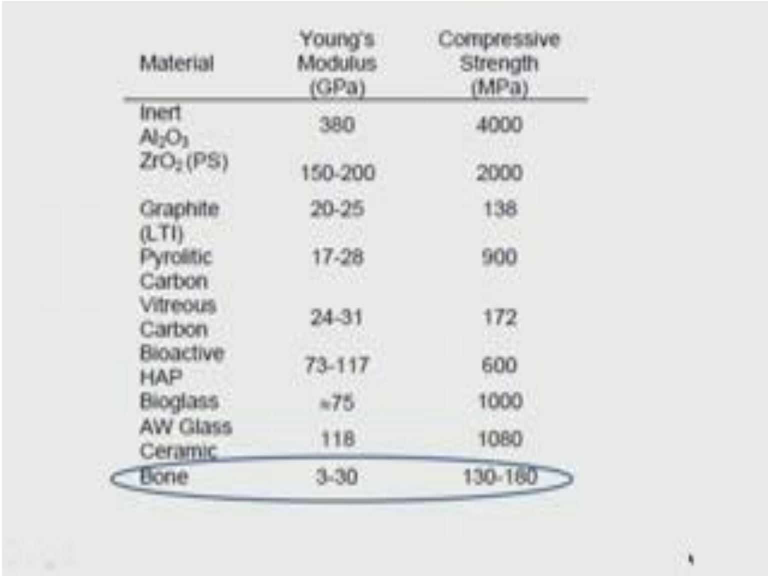

Material	Young's Modulus (GPa)	Compressive Strength (MPa)
Inert Al_2O_3	380	4000
ZrO_2 (PS)	150-200	2000
Graphite (LTI)	20-25	138
Pyrolitic Carbon	17-28	900
Vitreous Carbon	24-31	172
Bioactive HAP	73-117	600
Bioglass	≈75	1000
AW Glass Ceramic	118	1080
Bone	3-30	130-180

So, once again we can see alumina, zirconia, graphite, carbon, different hydroxyapatite bio glass. So, Young's modulus there is a lot. So, very low materials carbon pyrolitic carbon hydroxyapatite 73, and going right up to inert alumina 380. The compressive strength if you look with carbon is comparable to the bone material where hydroxyapatite is quite high. So, these table shows you, how each oxide varies, and carbon seems to have reasonably good properties when compared to the bone, hydroxyapatite comes here, and your bio glass comes here 75.

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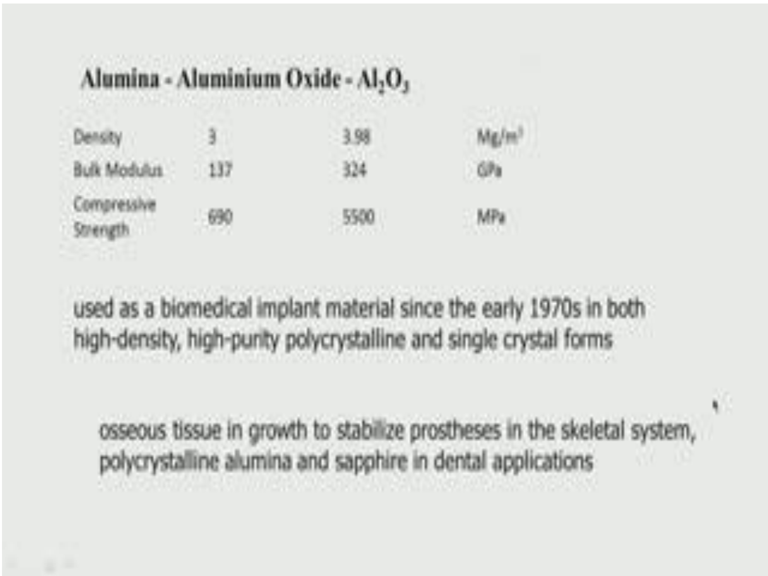

But it has got very high compressive strength. So, let us look at little bit on each one of these biomaterial, the oxides, that is the alumina, aluminium oxide it is called Al2O3 it is got density of 3 bulk modulus compressive strength is used, as a bio medical material early 1970s in both high density, high purity polycrystalline and single crystal forms actually, and this is the range of densities or modulus or compressive strength. It is used in osseous tissue in growth to stabilize prostheses in the skeletal system, polycrystalline alumina and sapphire in dental applications. So, as I mentioned mostly you will find in fillers, bone replacement coatings in the orthopaedic, and in filling in the dental.

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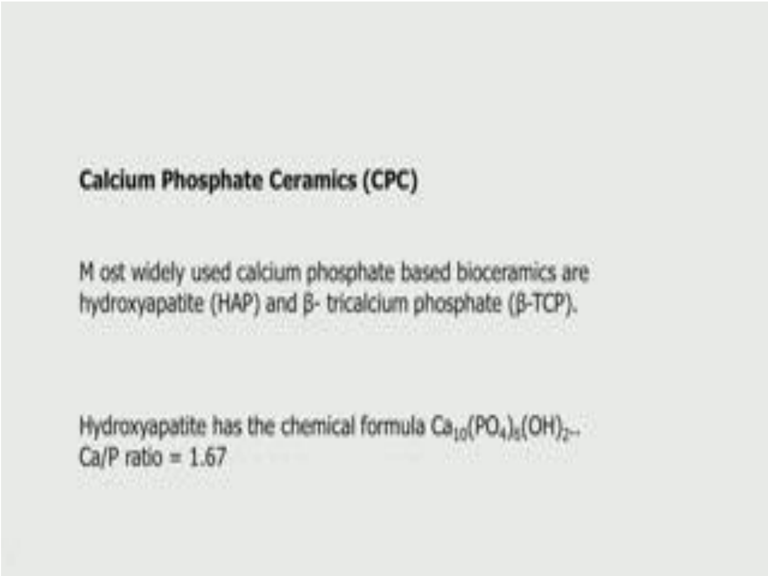

And calcium phosphate ceramics is called CPU; it is used bio ceramics hydroxyapatite and beta tricalcium phosphate. So, calcium phosphate is used as hydroxyapatite or beta tricalcium phosphate. The hydroxyapatite has the chemical formula, we have the calcium, they have the phosphate and the hydroxyl grope, generally the calcium phosphate phosphorus ratio will be 1.67. So, again calcium phosphate hydroxyapatite as you know it is widely used in bone filling, because the bone is predominantly calcium phosphate. So, the osteo integration happens very comfortably.

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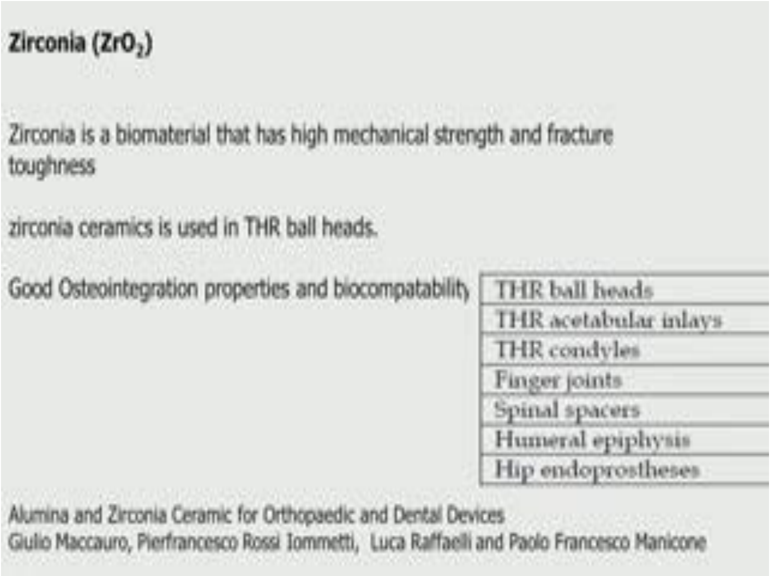

Look at Zirconia. Zirconia is finding good application of late, it is got very good mechanical strength and fracture toughness, because rest of the ceramics have very poor fracture toughness' whereas, zirconia is quite good. So, it is used in the total hip replacement t h r, total hip replacement ball heads, there is a ball and socket and you may have metals, metal in order to prevent metal on metal, mean it coated with zirconia. So, it prevents they wear, and also it is got good osteo integration property.

So, it integrates very well with the bone tissues, it is very bio compatible. So, total hip replacement ball heads, total hip replacement ace tabular inlays, total hip replacement condyles, finger joints, spinal spacers, humeral, epiphysis hip end prostheses. So, all these places where you have ball and socket type of moving zirconia finds applications. So, alumina zirconia have very good applications in orthopaedic and dental applications, but zirconia is coming of late, because it is got much better fracture toughness than any other ceramic, bio ceramics, bio glass.

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So, when we say glass it is mostly silica; that is why it is all generally you will find silica based material SiO4 4 minus, they are found places in prosthetics actually. They are embedded in a biomaterial support to form prosthetics for hard tissues, such tissues are bio compatible they show excellent mechanical properties, and are useful for orthopaedic and dental applications, and bio glass is generally silica based different types of combinations of silica will be present.

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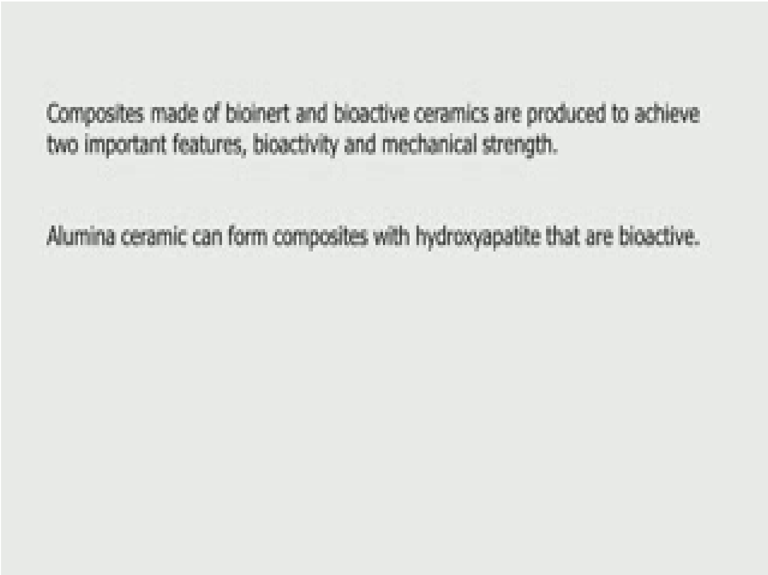

So, you can also think of composites made of bio inert and bio active ceramics. So, each can do certain activity. So, we can achieve bio activity, and bio inert can give you the mechanical strength. So, composites of these inorganic materials or also being looked at actually, so alumina ceramics are used with hydroxyapatite. So, hydroxyapatite may have poor properties, alumina may have better properties; whereas, hydroxyapatite is bioactive. So, we can combine these two properties to form composites. Of course, we can even think of coating metals with hydroxyapatite or bio glass so that you get good osteo integration and bio active property when compare to the metals. Again we can prevent atmospheric oxidation related corrosion of some metals by coating hydroxyapatite on top of metal charge. So, there are so many options available by bringing in ceramics into the picture of biomaterials. Let us look at one as simple problem in the area of the ceramics

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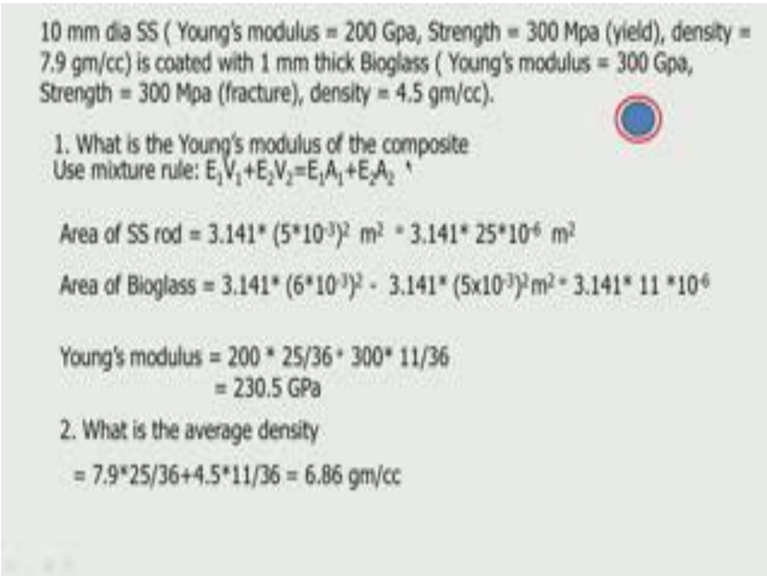

Imagine we have a stainless steel here, it is a rod used in say orthopaedic application, this is a 10 millimetre diameter stainless steel rod, it is called Young's modulus of 200 Giga Pascal strength, yield strength of 300 Mega Pascal ,density of 7.9 gram per c c this is the stainless steel. So, they coated with 1 m m thick bio glass, bio glass has got good integration property, as stainless steel may curved also. So, assume your coating it with 1 m m, Young's modulus 300 as I mentioned Young's modulus can be very high for ceramics, but then it does not does not have a plastic region at all, it is got 300 Mega Pascal fracture, density is 4.5 grams per c c. So, it just fractures as soon as reach this, so there is no ductile reason at all for ceramics. Now the question is what is the Young's modulus of this composite; of course, we can use this mixture rule right e 1 v 1 plus e 2 v 2 is equal to e 1 a 1 plus e 2 a 2, there is v 1 is volume fraction v 2 is volume fraction. So, we can put the area is into the picture area fraction, area fraction. So, what you do area of this stainless steel rod, it is a 10 m m diameter stainless steel rod. So, pi r square is the area pi into 10 m m dia. So, 5 m m is the radius 10 power minus 3 multiplying to make it into meter square. So, we get meter square.

So, we have 3.141 into 25 into 10 power minus 6 metre square. So, the area of the stainless steel rod, is pi into 25 into 10 power minus 6 meter square. We are converted into meter square, because we are we have this pascal we want to bring it there, 10 m m is dia, so we made it 5 m m. Now you have 1 m m thick coating of bio glass. So, how do we calculate the area of this bio glass, in school you must have studied bit calculate the area of this big one, area of this one and subtract that it will give. So, pi big 1 r square minus pi small 1 r square. So, pi big 1 r square minus pi small 1 r square. So, now, big 1 is, it is 1 m m coating it is radius is 5. So, it becomes 6 5 plus 1 is 6 1 m m thick. Now this in side is of course, 5 here right. So, 5, sorry pi into 6 10 power minus 3 raise to the power 2, this is for converting into meter m minus area of this rod which is 5. So, when I do this 6 square 36, 5 square is 25, 36 minus 25 is 11, 10 power minus 3 square is 10 power minus 6.

So, you get area of bio glass, that is this portion as pi into 11 into 10 power minus 6 metre square, area of the stainless steel rod is pi into 25 into 10 to power minus 6 meter square. So, the Young's modulus, we can calculate a fraction right 200 is for the stainless steel 25 is the area divided by 25 plus 11 is 36; that is the fraction of area, and then the Young's modulus of this bio glass is 300 area is 11, total area is 11 plus 25 26. Sorry 11 plus 25 11 divided by 36. So, this 200 comes for the stainless steel the area of stainless steel is 25, the total area is 25 plus 11 that is 36 plus the 300 comes from the Young's modulus of the bio glass area of the bio glass is 11 divided by total area is 25 plus 11 36. So, when we calculate that, we end up with 230.5 Giga Pascal. So, the Young's modulus of this composite is 230.5 Giga Pascal. We use the mixture rule and so Young's modulus of stainless steel into volume fraction plus Young's modulus of bio glass into volume fraction. So, instead of volume fraction we can use area fraction, because we do not know the rod length, so it does not matter. So, area fraction is, area of the stainless steel divided by the total area. Here area of the bio glass divided by the total area. Total area is, area of stainless steel plus area of the bio glass. So, 25 plus 11; that is why we have 36 here.

Now, the second question is, what is the average density. We can do it in the same way with the density of stainless steel is given here; density of bio glass is given here. So, we can do the same thing 7.9 multiplied by 25 by 36 plus 4.5 multiplied by 11 by 36. We use the same approach area fraction, area fraction for stainless steel, area fraction for composite. So, that comes to the 6.86 grams per c c. here we use mixture rule which is like a a both contribute based on their volume fraction or area fraction, but in real case it might not be so actually because if you remember there is another rule called Roy's rule, which studied long time back, where it is the equation is slightly different. So, you may get slightly different answer. So, if you use that particular rule.

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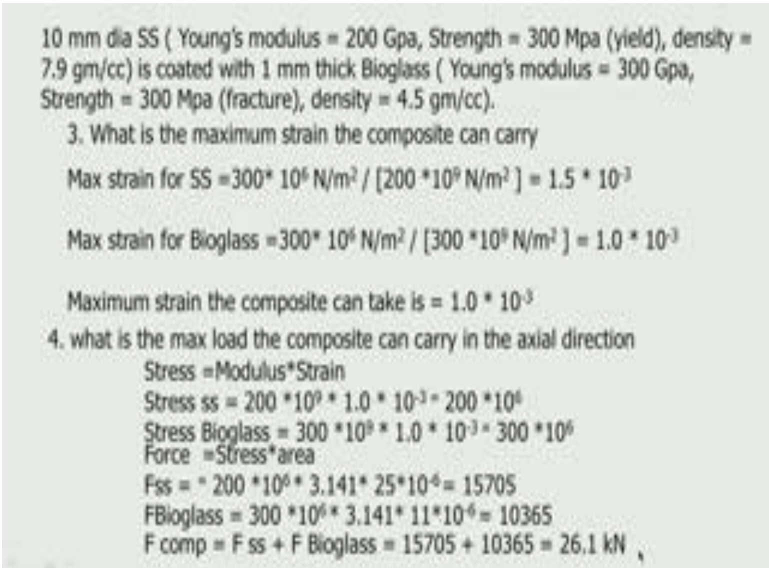

Let us proceed with the problem, same problem what is the maximum strain the composite can carry. So, we have now stainless steel rod, which is coated with bio glass and imagine it is pulled. So, what will be the strain, both of them will have different strains depending, because the Young's modulus is very different. So, how do we calculate the strain. So, we do stress based strain is equal to Young's modulus. So, stress divided by the Young's modulus. So, we have the, for the stainless steel 200 is Young's modulus Giga Pascal, so we convert into newton by meter square. For the bio glass it is

300. So, 310 power minus raise to the power 9 newton per meter square, and imagine we are putting in stress of 300, because stress by strain is equal to Young's modulus this is the stress. So, we divide this stress by the Young's modulus to get the strain, and same stress is divided by Young's modulus to get this strain. So, we end up with maximum strain for stainless steel is 1.5 into 10 power minus 3, maximum strain for bio glass is 1 into 10 power minus 3, but then maximum strain the composite can take will be the lower of these two, because by the time when the strain reaches one, if it slightly exceeds the composite will fail, because bio glass will fail. So, the material can take lower of these two, which is equal to 1 into 10 power minus 3. So, that is the maximum strain the composite can take. So, how do we calculate the strain? As you know stress by strain is equal to the modulus. So, stress by the modulus is equal to the strain. So, imagine if you are applying stress of certain value, this is the modulus for stainless steel, this is the modulus for this this one bio glass. So, we end up with that.

So, how did we take, why did we take this 300, this is the yield and here also this is the fracture. So, the numbers are same. So, we put this here, but the moduluses are moodily or different. So, we will end up with different strain values. And as I mentioned we always have to take the lower of the two strain values, because it is a composite. Once it reaches this value, the composite material will start failing. Next part, what is the maximum load the composite can carry in the axial direction. So, we will assume this as our strain maximum load the composite carry in the axial direction. Load as you know force by area is equal to stress. So, stress is the modulus into strain.

So, stress for stainless steel is equal to. So, we have 200 into 10 power 9, will use this. So, this is 1 into 10 power minus 3 for the bio glass, we will take the modulus 300 into 10 power 9, again we will take this as the strain. So, we are end up with two different stresses. Stress is given by this relationship force is equal to stress into area for stainless steel. So, we take this as the stress, and this is the area, if you remember last time we calculated for the bio glass, this is the stress this is the area we calculated. So, we get this particular the force, on stainless steel will be this force, on bio glass as will be this. So, the combined force will be sum of these two. So, it is 26.1 kilo newton. This is the combined force this particular material can take up.

So, we understand this problem. So, as you know we may get the different strains, but the point is we have to take the strain, which is the lowest and then use that in the next step. So, we calculate stress is equal to modulus into strain, this is the strain. So, we end up with this stress for stainless steel, stress for bio glass force is equal stress into area, we calculated this these two area from the previous slide. So, we get different forces, when you add up this gives you the combined force, maximum load the composite can take in the axial direction, but then there is a problem, generally we cannot use bio glass with stainless steel ,why. Can you tell me why? It is they have a different coefficient of thermal expansion. So, stainless steel has much higher. So, if there is a change in temperature it will expand, whereas, bio glass will not expand. So, there will be a crack.

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So, there will be a poor bonding between these two material; that is one point, another one is there will be very different thermal expansions. So, when there is a change in temperature, your stainless steel will expand and bio glass will not expand, so it will break, and then of course, bonding between bio glass and stainless steel is also very poor.

Thank you very much for your time.