Advanced Topics in the Science and Technology of Concrete
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Ultra High Performance Concrete (UHPC): Material Design and Properties
Part 1

So good morning everyone this lecture is going to be on Ultra High Performance Concrete and its material design and properties. So we will cover the material design part of Ultra High Performance Concrete for first 30 minutes and then the next 20-25 minutes on properties of UHPC.

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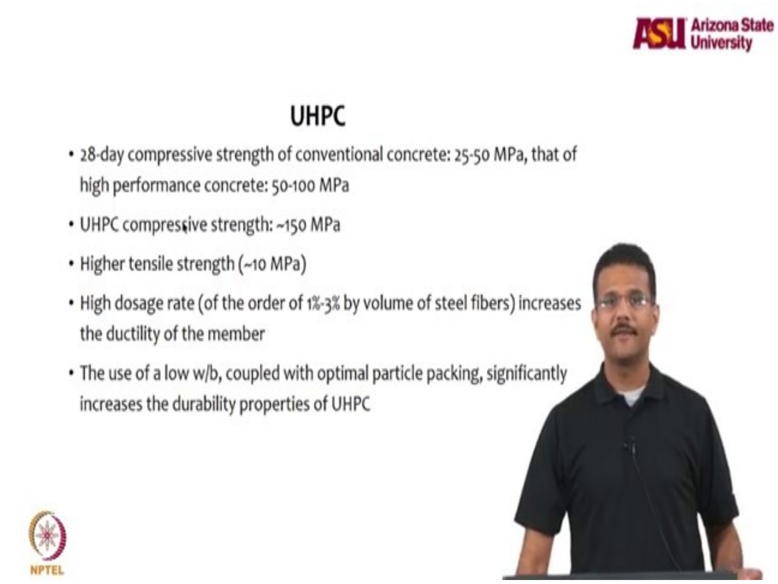

So we have conventional concretes that typically have a strength of 20-25 mega Pascal, up

to 50 mega Pascal for high performance concrete and can go up to about 100 mega Pascal, but ultra high performance concrete are designed with a compressive strength of 150 mega Pascal or about 25000 pounds per square inch. They are also designed for high tensile strength of about 10 mega Pascal.

You achieve this by extremely dense packing of particles, make the micro structure so dense so that the particles are so close to each other and stresses are transferred very nicely. You add quite a bit of steel fibers to these material so that you increase the ductility of these members. Also, water-binder ratio is extremely low that it will help to get a very high packing and very low porosity. So it is a combined effort of reducing the water-cement ratio, improving the particle packing and using steel fibers to improve the ductility.

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A high compressive strength is not just enough. You can have high compressive strength for certain applications but you need high ductility, high resistance to corrosion and aspects of durability also in ultra high performance concretes. So the idea is that you can tailor the material micro structure through careful selection of materials, careful design of the constituents and proper construction practices to get you really high property. So that is the core idea of designing USPC.

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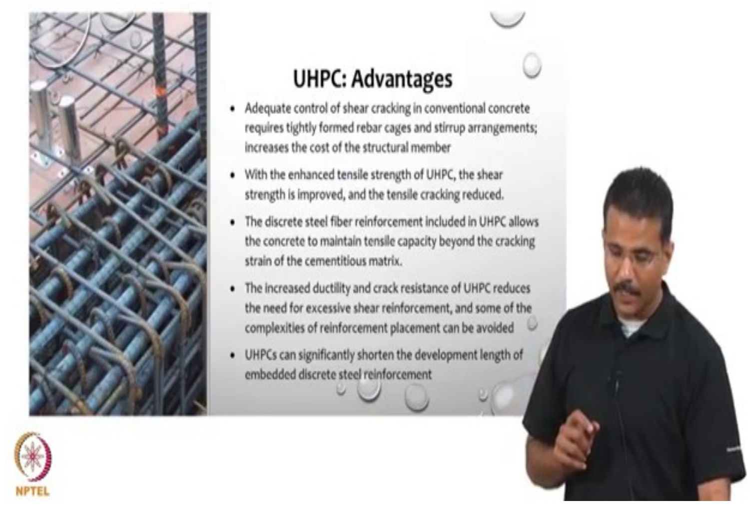

Now, what are the some of the advantages that you don't have with conventional concretes? So you can say strength, you can get strength of up to 100 mega with high performance concretes. But, in conventional concrete if you have a really heavy load bearing member like a bridge girder or a bridge column that is supposed to carry extremely high loads, you need extremely tight rebar bar cages. So if you have such tight rebar cages and you have so much of steel, it obviously increases the cost of the structural member and you need such kind of extremely dense reinforcement to controls shear cracking.

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With enhanced tensile strength you can reduce the shear cracking by improving the shear strength and also the tensile cracking is reduced. The fiber reinforcement, the discrete fiber reinforcement, steel fibers that are spread in a discrete fashion in UHPC helps maintain the tensile capacity beyond cracking which means you have high ductility of the member. The increased ductility reduces the need for excessive shear reinforcement, so you can control shear reinforcement and if you have such very high strength for your concrete your development length for your rebars can be reduced.

So you have a lot of these advantages which you don't get in conventional concretes through UHPC. A few applications is being used in United States for a few years now for very selected applications, these are a couple of bridges, Mars Hill Bridge in Iowa, Cat Point Creek Bridge in Virginia, these are some of the bridges that have used UHPC's in its construction. The way they normally want to use the UHPC is for bridge decks because bridge decks are supposedly very heavy load carrying members that are supposed to last for a much longer period of time.

But before UHPC was used for bridge decks, the more critical application was bridge connections. When you have precast concrete bridges you can do normal high performance precast bridge decks but when you bring on to the site you need to join the precast bridges and as you know for any connection, for any chain the week links is a connection so if you have those connections which are normally site cast concrete, if you don't have really good quality control those connections are normally weak and if you can think of vehicles driving through a bridge you can think of these connections being subjected to extreme fatigue loading.

So you will have much faster failure of those connections. They used steel connections to improve that but then steel and concrete you have issues with corrosion and so UHPC is now a preferred option to connect girders. You can do complete UHPC bridge decks like you see in those pictures. You can have UHPC overlays for bridges, existing bridges you want to retrofit them for higher traffic you can have a thinner 3 inch, 4 inch thick overlay for bridges. You can have column encasings, that is a column for a bridge that is now required to take a higher load can be encased with UHPC, very similar to encasing concrete columns in steel as a retrofit methodology, so a lot of applications. Structural design is going to be different but I will concentrate mostly on the materials part in this talk.

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These are again UHPC Pi-girders, Pi-girders are called Pi-girders because they have a shape of the Greek alphabet Pi and these are very common bridge girder elements. So Pi-girders are very common. You can see Pi-girders being implemented in Jakway Park Bridge in Iowa.

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Ok field connections like I talked about, you can have deck level connections, connections at the deck level where the two panels of the deck are connected by UHPC or you can have the deck or the Girder connected to the support structure through UHPC, so multiple ways of doing it. The advantage of such extreme high strength is that the connections can be small and you are always better of doing smaller connections than larger connections because connections are the weak points.

So you can now afford to have smaller connections and you don’t require post tensioning of concrete within those connections because this have extremely high strength, extremely high tensile strength also.

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So lets talk about material design, let's talk about how do you design ultra-high performance concrete for such very high strengths and very high durability.

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The idea is that there are commercial mixtures, you can buy commercial UHPC mixtures for about 2000 dollars per cubic meter. Extremely expensive to give you a perspective, a conventional concrete cost about 125 dollars a cubic meter.

So talked about 15 to 20 times the cost because these materials are proprietary and they use very special admixtures and the additives. But the idea is to make the science simpler, to show that you can make these materials with locally available raw materials. You don't have to go to very fancy powders and chemical admixtures, you can actually make it with local admixtures, locally available materials if you control what you choose to put in your concrete and how you make your concrete really-really well.

You need extremely high admixtures dosage because your water cement ratio is going to be very low that is water cement ratio lower than 0.2. So it has to be a lot of admixtures. Now, we talked about connections. If you have to do connections the concrete has to be self-compacting to go and be poured into connections, I also showed you very dense reinforcement caging.

If you have to get concrete into that you need really-really flowable self-compacting concrete. So one of the challenges is a 0.2 water cement ratio and to get itself compacted. And then you want to look at packing of particles, you want to make sure that the powders are extremely well packed and for that you need a range of powders. If you remember, the science of packing, a single size will be able to fill in the space well.

You need a gradation of sizes so that every space is sequentially filled and we have to do it with all the different size ranges. If you look at concrete you have size ranges starting from 5 millimeter or 10 millimeter or 20 millimeter size aggregates to submicron particles of silica fume, so you have such a vast size distribution. The other challenge is make sure that you have enough particles in all these size ranges to fill the pores really well, use lot of admixtures to make sure that this gets really well flowing and you can pour your concrete well into all this very tiny areas, so that is the challenge.

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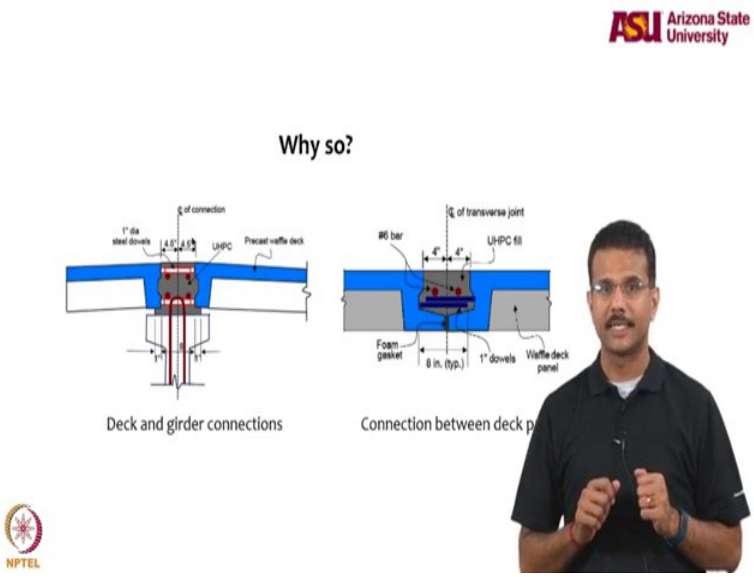

So we will attack this problem in two different stages like I said two different ways of doing, you can deck and girder connection or you can have connection between deck panels you can see the reinforcement in both cases being different.

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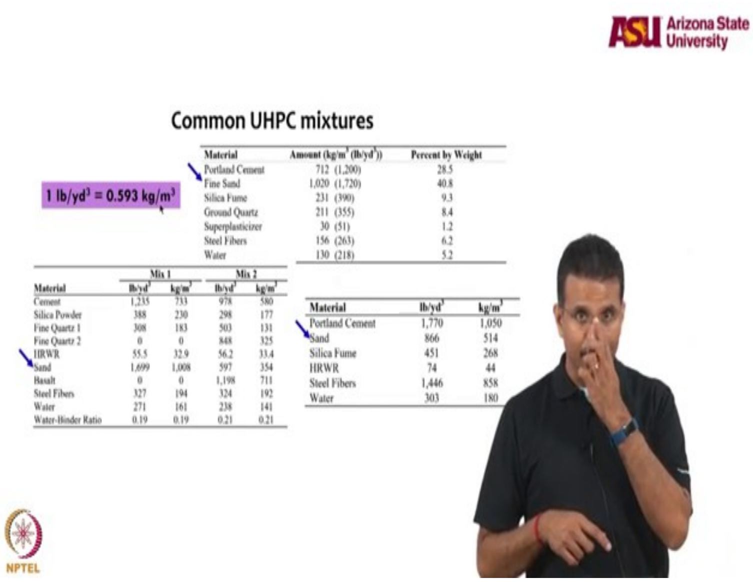

So here are some of the common ultra-high performance mixtures available in the market. There are mostly commercial mixtures, I have put the conversion between pounds per cubic yard and kilo grams per cubic meter for you to quickly make the conversion and the first thing that you notice is very high amount of cement.

You need very high amount of Portland cement for two different reasons. One, my water cement ratio is very low, which means only a small fraction of cement is going to be hydrating. If only a small fraction of cement is going to be hydrating I need more of cement to make up enough of the reaction product. The second reason is that I need lot of fine powders, cement being a fine powder the property of which you know really-really well that you can control.

So that is why two reasons why people do high amount of cement, the downside high shrinkage. So that is why this has to be really-really well controlled in terms of curing and in terms of using materials like internal curing admixtures, super absorbent polymers something like that. Now I have put an arrow on fine sand in all this slides, one of the reasons is that sand is pretty much the only aggregate in ultra-high performance concrete. The reason being again you are basically looking at ultra-high performance mortar, generally all the commercial mixtures but I will show you actually how to design ultra-high performance concrete.

The reason why everybody uses mortar is to control mortar properties is much easier than controlling the concrete properties. Anybody who has worked with concrete and mortar know, if you want to look at flowability mortar is much more controllable as far as flowability is concerned than concrete because in mortar you rarely have the problems of bleeding and segregation.

Whereas with concrete you end up with bleeding and segregation if your quantities are not proportioned correctly. So one reason why we have most ultra-high performance concrete using sand is to make sure that flowability criteria is satisfied and also you will see in these tables a lot of other fine powders, there is silica fume, there is ground quartz. There is lot of different types of fine powders people use to make sure that you have wider particles size distribution to fill in all the pores. So some few mixtures that the people have tried in the past.

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So how do we design this material? How do we start designing it from first principles? So you have to select what binder materials you actually want and that is the most important part. Cement is a given you need it, what other than cement? What are the common ideas that we have to select a material other than cement? One is sustainability, you have to make sure that you are using less cement as possible so you can use lot of other base materials.

The other aspect is your cement has a certain size distribution. If you look at particle size distribution of cement you will have sizes from 1 micron roughly to about 100 microns, normally distributed. What happens to sizes smaller than 1? We don't bother about sizes more than 100 because sand will fill in those bases. What about sizes smaller than 1? What can be used? The thing that comes to mind quickly is silica fume. So you have to now have materials that are smaller than 1 micron which is silica fume.

You can have Metakaolin also which you can use if you need some aluminate effect in it. We have used both silica fume and Metakaolin and I will tell you why we have done that. Then you have to ensure that the particles are packed really well, not just packing but you have to ensure that they are reactive enough. So what is mostly reacting in your system initially? It is a cement and all the other materials that you put in are helping cement do its job better.

For example if you put in silica fume, silica fume at very early ages access nucleation agent, nucleation sites. So all those materials are helping cement which means you have to put those them in a volume and ensure that they are distributed enough for the cement to do its job. And remember all of these are happening at a water binder ratio of 0.16 or 0.18. So now the challenge is to make sure that all these family of materials act synergistically at that low water cement ratio, challenge number 1.

Getting to aggregates, I can avoid aggregates completely and have a self-consolidating UHPC mortar but the problem of not having aggregates is dimensional stability, your shrinkage is going to be much higher if you don't have aggregates. What size of aggregates then can I use? I can't use larger 25 mm aggregates because this won't flow, the space between rebar is probably 10 or 15 mm so I need very-very small aggregates to go in, what kind of aggregates you can choose, how do I choose those family of aggregates?

So choosing the binder, choosing the aggregates and then proportioning the mix so that all the contrasting requirements are satisfied, so we will go one by one.

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The first strategy is to design the paste and this is the most crucial strategy. It is not because nobody knows how to design the paste but because you have so many different combinations of materials that you can choose for paste. So the first idea should be what is locally available? Everybody has cement, slag is generally available, fly ash is generally available, silica fume and Metakaolin are not very hard to get. Lot of times people use ground quartz, they take quartz and grind it really fine to improve the reactivity.

We stayed away from the ground quartz because it is very expensive and also it is not very locally available. If I want to ask a ready mix company to manufacture UHPC, they will manufacture only with the locally available materials. It is very difficult for them to source grounds quartz, have a different silo for that and be able to process it. So I will show you two methods or actually combine one method which will help you design any kind of paste. So this is a very generalize method that you can use for any kind of paste that you want to use for ultra high performance applications and we rely on two different requirements.

One, as you see on the right, packing of particles and the other one on flowability or rheology. So these are the two things that we will look at.

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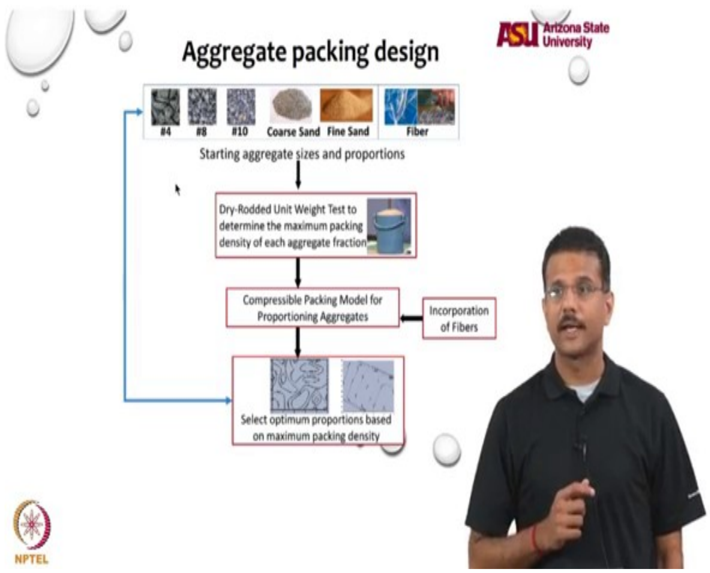

And then the second strategy is on packing aggregates and I will give you a strategy and a methodology to actually pack aggregates and then put paste in the aggregates together to form the material that you want.

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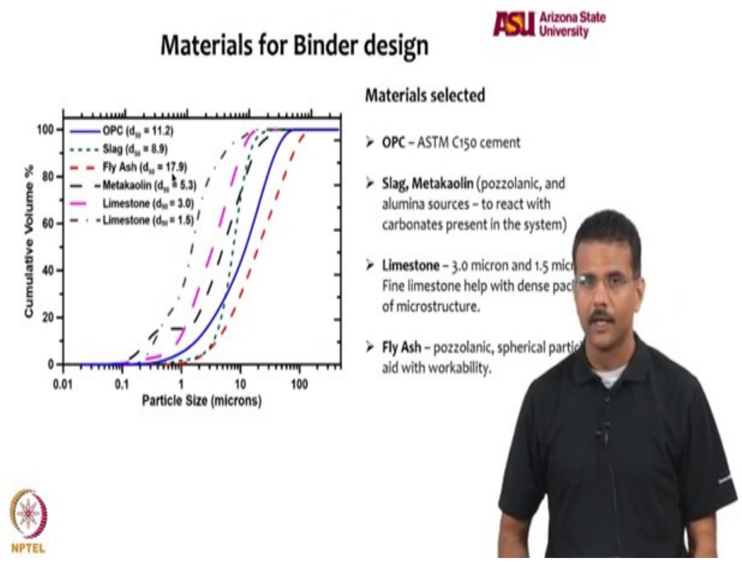

So we have different types of materials and you can see here: cement median size of 11.2, slag a median size of 8.9, fly ash a median size of 17.9 microns, Metakaolin 5.3, silica fume I didn't even show in the picture because it is submicron if you completely deagglomerate it. Then we use two different limestone powders of 3 microns and 1.5 micron size. And most of you would know now because I have limestone, I use Metakaolin because I have now the limestone alumina synergy which is typically the LC3 story. So limestone is used so that you can have alumina also from Metakaolin, you can have combination of limestone and alumina to react better, that will be a better strategy than using silica fume even though we have used silica fume also.

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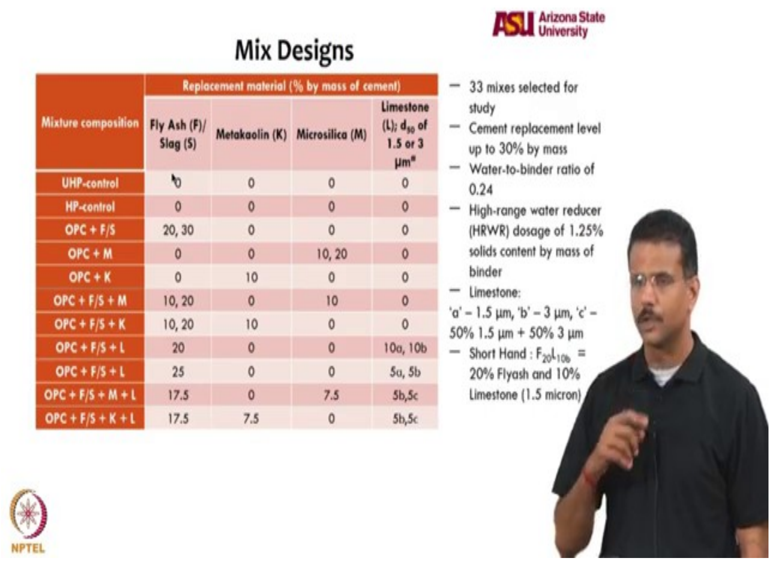

So what we did is, with the available materials we designed a large number of systems of paste mixes, actually 33 in this study, very low water binder ratio 0.24, we actually went down even further, 1.25 percent of high range water reducing admixture, a polycarboxylate base water reducing admixture, 1.25 percentage of solids by mass of binder which actually translates to about 5 percent of super plasticizer by mass of cement, 5 percent I will show you how to add that also.

If you have 5 percent of super plasticizer you mix it with all the available water and you pour it in, you are going to get one large clump, nothing is going to happen, and I will show you mixing methods that need to be changed if you want to design such mixtures.

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So packing, so we did some computational work and again this doesn't have to be computational if you know what you are using, but we want to do a wide range of materials so that we can start looking at packing of all these materials in different spaces. So if you see the bottom left most picture, it has only two size of particles say cement and fly ash maybe. If you go to the next one I have introduced another size of particles, red particles maybe that is Metakaolin.

If you go further down I have green particles maybe that is limestone. So as I sequentially increase the number of particles and change the size of particles I get completely different packing. Then in the graph on the right side, I have plotted three different parameters, three very useful parameters of microstructure which is basically material science parameters that any material or any lattice structure guy would use.

First one is a coordination number, coronation number just means the number of nearest neighbors. What is what are the number of nearest neighbors of each particles? If I take one particle, how many nearest neighbors it has? Basically how many particles it has touch? What is the significance if I have many nearest neighbor particles that just tells me that my packing is much higher. It also tells me indirectly that when I have more particles around one cement grain, it is more likely to react because there are reacting species around it.

It does not tell me what exactly it is but it gives me a broader range. Number density will tell me how may particles are there in a unit volume, the more number of particles the denser the structure. If the particles are smaller you will have more number of particles and denser will be the structure. Then the mean centoidal distance, if I take one cement particle I will know what is a mean centroidal distance between that particle and a like or a dislike particle. So it could be a cement it could be fly ash, it could be limestone.

So you can categorize all of that and using these three terms you can come up with a nice idea of how the microstructure is packed and this is fundamental material science which will help you to design the paste. We do this unknowingly most of the time. We select materials without quantifying this but for an ultra-high performance concrete like material you cannot afford not to quantify it because the sensitivity is so high that a minor mistakes can change a lot of different things. So you have to plan that really carefully.

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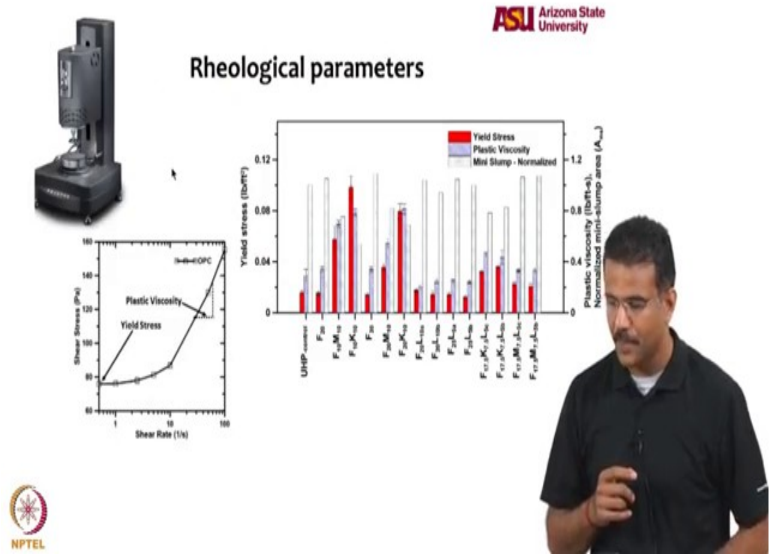

The next one is rheology, because you want to have this thing flowing through a space, because you want to flow this through dense reinforcement, I need to control the rheology. So I have done yield stress, plastic viscosity and mini slump. The reason we did mini slump is because I cannot tell every lab to design such mix to have yield stress and plastic viscosity measured using a rheometer. So I need to give them some simple tool and that is a mini slump, so do a mini slump flow and we get the rheological parameters.

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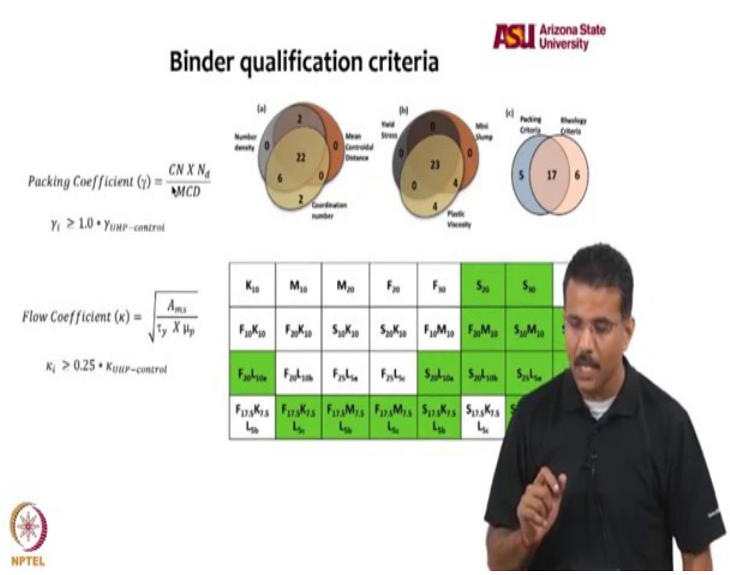

Now using these two parameters, and I showed you this 33 mixes to start with, we define what is called a packing coefficient. It is just a simple mathematical transformation of those three parameters that I talked about. Coordination number means the number of nearest neighbors. More number of nearest neighbors, higher the packing therefore I put that in the numerator. Number density, number of particles in a unit volume, more number of particles better the packing and therefore I put that also in the numerator.

Mean centroidal distance, the distance between a cement grain and a like or dislike particle, the closer they are the better packing which means smaller the distance better packing, I put that in the denominator. Now I get a packing coefficient which is the exaggerated effects of all of these three thing, that is, number density, coordination number and mean centroidal distance. You get a packing fraction and my packing fraction has to be greater than the packing fraction of a control mix that has only cement, just to have some kind of a comparison.

You can use any comparison tool for that, I just said one, it doesn't matter you can say 2 times, you can say 5 times, you can say 0.5 times depending on what you actually need, that is where a designer comes in and says here is the kind of packing that I would need, I have my combarable material with a plain cement paste and I want 5 times more packing or 8 times more packing, how would I need it.

Then, for flow I did the same idea - slump flow area. The more the slump flow area the larger and the better the flowability, the higher the yield stress the lower the flowability, the higher the viscosity lower the flowability. So I put one in the numerator and the other two in denominator. But, if you do that, yield stress plastic viscosity if you remember those numbers are very different, and this you will get large un-linearly(23.53) numbers for people to think and remember. So I put in a square root to make sure that numbers lie between 1 and 10. For people to remember it quickly and make sure that this is a tool that somebody can use.

Again there is no logic for why a square root is, if numbers were even larger I would have made a cube root right. Just to understand and make sure that you can think of these number fairly quickly and in comfortable manner. Now, I do venn diagrams. The first venn diagram is for packing and I get 22 mixtures that satisfy all the criteria, see that in the middle, 23 mixtures from this list that satisfy all the rheology criteria and then I do a union of those and I get 17 mixtures that satisfy both the criteria and those 17 mixtures are shown in green in the box below.

Now, if I change the gammas and the kappa's in packing and flow coefficient you can reduce the number of mixes you want. You say that my kappa is greater than 0.25 times UHP control and if I actually wanted 0.5 you will reduce the range. I want packing twice better than the control mix and then also I will reduce the mix. So this gives the designer a tool to play around. So now you are not shooting in the dark. You are actually choosing exactly how you want your packing and flow so that you get the properties and you select the mixes.

Now I can add one more qualification criteria, I can add a qualification criteria for cost, minimize the cost among these binders. Once the first two criteria is satisfied I can put in a third criteria and the advantage this is that you can write a computer program to do all of this. This makes it much easier now to select a mix rather than going to the lab and doing 250 trials and finally coming back with one or two which may or may not work. Now it is a much more rational and much more sensible strategy to understand what is happening. So that is a binder qualification criteria.

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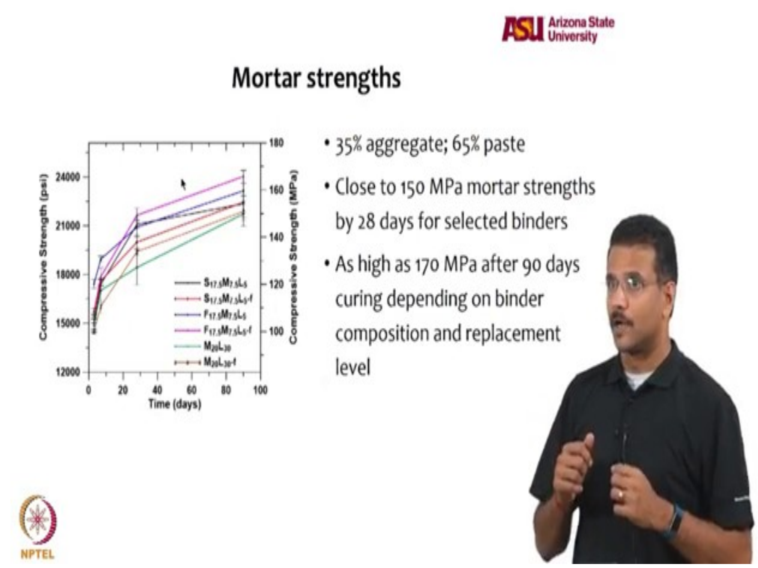

We did mortar strength and you can see that we can get upto 150MPa strength at 28 days. This is 35 percent aggregate and 65 percent paste, that is not a typo you normally see it the other way in mortars and concrete, you need that amount of paste to satisfy the workability and the strength criteria and we get 170 MPa after 90 days with all these mixes which have 30 percent cement replacement. So that is fairly good.

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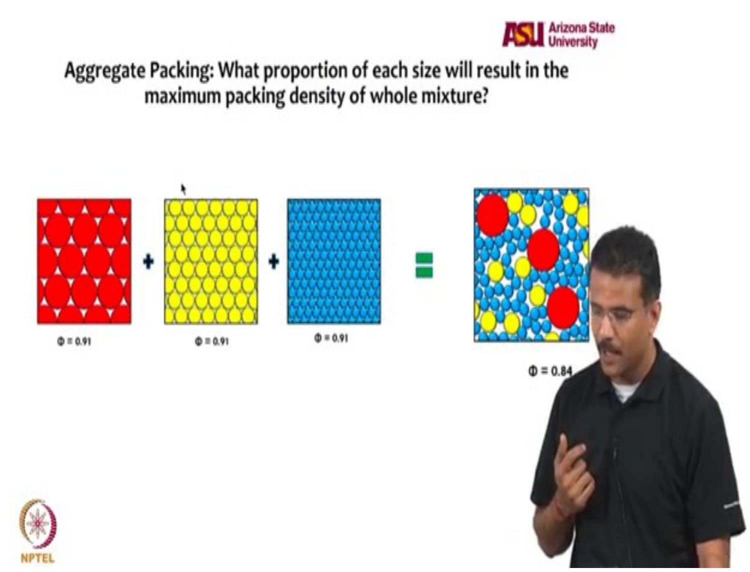

Now aggregate packing, so how do you do aggregate packing? If I have one size of aggregate, the best I can do with small size aggregates is to get a packing fraction of 0.91 . But if I start adding more and more, you have separation effects if spacing difference and stuff your packing fraction will start to come down, again this is not applicable to all sizes, this applicable to really small sizes of microns scale. If you look at hexagonal close packing you get 0.74 which is the theoretical maximum packing, this you can manipulate and put in a few more sizes and get to a higher value.

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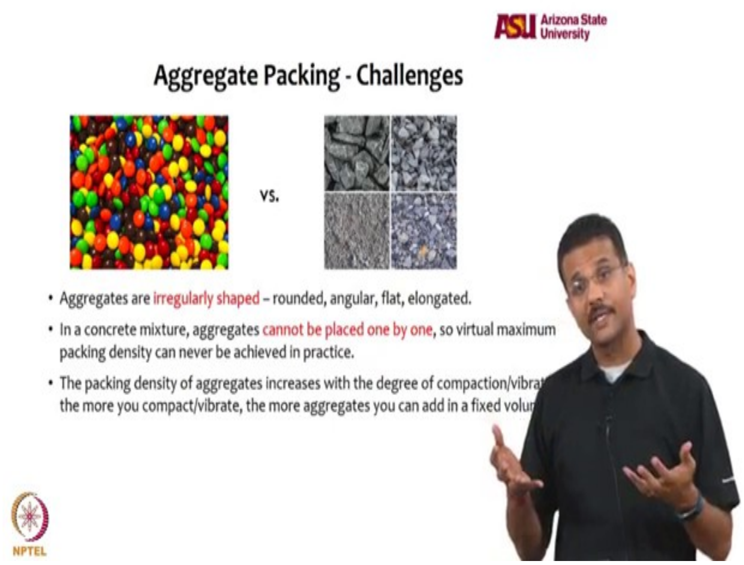

What happens when you have irregularly shaped aggregates? The challenge is with your irregularly placed, so we have something called a virtual maximum packing density. We want as much of aggregates in concrete as possible because aggregates gives you dimensional stability, aggregates will control the shrinkage, aggregates will give you better properties, aggregates will give you higher elastic modulus. So you want all of these, but then to pack these aggregates well is a challenge because the shape and the size are very different.

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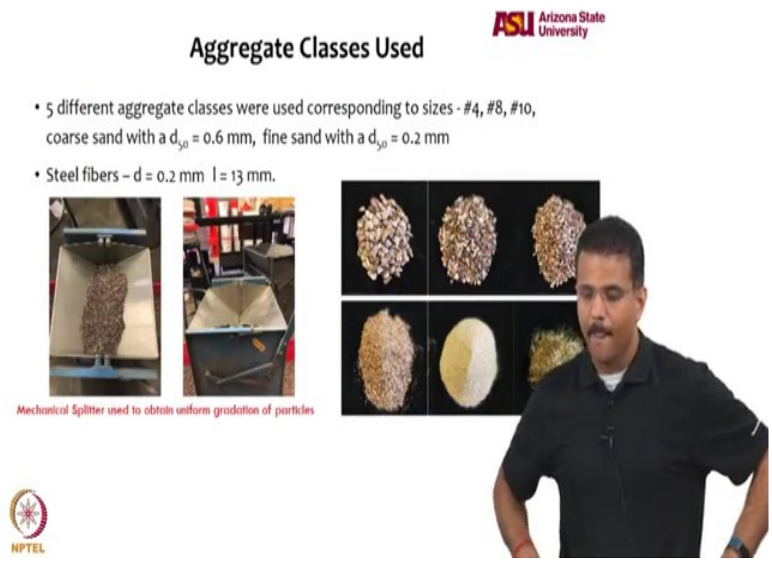

So what we did for UHPC is that we did not go for aggregates of size more than number 4, number 4 is 4.75 millimeters that is passing 9.36 and retained on 4.75, number 8 is passing 4.75 and retained on 2.36 and number 10 is passing 2.36 and retained on 1.18. So 4, 8 and 10 are the only aggregates that we used. We also used two different sands, a course sand with a median size of 0.6 mm and a fine sand with a median size of 0.2 mm and then steel fibers 0.2 mm diameter and 13 mm. So what we did is, we separated all these aggregates into different sizes because you really have to pack them well and then you use what is called the compressible packing model.

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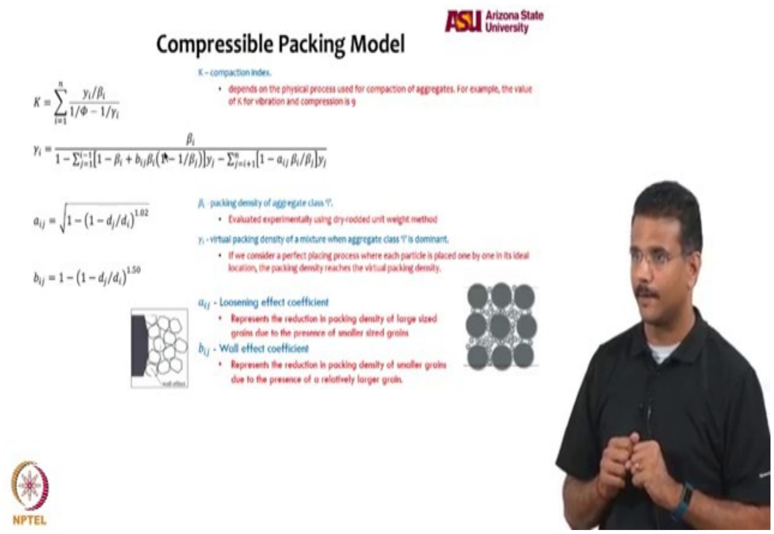

Again you have to figure out a way to pack the aggregates. The derivations are there in the publications that we have done, I will give you a list of that at the end. So it is not very complicated, you can again put this in a computer program and do and have all the choices made.

So you select a compaction index K. You can say that you are compacting it really well and so a number of 9 is typically used and then that is a function of the virtual packing density's of the mix, the packing density of each of those aggregate classes, the volume fraction of each those aggregates classes and all of that. Then, I have two different coefficients A i j and B i j which will take care of the loosening effect, so if I have a large aggregate that gets in between the small aggregates it loosen the structure. So I have to account for that and then I have to account for the wall effect. When I have aggregates placed along the wall, I will not get the maximum packing density and so I have to account for those two effects also.

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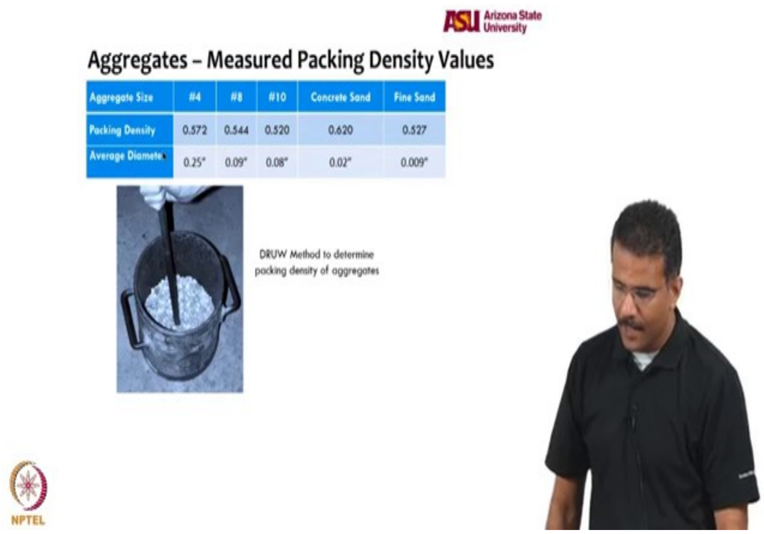

And then you have to find out the measured packing density of each of the aggregate classes. This is the only lab experiment that you have to do for that, for each of those sizes you find out what is the actual maximum packing density by doing a dry rodded unit weight test in the lab and that will give you a maximum packing density.

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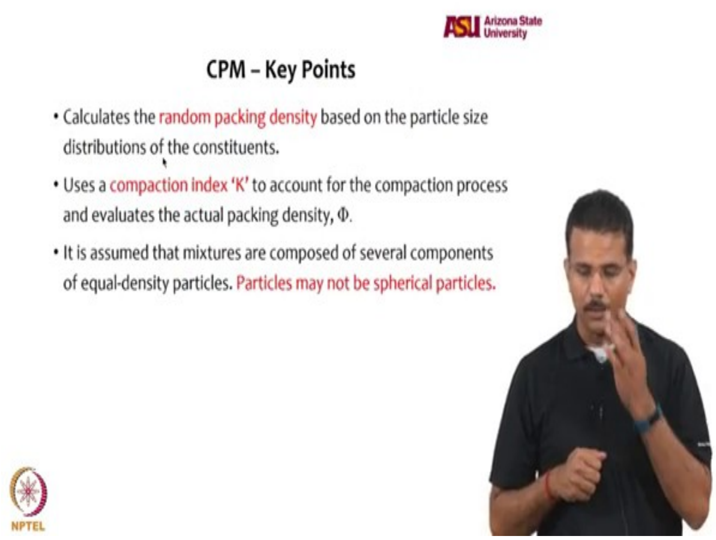

So what this model does is, using all of those and the equations that I showed you earlier, it calculates what is called the random packing density. So if you do a packing randomly, randomly meaning you pick up a particle with your eyes closed and throw it in the box until it gets filled, it is not selectively by opening the eyes and placing one next to other where you can actually fill in space. So the random packing density will always be lower than the maximum available or maximum possible packing density and then because in real life you put the aggregates randomly, you don't place them one by one. But then what you do, you place them and then you compact concrete, the process of compaction takes care of some of the effects of random packing by moving things into spaces that were present. So then you add the compaction index to account for the compaction process to get you the actual packing density, that is what's in the field, and then you are assuming that all these particles have equal density, particles may not be spherical but you have to make some adjustments for that.

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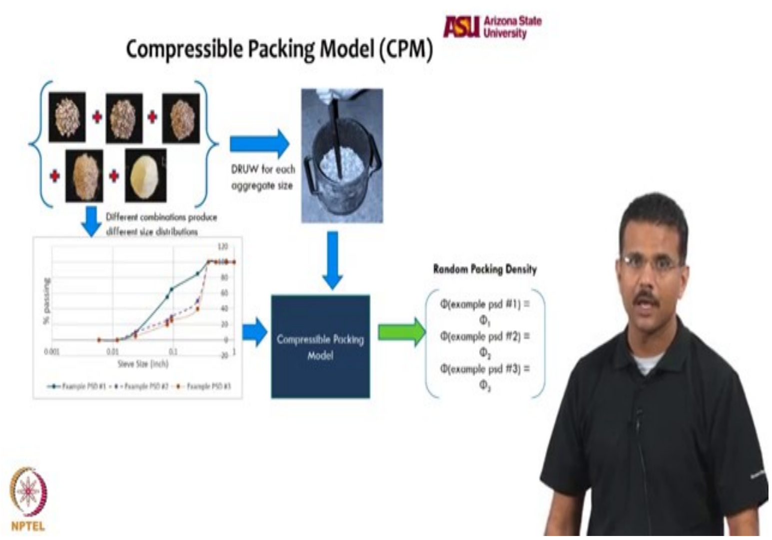

So here is a compressible packing model, get all the different sizes of aggregates that you want, get the dry rodded unit weight for each of those class of aggregates, put all of them in the compressible packing model along with particle size distribution, come up with random packing densities, if you do that you will get random packing densities.

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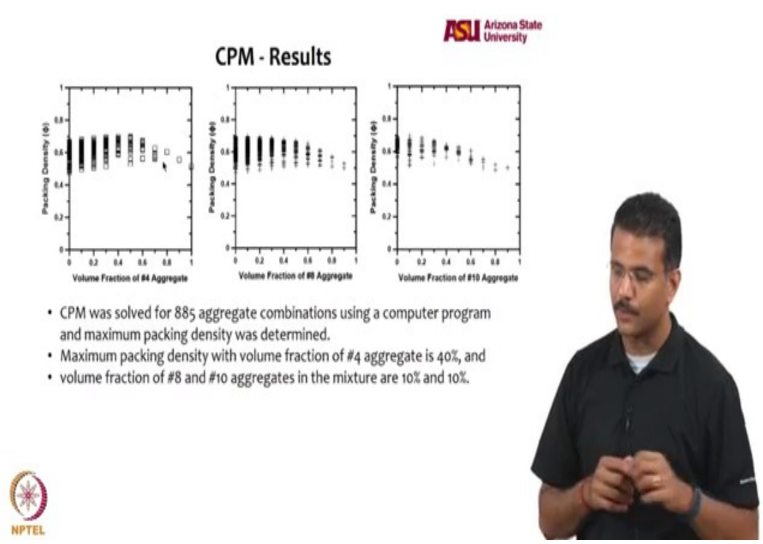

This is some plots for 885 different aggregate combinations, MATLAB code will do it in 2 seconds, and then you plot the random packing density as a function of volume fraction of different aggregates and you can find out where is a maxima in the packing density for different combinations.

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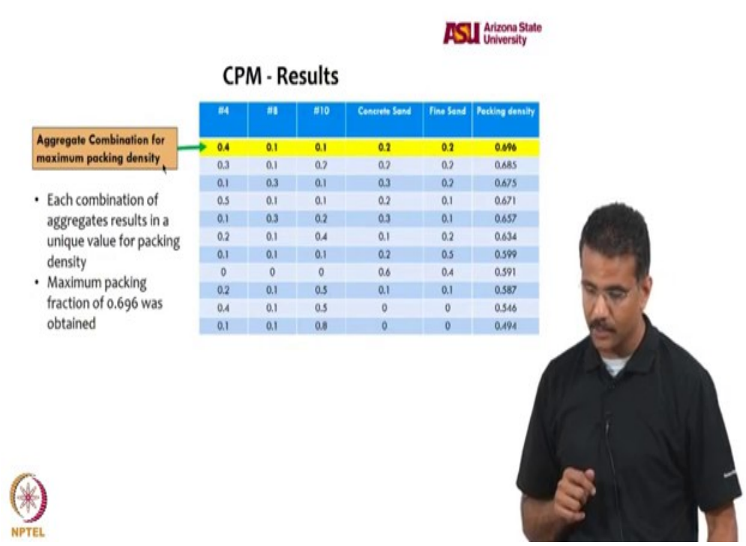

Based on those combinations pick up the one with the maximum packing density, in this case it is 0.696 where I have 40 percent of number 4, 10 percent of number 8, 10 percent of number 10, 20 percent of concrete sand which is 0.6 mm and 20 percent of fine sand which is 0.2 mm. Now don’t ask me why 0.4, 0.1, 0.1 why can’t it be 0.38, 0.265, 0.4. You can, but if I am going to give this to a ready mix concrete operator I am better off giving him number like this rather than telling him 26 and a half percent, 32 and a half percent because he is going to make mistakes.

So it is better to stick to numbers where somebody can actually produce those concrete with minimal complications. You can get to as many significant digits as you want, you can do this in as much of refinement as you want. If you say that 0.4, 0.1, 0.1, I think it will be 0.38 0.08, 0.12, all power to you you might be able to do that but again practically it is not a great idea.

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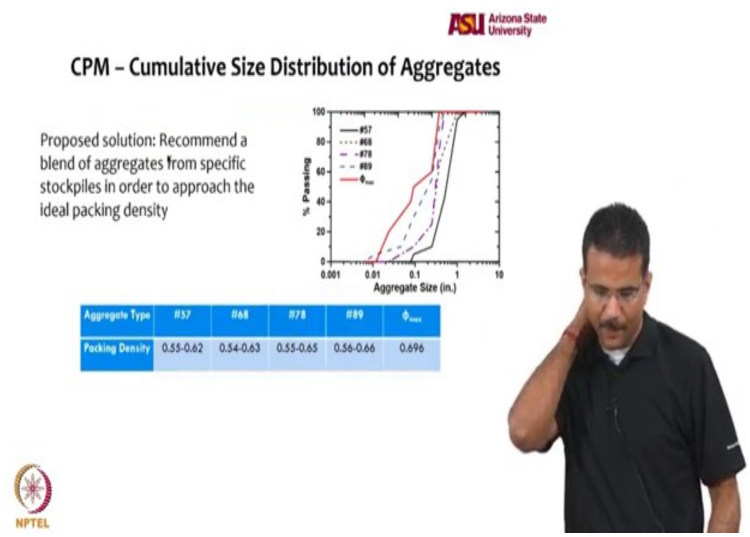

So that is a proper solution, you get a recommended blend of aggregates and then you see this in the table number 57, number 68, 78, 89, this is how they call aggregate piles in the US. So again communication, if I have to tell the guy in the ready mix plant, I cannot tell them number 4 so much, number 8 so much, he will say what to do with my number 57, because that is the packing that is the gradation that he has. So I should tell him that number 57 will give you roughly a packing density between 0.55 and 0.62, what should I augment in 57 to get him what I want.

Or of he says I have only number 78, what I should augment in 78 to get what I want. So again it is more a practical idea of how to communicate to somebody in the ready mix plant on what aggregate combination you need.

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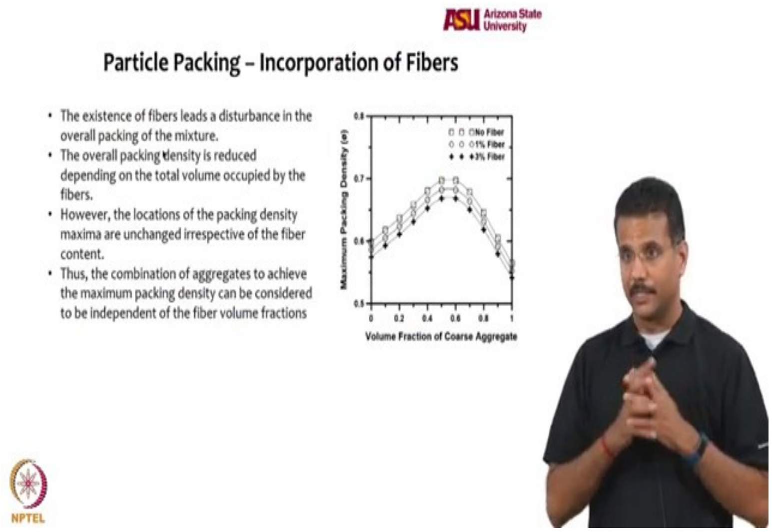

Fibers, if you incorporate these long fibers in this matrix of aggregates then the fibers are going to displace some of the aggregates. You are going to have a lower packing anytime you put in something of a different aspect ratio. You will see in this picture that the maximum packing density is reduced a little with the addition of fibers but then the advantages that the fibers gives is so much. In terms of ductility you live with it you say that that is a necessary evil that I have to take with and you live with it.

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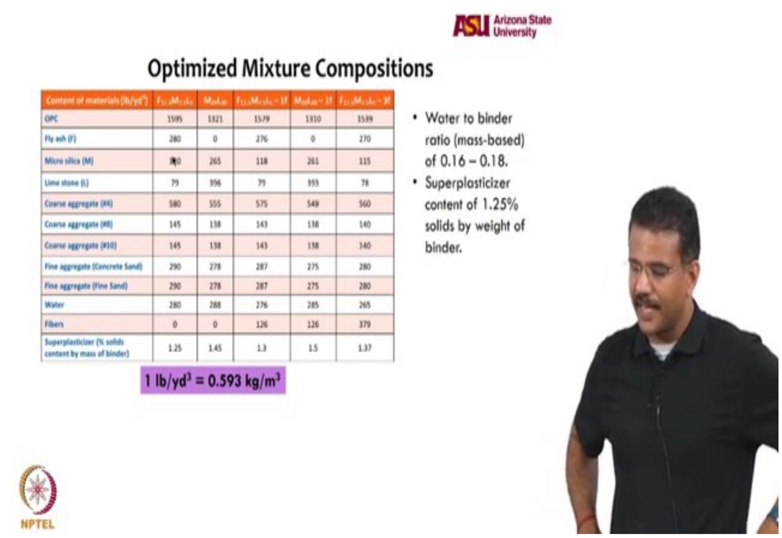

So here are the final mixture compositions. I used the selected aggregate combinations that I showed you here that is, 0.4, 0.1, 0.1, 0.2, 0.2 by mass of all these aggregates and two different paste mixes, one with fly ash Metakaolin and limestone and the second one with limestone and silica fume. Two different mixes with and without fibers with water cement ratio of 0.16 to 0.18 and a super plasticizer dosage of point 1.25 percent by weight of the binder of all the powders, that is about 5 percent by weight including the liquid content of the super plasticizer.

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Ok, just show you some pictures or scaled-up mixtures and show you how we can actually do this.

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So aggregates are washed and dried, aggregates are added to the mixer, fine aggregates are added, mixing water is added to the aggregate to attain a saturated surface dry condition and then mix it together and blend all the aggregates together, and add silica fume first.

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Silica fume is added first to break down the silica fume agglomerates. So you put the silica fume in and make silica fume dispersed by mixing and then add the limestone because limestone are the next larger size. Then you mix this well so that you get a good mix and then add fly ash.

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Then add first one-third of water and superplasticizer, mix it and then add second one-third of water and superplasticizer. So you have added two thirds of the water and two thirds of superplasticizer and see how the mix look like, once you add them that is a right bottom mix. And then, between that and the next when you see the difference, that is purely by high shear mixing. You have just mixed it for 5 to 7minutes at extremely high shear to break all the particles and to release the water from all the agglomerates. Now you add the last one third of water and the superplasticizer and you see the mix being extremely fluid and then you add steel fibers and mix it

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The mix obtained is so good that even with that flowability there is absolutely no bleeding or segregation. You see a very cohesive, very dense mix and it is very hard to believe that this is a 0.16 water cement ratio mix. So, you need intense mixing and you need to mix it for longer periods of time at high shear. So now you have a good ultra-high performance concrete mix which we designed from first principles, by packing the particles, by controlling the rheology, by selecting aggregates of sizes so that you can have all those properties satisfied.