Advanced Concrete Technology
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Lecture – 25
Mixture Proportioning

Good evening everyone, so today we will start of a new subject that on HPC or high performance concrete mixture proportioning. So far we have learnt about different types of concrete making materials, we started up with cement, we discussed extensively about cement chemistry, we talked a bit about aggregates and the relevance of aggregate geology to the properties of aggregates in concrete.

We then, discussed about chemical admixtures and how we can optimise their use in concrete to produce different types of speciality concrete and then finally we talk about mineral additives in quite a bit of detail because essentially, today we are dealing with concrete which is more or less always made with mineral admixtures, so from now on we will get more into how we can proportion the materials together and what are the properties and characteristics of the concrete which is prepared with a blend of these kinds of materials.

So, today, we will talk about some techniques which are available today to proportion your concrete mixtures to get the best out of the ingredients and optimise the performance based on the ingredients that you have used. So, we will talk about specific techniques of course, you are also expected to read on your own the regular mixed design procedures that are typically followed in different design guidelines.

For example, the Indian standards has a mixed design guideline, IS 10262, which was modified recently; by recently I mean about 8 years ago, so you have the latest version that is available in this practice in the industry with respect to mix design of concrete, the previous guideline was nearly 20 years old, so it was high time for a change because people wanted to understand how well we can proportion with different types of admixtures in the concrete.

And so, this new guideline is quite useful, please also remember that the design guidelines specified in IS 456 still happens to be the parent document as far as designing materials or using any material in concrete is concerned. So, IS 456 still stipulates the kind of materials that can be used in concrete, IS 10262 simply gives you a guideline to do a mixture design, supposing you do not really have any prior knowledge or experience based on the type of materials that you are going to be using for your project.

So, it is like you can start of from scratch and then do a design process based on that but truly speaking any design is all right as long as you are satisfying the requirements of, IS 456; what are the; I mean all of you have done reinforced concrete design, so you must know what are the regulations regarding materials in IS 456, can you name a few; the cement content to be used in different types of environments.

For example, when you have chloride related environment, you divide that into 5 different exposure conditions; mild, moderate, severe, very sever, and extreme. In terms of sulphates, depending upon the sulphate concentrations in the soil, you are expected to use a certain maximum water to cement ratio and a special type of cement and so on and so forth. Of course, we will discuss these requirements in our topic on durability towards the end of the course.

But for now, we need to understand what are these requirements in IS 456 that need to be satisfied, so as long as you are satisfying those requirements, any mix design you can put together on paper which satisfies the requirements as well as which measures up to the correct volume of concrete that you want to prepare is fine.

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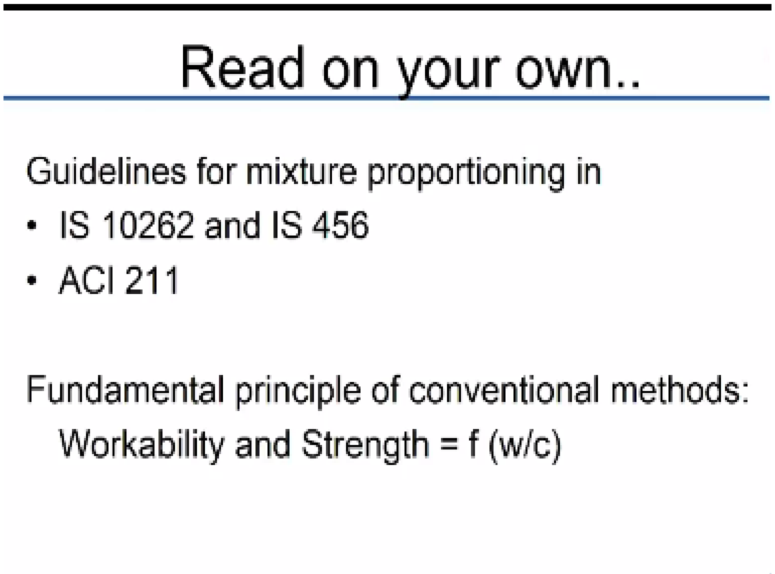

So, that means you already have prior understanding of the kind of materials you are dealing with in a project with which you can actually put together the mix design required for a specific grade of concrete but if you do not have any prior knowledge or prior idea about the materials that we are using following the guidelines quite helpful. ACI 211 is the American concrete institute guideline which is on a similar line as IS 10262.

Of course, every country has their own mixes and guidelines, EN 206 is a European guideline or rather European norms for concrete and those also link you to different kinds of mixes and guidelines that are available, but the fundamental principle of all conventional design methods is that your workability and strength are both the function of the water to cement ratio. So, while this tenet may not be different in the modern principles also.

Of course, in modern principle also, we primarily base it on the same fact that your strength is primarily determined from the water to cement ratio but what we will try to do is optimise the contents of your concrete in such a way that we can maximise the packing of the ingredients and minimise the amount of paste that is required to produce the concrete.

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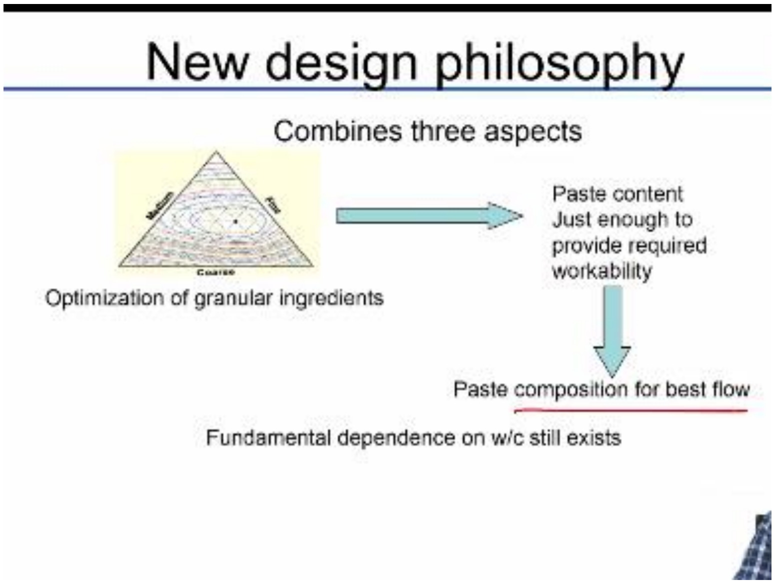

So, the modern philosophy or mix design combines 3 major aspects; one is optimisation of the granular ingredients that means, your aggregates as well as your cementitious combinations for example, if you are using mineral additives as a replacement for cement, how to optimise these constituents to get the best packing, you know very well that concrete is proportioned in such a way that the fill up a certain volume typically, 1 cubic meter. So, the requirement for water is going to be lowered if you are able to pack the granular materials well enough together.

That means you have less voids to be filled up with water, if you take it as a two component system, aggregates and paste, your fill up the aggregates into the volume first, if you fill it up in an efficient manner, you do not need so much paste to fill up the voids that are left behind by the aggregate, of course, just filling up those voids may not get you the desired level of workability.

You need to determine, what is the amount of paste to require over and above that void level to give you the workability characteristics, I hope you are following me on that so, when you fill up your volume with aggregate or aggregate combinations, some voids are left behind and you are filling up these voids with paste but that may not be sufficient to provide sufficient workability into your system.

So, you want paste in addition or in excess of that void content and for that you need to actually determine how much is this void content and what this does is paste content is restricted to what is just enough to provide the required workability, you do not require high flow conditions for all applications, you do not require concrete to be self-compacting for all applications. At the same time, there are applications in which you also require high flow conditions.

There are applications in which you require zero slumps; can you tell me some applications which zero slump? Roller compacted concrete, sorry; curve casting, or slip formed concrete for pavements where you need very low slump requirements, so you can design your content adequately for different types of requirements by doing a combination of these 3 aspects.

One is optimisation of granular ingredients, the next is paste content determination to be just enough to provide the required workability but at that paste content, how do we maximise the characteristics of the paste by understanding what is the best composition for the best flow properties, so that what is critical to design the paste for a best flow and this would be linked to our next chapter in fresh concrete also, where we talk about rheology.

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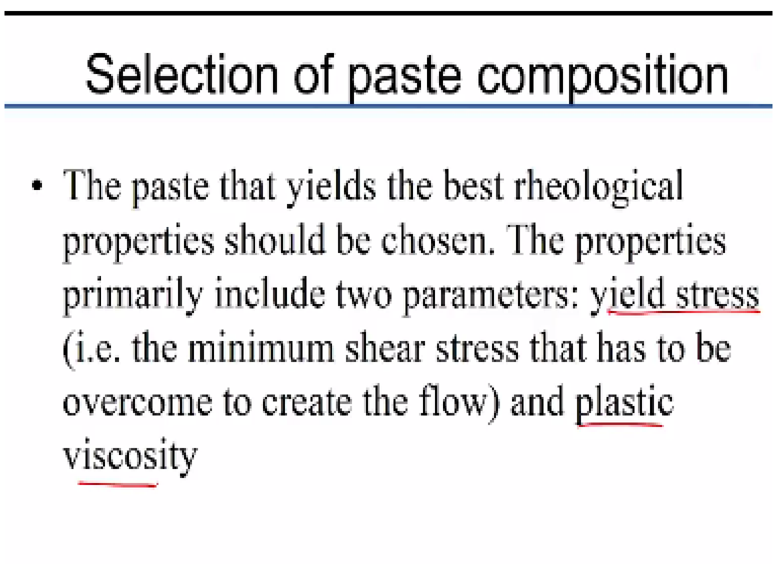

Rheology is essentially the science of flow of matter, so rheology of concrete nowadays is gaining a lot of significance primarily from the aspect of looking at flowable concretes, so we will look at how this is used before that what we need to discuss is; coming back to the paste composition; we talked about rheology and I link this up in a major way in the next chapter when we talk about fresh concrete.

The rheological parameters are essentially consisting of 2 components; one is the yield stress which is the minimum shear stress that needs to be overcome to initiate the flow, again, we will discuss this in detail in the next chapter but just to pre-empt, when you pour concrete into the form work, if it is going to be a conventional concrete; vibrated concrete what happens to it? It just remains in one place.

But if you have to get it compacted, what you do; you insert the vibrator, what does a vibrator do; it overcomes the initial yield stress that is present in the material and makes it flow and fill up the form work, so yield stress is the in-it quality of the material which prevents it from flowing and once the material flows, the resistance to flow is governed by the viscosity of the material or the plastic viscosity of the material.

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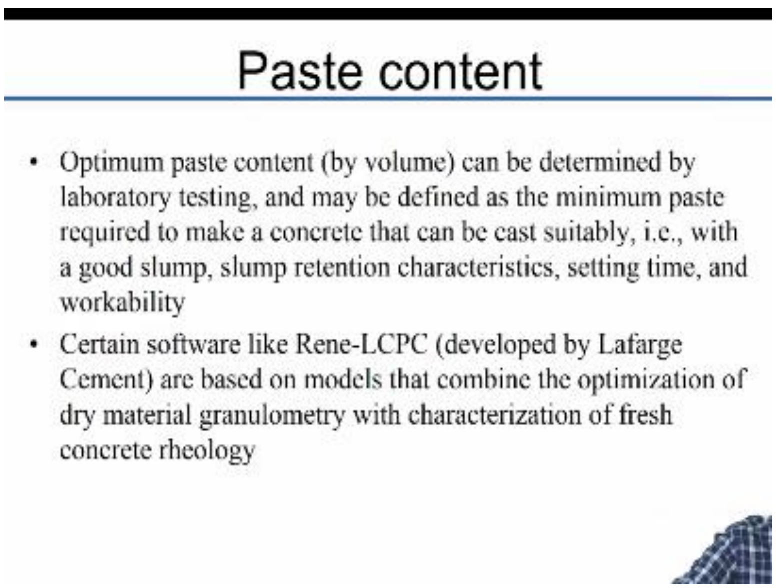

So, we learn later about the different types of rheological models and how we can actually estimate these characteristics for cement paste in concrete. Now, how do we determine how much paste is required, do that we have to understand how much is the void space left behind when we are packing the aggregates in a given fashion and already we said that one of the basic tenets of modern philosophy of mixed designer is that you maximise the aggregate composition to obtain minimum void space.

So, optimum paste content can be of course determined by a laboratory testing and it can be defined as the minimum paste required to make concrete that can be cast suitably, now of course, this casting requirements will differ based on the type of application, if you need flowable concrete, you will require certain type of paste, if you need semi workable or less workable concrete, your paste requirement may not be that high anyway.

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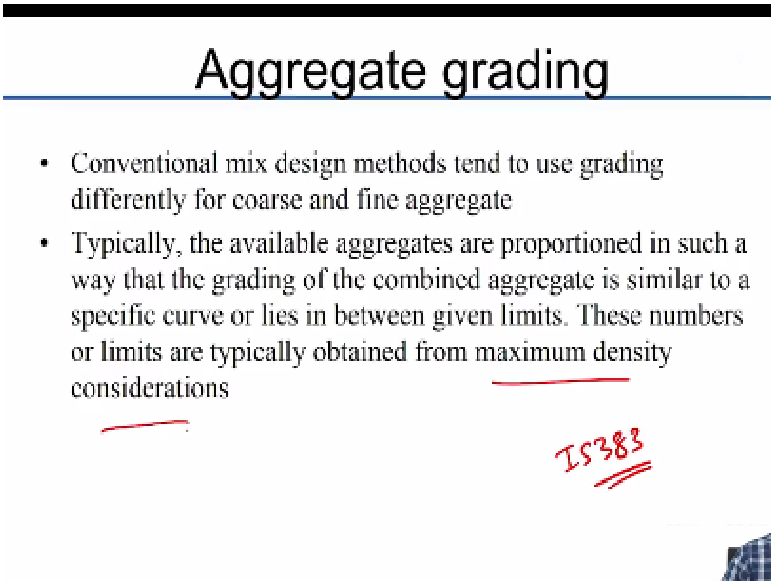

So, there are software available which can actually determine for a given combination of the granular materials, what is the amount of paste that is required to fill up the void spaces, we will talk about this in more detail by first looking at how do we actually do aggregate grading and how can we optimise this a little bit better to ensure that we can determine the void content much more accurately.

Now, when you do mix design of concrete in the conventional fashion, how is the aggregate grading taken into account, the proportion of coarse aggregate depends on the zone of the fine aggregate, exactly. The zone of the fine aggregate defines its particular level of fineness; mean between what sieve sizes is the size distribution of the fine aggregates, based on that zone, which is divided into 4 types; zone 1 to 4, as you go from 1 to 4, what happen to fineness?

Fineness increases, it gets finer and finer as you go from zone 1 to zone 4, the typical sand that is used for mix design process is called zone 2 sand and for a particular zone of the sand, you determine the content of the coarse aggregate that is required. Now, of course, before that in a regular mix design process, you would have already worked out for the particular strength what is the water to cement ratio.

And based on the maximum size of the coarse aggregate, you would have fix the water content, that is the basic mix design process. So, now typically, what happens is; we proportion the aggregates in such a way that the combined aggregate gradation lies between very specific limits of course, we picked the sand based on the zone but once we proportion the coarse aggregate and sand, it ends up making the aggregate fit a particular grading curve.

And that grading curve obviously is defined in IS 383 that is a specification for aggregates for concrete, so the combined aggregate gradation is defined in this and all your concrete has to satisfy the combined aggregate gradation. Now, how are these gradation numbers obtained? These were obtained obviously from some packing criteria that were developed quite a few years ago.

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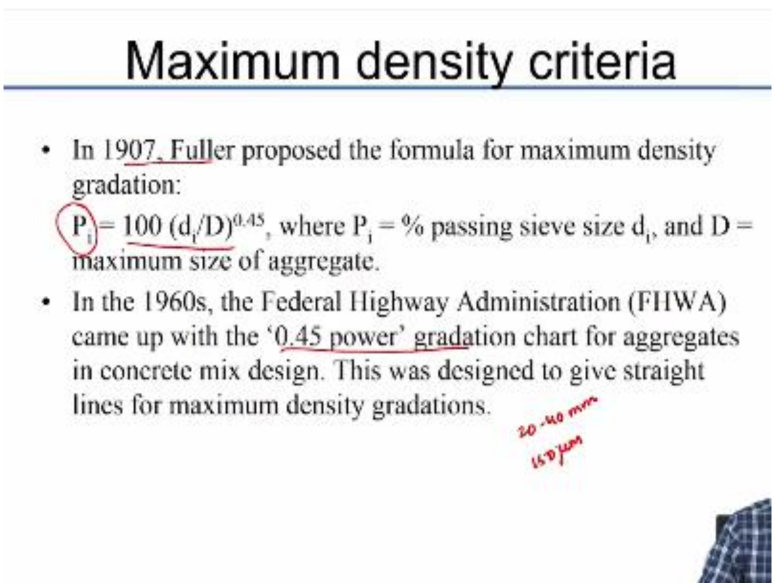

So, again these are based on maximum density considerations and let us look at what this criterion is; so, the maximum density criteria that was used in conventional design process was based on some work which was done as early as 1907 and this was Fuller's proposition for the formula for maximum density gradation,

$$P_i = 100\,(d_i / D)^{0.45}$$

Where P_i is a percentage passing a particular size d_i, D is maximum size of aggregates, di is the specific sieve size.

So for each sieve size, you can determine what is the ideal gradation or ideal amount of material that should be passing to satisfy the required gradation limits, of course, the gradation is not a single curve, it gives you a range, it give you a particular range, so that if your curve is falling within that range you are satisfying that particular gradation requirement.

So, this is again based on Fuller's formula which was also called 0.45 power gradation and this was again adopted by several highway agencies and public works departments all across the country and of course in the world. So this 0.45 power rule has been followed largely everywhere in the world until the recent past, now people have started realising that this 0.45 power rule probably does not support the modern concretes, where we are increasingly using very fine constituents,

We talked about the fact that mineral admixtures could not just contribute to supplementary cementing reactions, there could also be filler effects which can be quite significant as far as mineral admixtures are concerned, so now if we try to incorporate those fillers along with other fillers that maybe sometimes used as aggregate replacement, you need to start considering particle size gradations, which are more reflective of the actual sizes that you have in the concrete.

So, when this was derived obviously, what was the maximum size of the aggregate? May be 20 to 40 mm would have been the maximum size of the aggregate, what about minimum; 150 micron, so sand size essentially, we are talking about 150 micron not much less than 75 microns, but when we start putting fine mineral additives with the mix, we are increasingly getting sizes below 100 microns.

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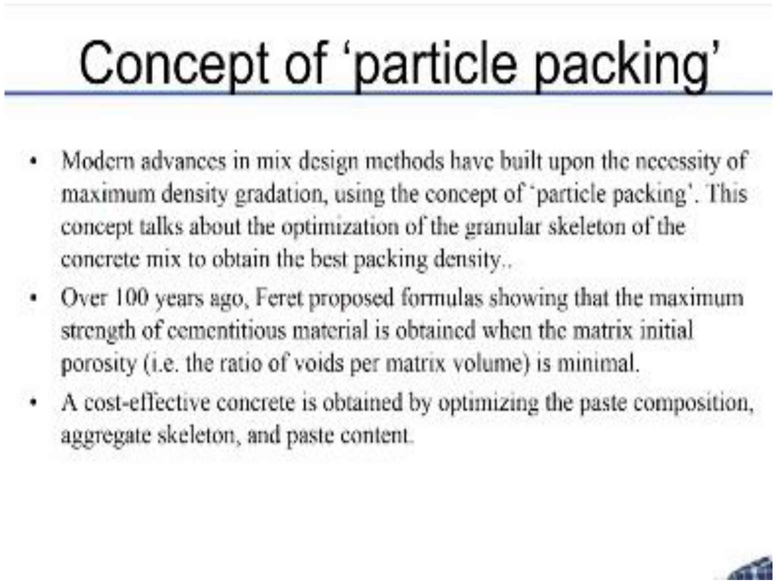

Now, how do we take account of that and propose a maximum density gradation that is able to account for the extra granular constituents also. So, let us look at that; that is why the concept of particle packing started becoming popular, now of course, this concept is not new, it has been applied in the powder metallurgy industry for a very, very long time, so where they make castables from powders.

What they do is; they combine different types of powders based on the size gradations into one ideal gradation, so that when they packed these powders together they get the maximum density, but that is a refractory castable industry what the concrete industry started doing was adapting the same technology for mix design of concrete also. So here what we have done is; based on the formulas that were previously used, a cost effective concrete can now be obtained by optimising the granular constituents.

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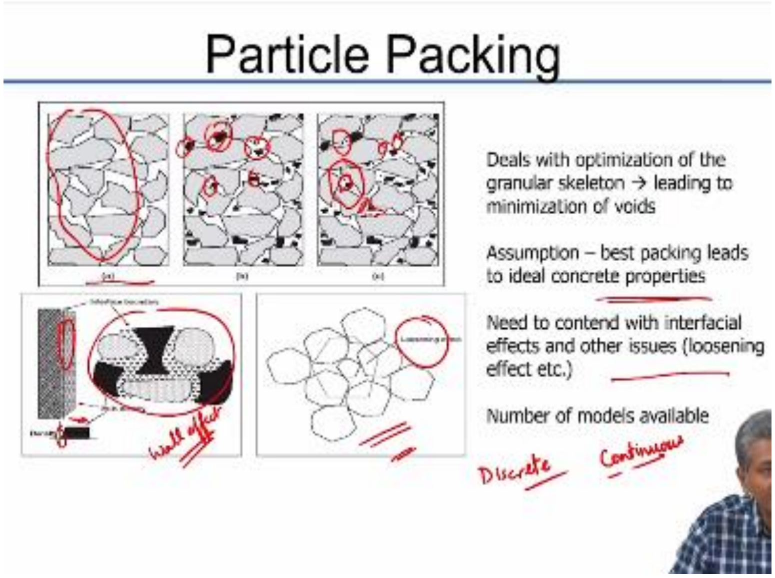

In the same way that refractory castables optimise their packing of the granular materials, so let us look at how this is done, you have a first system of coarse aggregate, then you have a system of aggregates which is less coarse which starts filling up these void spaces, you have these particles which are filling up the void spaces left behind with the first set of particles and then you have still further smaller particles which are filling up more of the particle spaces and so on and so forth.

So, this is done Ad infinitum, so that when you have a group of particles which have sizes all across the range, you have consistently more spaces in the system getting filled up and this basically a concept of particle packing, you are using different sizes of aggregates combining it in such a way that you get maximum packing. Now, what you need to be aware of is that when you are measuring the packing of these systems, you may encounter one or two issues.

For example, one is the wall effect, now this we have discussed with respect to the interfacial transitions zone also, the packing of granular constituents near the walls of the container is going to be quite different as compared to the packing away from the walls. So, for example if this is the granular materials getting packed, if you are going close to the walls of the container the density will be quite low.

Whereas, if you are away from the wall zone container, your density is going to be higher. So bulk density is going to be greater than the density at the interfaces and that is exactly what we saw in the concrete microstructure when we saw that the paste was not very well packed in the vicinity of the aggregate but away from the aggregate, there was good packing in the paste. The other aspect is a loosening effect.

Now, what happens is when you have these spaces between the aggregate particles, if you try to fill it up with a particle size that is greater than the space available, what it will do? it will split apart the particles around it and spread them out, so that is called loosening effect, so that is why when you are doing particle gradations, you need to be careful about picking the right size of particles that can fill in the gaps provided by the previous size particles.

This could also apply if you are simply choosing smaller sized particles which can still fill up these void spaces but if you choose such a large volume that the smaller particles are able to actually fill up more than what is actually available, to give you an example, if you are substituting cement with silica fume, cement particle sizes are how much; about 10 to 15 microns on the average, silica fume particle size is all < 1 micron.

We are talking about 0.5 micron and even lesser, so if you have too much of silica fume as the replacement of cement, what you will have is the silica fume particles getting in between the voids left behind by the cement particles and probably filling excess of those void spaces causing the particles to start drifting apart. So, in other words too much of silica fume replacement may actually end up producing a negative particle packing effect.

Because of the loosening aspects, so when you have fine particles, it should have the right fineness and the right amount to fill up the void spaces left behind, so the assumption in all this is the best packing leads to the ideal concrete properties. Now, of course with respect to strength that is understood, if we pack more of the volume with solids, we have lesser porosity, so obviously we will have better strength.

But with respect to workability, it is a little bit of a hard cell, when you are trying to maximise the density of the material, so how do we maximise the workability of this composition, it is not going to be easy, so for that you need to determine how best you can optimise the paste properties to make the material flow. So, of course, the wall effect and loosening effects have to be looked at seriously to consider what best you can achieve with a given set of materials.

Now, there are number of models which have been developed for particle packing, some have been based on experiments, some have been based on theory, when you use theory obviously, there is a lot of assumptions you need to make about particle shape about the range of particle size and so on, so I am not going into the models but for those of you are interested, I will give you a couple of references at the end.

But generally, these models are described; are split into 2 types, you have discrete models and continuous models. So, discrete is like what is shown here, you have one uniform sized aggregate, you fill it up with another uniform size aggregate in between and then another uniform size aggregate fills up that space and so on. In the case of a continuous model, you have aggregate of all possible sizes.

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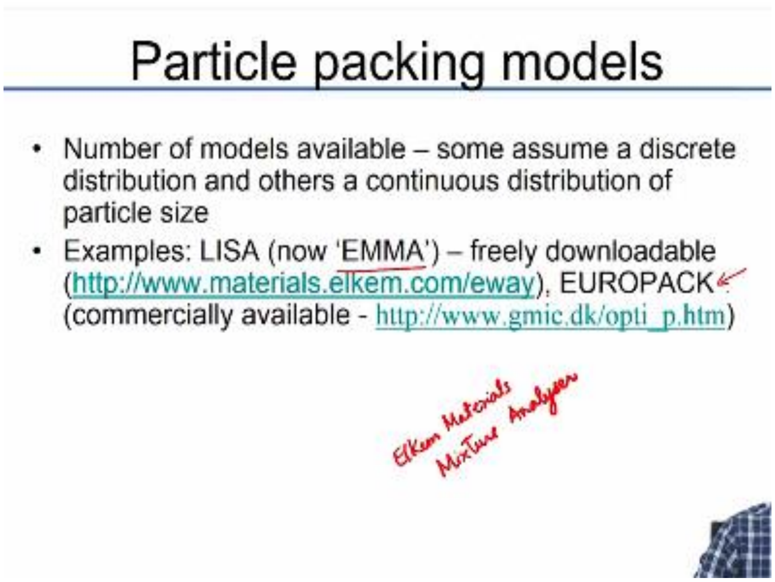

And they continuously pack against the voids that are available from the previous size, anyway, so that is something that you can read on your own, we are not go into the details there. There are several packing models that have been coverted to software also and there is a popular software available on the Internet called Emma, which is Elkem materials and mixture analyser, Elkem materials mixture analyser; EMMA.

Okay, they are used to call it LISA, I am not sure what LISA stands for, EMMA is elkem materials mixture analyser, now elkem materials is the company that manufactures silica fume, so they wanted again to have some sort of the USP to sell their product, the previous USP, we talked about was the rapid chloride permeability test, where it gives excellent values in terms of very low charge passed owing to the high resistivity you can get for these systems.

So, again one more USP, they wanted to bring out was how well we can utilise the concepts of powder castables in concrete technology, where we are trying to use silica fume and pack it into cementitious system and show the benefits in terms of high strengths, so EMMA is quite user friendly, I will show you how we can use this and it is also freely available on the Internet, the web address is also given there, you can download that on to your own laptop and check out how we can do the design.

Then, there is other software also available like EUROPACK; EUROPACK is commercially available software and is quite expensive, it is not cheap but then it may be worthwhile to buy this if you are an owner of ready mix concrete industry for instance.

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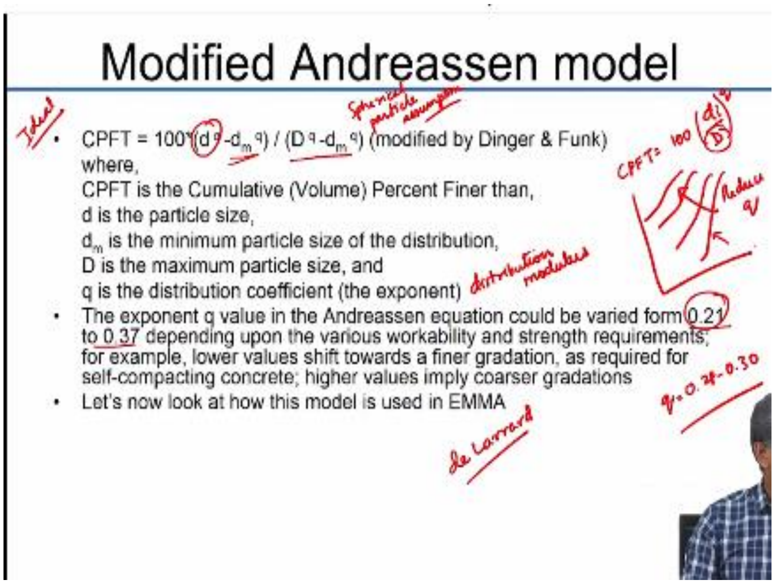

So, let us look at what EMMA does, it actually modifies the previous equation, remember the previous equation was based on the maximum density gradation based on the 0.45 power rule, so what the new design models do is; they modify this exponent 0.45 to more suitable values to bring in a larger range of particle sizes.

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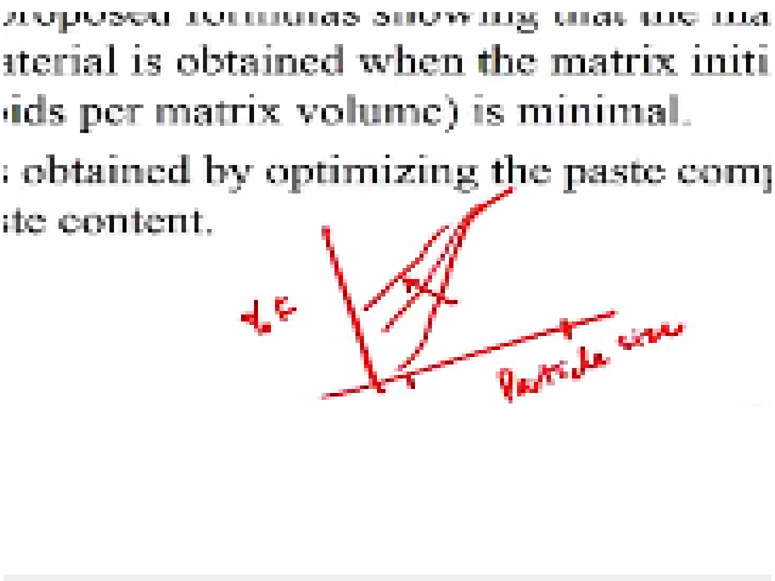

So, please remember when you plot your particle size diagram, I will do it here, if you plot your particle size distribution diagram; percentage finer versus particle size, what is a typical shape that you get for a well-graded system, an S shaped curve, so this is percentage finer, this is largest particle size; that is the smallest particle size in the system. Now, what happens is when you start spreading to smaller and smaller particle sizes, this curve should increasingly go in that direction.

Because there is more range of particle size is now available, so what the modern philosophy of design does is that instead of using this 0.45, they ask you to choose the value of the exponent based upon the system that you are working with. So, how do you do that, I will talk about in just a minute. So for that what we use is the modified Andreassen model, so original andreassen model was simply a simple replacement of your 0.45 with this exponent q.

So, the original model was CPFT = 100 * di/D to the power of q, the 0.45 was modified to q that q was basically capturing the range by shifting curve upwards, so now what the Dinger and Funk did was that they modified this a little bit further and utilised not only the particle size of the power of q but subtracted from that the minimum particle size to the power of q and the denominator instead of only having the maximum particle size, it was made up with maximum to the power q - minimum to the power q.

$$CPFT = 100\,(d^q - d_m^q) / (D^q - d_m^q)$$

So, CPFT of course is the cumulative percentage finer than, d is the particle size, the particular sieve size that you are considering, dm is the minimum particle size of the distribution and D is the maximum particle size and q is basically your distribution coefficient or the exponent or sometimes it is also listed as the distribution modulus, so generally this q value varies between about 0.21 to 0.37 for modern concrete mixtures.

Now, I know that is the large variation depends on what you use you may actually get completely different ideal gradations, so please remember this is for an ideal particle gradation, this is an equation that defines the ideal particle gradation, when you have a bunch of particles in a mix, so depending upon the fine components in your concrete, if you have excessive of fines in your system, you move to smaller values of q.

Obviously because this graph becomes more and more shallower as you are going to greater amount of fines in your mix, that means you are reducing a q, so if you are reducing q, you are going in that direction and when you are using mixtures with large particle sizes for example, if you are producing roller compacted concrete for instance, you can start using the higher values of q closer to 0.35 or 0.37.

For conventional concrete which has 20mm aggregate generally, people have been able to work reasonably good mix designs with q values between 0.28 and 0.3, so for conventional concrete, 0.28 to 0.3 can be satisfactory, when we go for self-compacting concrete or reactive powder concrete which are incorporating extremely fine materials, you go for lower values of q closer to 0.21.

How is this found out? Again, mainly by extermination, people have not really done, of course this has been fitted mathematically but it has been validated by experimentation that the lower values of q seem to fit very well with self-compacting concrete and reactive powder concrete type mixtures.

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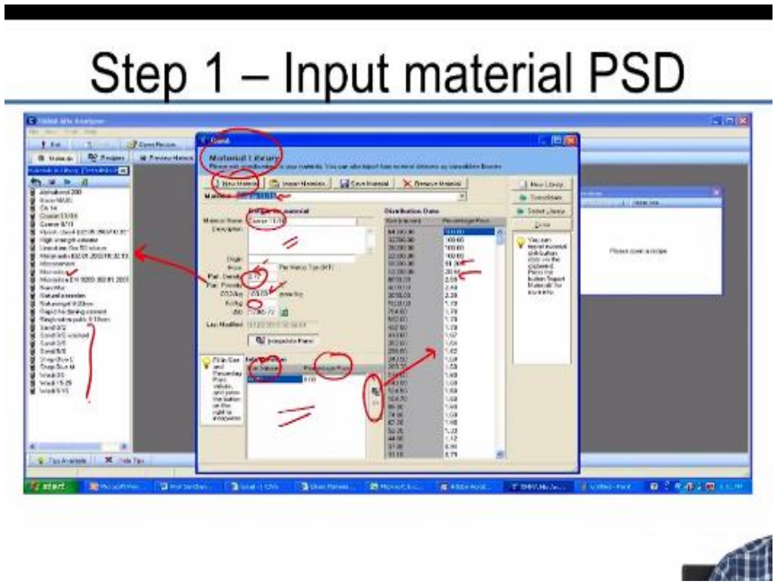

So, let us see how this is used, so this is your material, the software interface as far as EMMA is concerned, so good question as far as this modified andreassen model is concerned, the fitting is done based on an assumption that all the particles are spherical, so we are not considering the angularity of particles here. So, here this assumes that all particles are spherical, you should state that here; angular aggregates, correct.

No, well, this equation will not be completely satisfied if you have angular aggregates, so there are some discrete particle packing models which are better suited for angular aggregate systems and in fact, there are models which combine particle packing and rheology together to produce the mix design for your concretes but again, those get very complicated and in fact, there is actually a book on high performance concrete mixture proportioning by a scientist named de Larrard.

So, if you are interested in mathematics a lot, you can read that book because it is highly mathematical but some people may really like it because the way that he has worked out the different strategies for combining different types of the components together. **“Professor – student conversation starts”** okay, the philosophy behind this is that you are shifting your gradation curve to incorporate more and more finer ingredients that is all. **"Professor – student conversation ends"**

Instead of using a 0.45 power rule, which was essentially devised based on coarse and fine aggregate, now you start considering your other granular components like cement and fly ash and silica fume etc. also to be part of your granular mix and what that does is; it pulls the aggregate sizes or pulls the particle sizes; range of particle sizes to a very wide range, of course, I mean you are considering the effect of those granular particles also in the packing.

Of course, please remember we are not really modifying or modelling the cement reacting with water and those products also filling up the space available, we are not considering that at all, what we are simply considering is that concrete is made up of water and granular ingredients and how well we can pack the granular ingredients is done with the help of modified andreassen model.

So, the software first requires your input obviously of the material particle size distribution, so for your own set of materials, first you will need to do a sieve analysis obviously, when you do a sieve analysis, you have very specific set of sieves across which you measure the particle sizes. So, what you can do is; for any material you can create a new material library, in the material library, you can actually create the library for a new material.

And for that material of course, you can give a name, you can give the description where it is from and so on, the origin, the price, the particle density and that is important because what happens is; when you input your particle size distribution, it is based on mass but what this software does is it converts that to a volumetric PSD, because ultimately, the curve is giving you is actually in terms of the volume.

So, you need the particle density, interestingly you can also input the carbon dioxide emissions per kilogram of this material, so that is quite interesting, of course I do not know how accurate that is given in modern day systems and so on but it can also calculate for example, the CO_2 imprint of your concrete mixture, then in terms of the energy, kilojoules per kilogram, so if you are processing this material out of another industry, how much energy are you spending in actual processing this material.

You can also input that of course, the CO_2 and energy are more from a sustainability impact analysis point of view but that is not what we are talking about here; we are primarily looking at the actual particle packing approach. So, what you do is; after you do your sieve analysis you input the values here in terms of the sieve size and the percentage passing, and then what you do is; you click this button and this convert this into a volumetric packing distribution for each particles size.

So, for example what is given here is the material coarse aggregate between 11 and 16 millimetres, so you can see here from this that your percentage passing at 12 millimetres about 28% and percentage passing your 16 millimetres about 91% and that is the 16 to 11 particle size aggregate. So, based on the aggregate types that you have in your laboratory, you can input the values for the particle size distribution and the density for those aggregates.

So, this is how, you create a material library, once you create it, it goes to the actual library which is displayed alongside the; the kind of inputs that you need, so here for example there is a built in library which has micro silica or silica fume already built in there, now we talked about this problem right, when you have condensed silica fume and you try to determine the particle size by laser, there is a difficulty in dispersing the condensed particles.

Because of which you are actually get a particle gradation which is reflecting the condensed material and not the individual particles, so if you do not have the individual particle distribution, you can actually go and refer to this library because the Micro silica distribution here is the actual particle size distribution of the Micro silica sold by a elkem material, of course that will apply only to the elkem micro silica.

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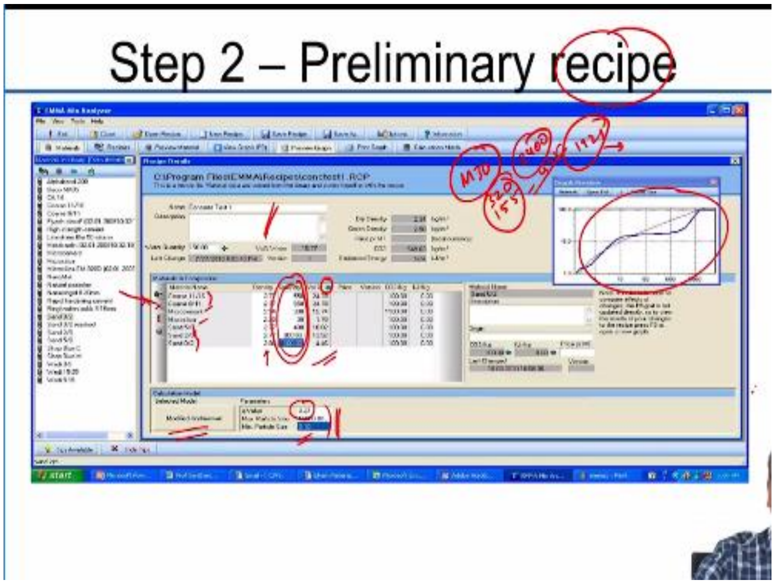

If you are buying it from another brand, it may not actually fit in here, so there are obviously all kinds of material you can enter into this library, what do we do next; we make a preliminary recipe, I always keep talking about the fact that the concrete is like cooking, so we mix several ingredients together and see how it works, so here also it is called a recipe, you make a recipe file.

What you do is; you enter from the library, you add materials into the recipe, of course you can give the description of your recipe that you are making, so you add materials into your recipe of course, here there is cement, the silica or micro silica, there is sand of 3 different particle sizes that is coarse aggregate of 2 different particle sizes, for each the density is given here, your preliminary recipe talks about the kilogram per cubic meter of the ingredients that you want to put in.

For example, if I have to start of with an M 30 concrete design, let us say I want to design M 30 mix, what should be the water cement ratio in M 30 mix or what can be an approximate design in terms of cement and water content from M30 mix, 0.4 is too less, I will go probably more 0.48 or something like that, so anyway let us put that in to numbers, if I make an M 30 concrete, maybe I can work with about 320 cement content to start with.

So, with 0.48 water to cement ratio, how much do you get as a water content, about 155, water content of 155, how much aggregate should be there, what should be the unit weight to this concrete, 2400 approximately, when you subtract the cement and water content from 2400, what you get; that will be the total aggregate content, so you get 1925 as a total aggregate content.

Just for starters, let us say we have 60% coarse aggregate and 40% fine aggregate, so this 1925 can be divided into 60% of 1925 and 40% of 1925, in fact truly speaking that is how we will do any mix design process, as long as you are able to put your hand on this part that is cement and water content, the aggregate content determination is not that big a deal, once you have that recipe worked out, you enter it here, in terms of the quantities in kilogram per cubic metre, of course the water is not really input here, you do not need the water input here.

You only need the granular constituents, once you do that and you click this green button, it converts that into a volume percentage and once you get that it gives you a sample curve, what is a sample curve looking like, of course, before that I should also talk about the choice of the model, if you come down on the screen, there is actually the choice of the model where you can select between the original andreassen model or the modified andreassen model.

So, for example here, the modified andreassen is chosen, what you need to do is; enter the value of q and that is where it is a little bit fuzzy, what kind of value do you enter, unless you have an experience working with the software, we do not know what kind of value to enter, as I said for most conventional concrete 0.28 to 0.3 is alright, so in this case of course we wanted to make something with silica fume.

So, we are looking at a high performance concrete, so 0.27, maximum particle size is the overall maximum particle size that is there in the mix, so that is your 16mm coarse aggregates, so 16,000 microns is a maximum particle size, minimum is from silica fume, 0.1 micron, if you look at the particle size gradation given in this library 0.1 is the minimum size given for silica fume.

Why are these two require; why are these 3 characteristic required because all that fits into the equation, it all goes in the modified andreassen equation, so once that is done it gives you this curve as an output.

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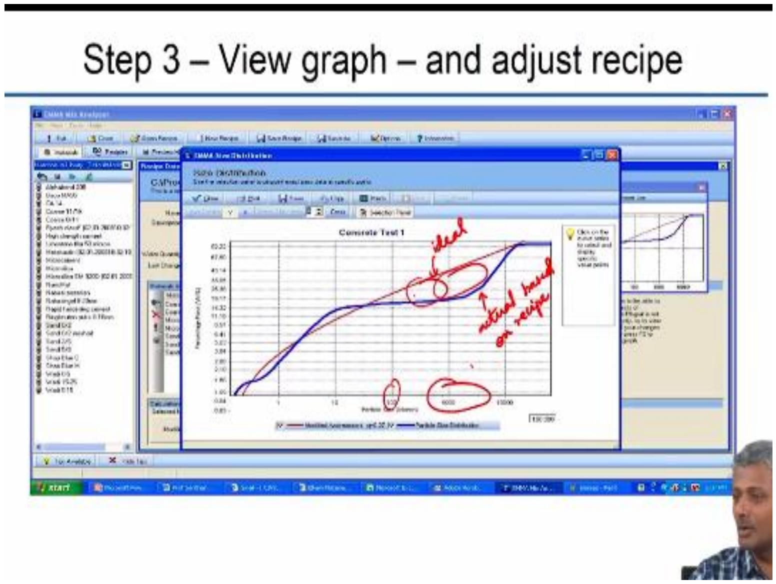

Let us look at this curve more closely, so first you need to view this graph, to look at what your particle sizes are as compared to the ideal gradation that is suggested by the software, so this red line is your ideal gradation, this blue is your actual based on your recipe, so what is this tell you; by comparing the ideal and actual, you have aggregates that are lacking some sizes here, for example in the fine aggregate particle size range, 1000 to 5000 microns, 1 to 5 millimetres.

You do not have too many particles left, so even the 100 micron; 100 to 1000 also you have a lot of gaps in that case, so what you do; you adjust the recipe until you get this blue curve as close as possible to the red curve, all this while you have not stepped into the lab, all you are doing is; working on the computer trying to get this blue curve close to the red curve. What happens when you get the blue curve close to the red curve?

You go to the lab and make a trial, if the trial works all well and good, otherwise we will have to start making adjustments to a mix design, so let us see how this is done with an example of particle packing for producing high performance concrete with low cement content.

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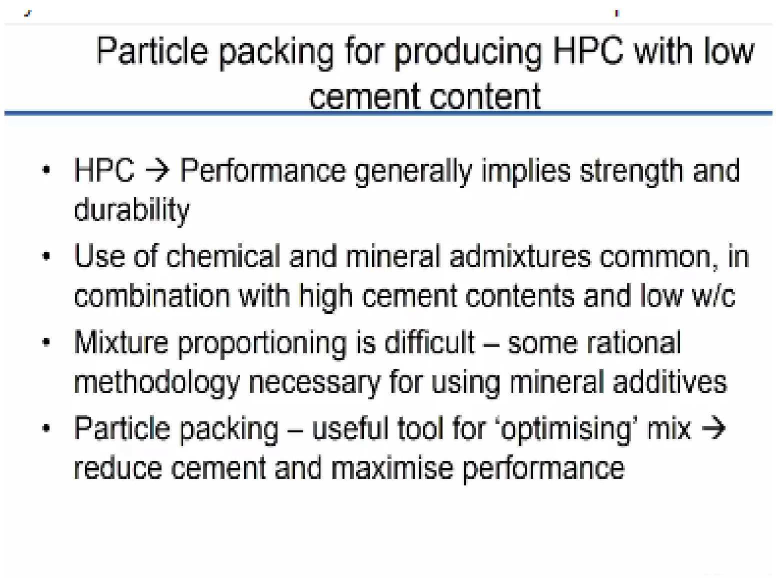

Now, usually those 2 terms do not go together, when we talk about high performance concrete, we expect a very high strength and durability and generally, we expect that combination of chemical and mineral admixtures will be there in the system with a low water to cement ratio coupled with high cementitious materials content but there are obvious issues when high cement contents are used in the system.

You have more potential for shrinkage, there will be greater thermal effects, and of course your cost of the system also goes up more and more, so mixture proportioning of such systems becomes quite difficult, this is where tools like particle packing could be useful to optimise the granular constituents and minimising the amount of cement that you require for such mixtures.

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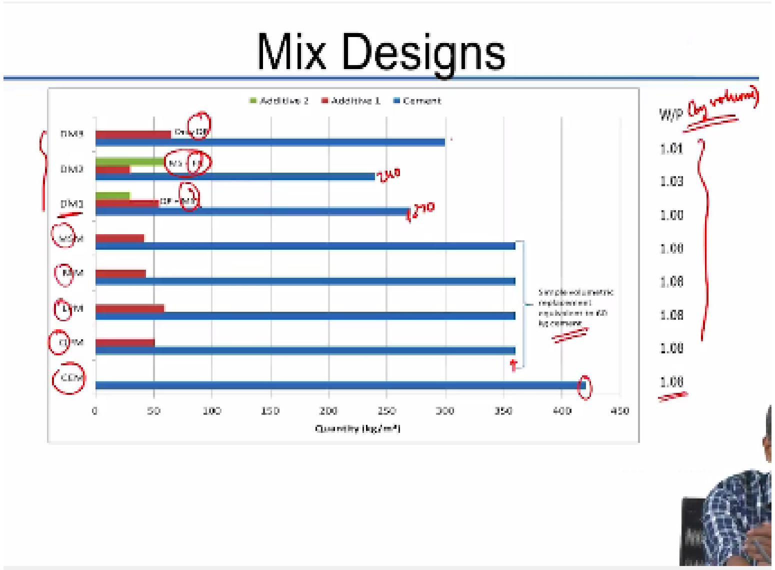

Let us see how this is done, this was actually part of M Tech project done by one of the students and this resulted in couple of papers also which I will give you a link to at the end of this chapter, so let us look at the mix design I have said actually, used in this case, at the bottom we have this mix which is called CEM, and that has got 420 kilograms of cement and the water to powder ratio, this is by volume, 1.08 by volume, that translates to approximately about 0.32 or 0.33 by mass, 1.08 by volume translates to 0.33 by mass.

All you need to do is divided by 3.15, the density of cement, so 1.08 / 3.15 that gives you about 0.32 or something, your overall specific gravity will change, so based on that your water cement ratio by mass will also be different, so here we kept almost a constant water to powder ratio by volume and we used a super plasticiser to ensure that the slump was always in the same range.

So, please remember all these techniques that we are talking about will fall flat, if you are not using super plasticiser in your concrete system. So, all these are assuming that you have super plasticisers because that is what you will be using as we will discuss in the next chapter to optimise the paste flow properties. So, here the CEM mix has 420 cement content and about 0.32 water to cement ratio.

Now, typically what do we do; when we designed the mineral admixtures, we replace part of the cement with the mineral additive, so here what was done was a simple volumetric replacement was done, 60 kilograms of cement will be removed and whatever volume was left behind with this 60 kilograms was filled up by the mineral additive, in the first example, it was filled up with quartz powder, QP.

The second one it was limestone powder, then fly ash and then finally micro silica, so amount of material added in this case was equivalent to 60 kilograms of cement, volume of 60 kilograms of cement, so here again in all these mixes, the cement content is 360 kilograms and of course, you have variable quantities of your mineral additives based on how much you need to add to make up that volume, alright.

Now, when you go to the mixes that are based on particle packing, they were quite differently done, so of example this DM1 mix has only about 270 kilograms of cement, and the choice of micro silica and quartz powder as a combination replacement of cement was done based on the curve; the andreassen curve that we talked about earlier, I will show you that in a minute.

This next one has an even lower cement content, 240 and the combination replacing the cement is micro silica and fly ash together and the last mix here, DM 3 is based on a simple fact that if you simply replace cement with a filler like quartz powder in this case, and try to optimise the particle packing, does that still result in concrete that is of good quality, so that is what we wanted to see.

Of course, we all know very well about fly ash and micro silica and their beneficial effects as cement replacements but what if we simply choose a filler and reduce the amount of cement in the mix, can that still get us the required result in terms of the grade of a concrete as well as the durability of the concrete.

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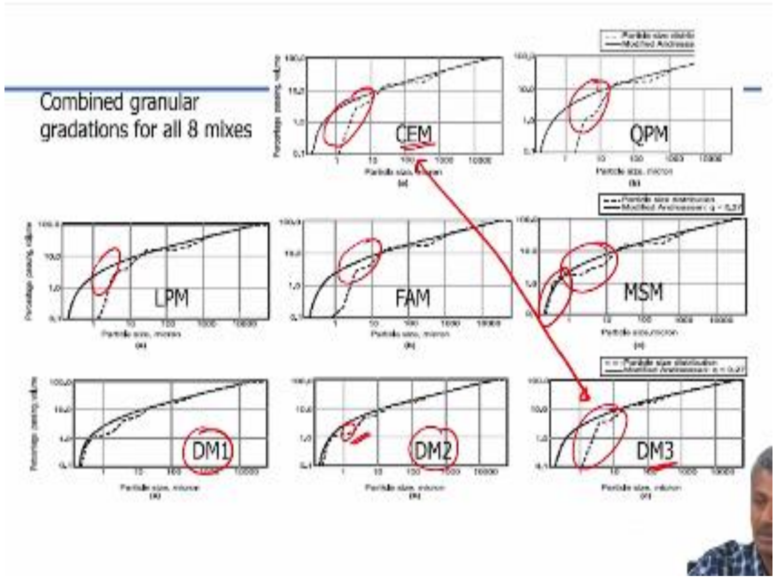

So, let us look at what results were produced before that let us look at the comparison of the combined particle size gradations with the ideal gradation curve, in all these cases a q value of 0.27 was chosen, modified andreassen model was chosen in this case, so that is your CEM mix, your particle sizes in this range between 1 and 10 microns are really deficient, otherwise aggregates seem to be quite well packed.

In all the systems, you have no problem with the packing of the aggregate, it is matching quite well with the ideal curve but all these simple replaced system seem to be missing in the 1 to 10 micron range, the fly ash mix, the little bit better, the micro silica mix a lot of the deficiency has been now removed and in fact, even sub 1 micro meter range, you can actually start filling up with a lot of micro silica particles.

Look at this one now, DM1 where, we had combined quartz powder and micro silica with only 270 kilograms of cement and this is giving you a curve which is quite similar to the ideal gradation and this DM2 again very similar to the ideal gradation, it is only a small deficiency in this range, DM3 has compared to CEM which is 420 kilograms of cement, now the cement is simply been replaced by quartz powder, the resultant cement is only 300.

That means about 120 kilograms of cement has been removed and replaced by quartz powder just to get this curve as best close to the ideal gradation as possible, quartz powder is of particle size is not much different from cement, but it is a little bit finer not like silica fume.

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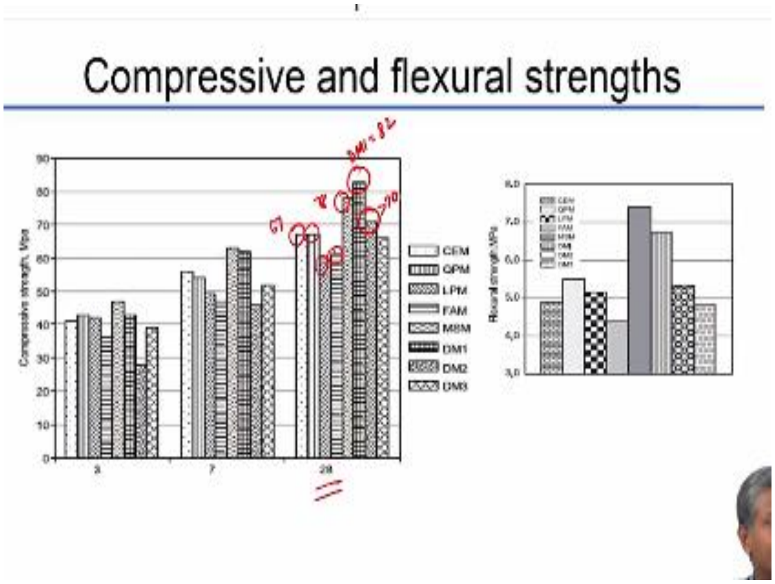

So, let us see what happens with this in terms of the results, so on the left are compressive strengths and the right are flexural strengths, so if we compare the compressive strength like let us look at the 28 day values because of 3 and 7 days' values will not be very good for fly ash paste mixtures, so what happens is; the plain cement makes is getting a strength of around 67 mega Pascal's.

The cement when it is replaced by quartz powder 60 kilogram equivalent, there is absolutely no change in the strength, when it is replaced by limestone powder or fly ash, your strengths are about 60, which is only about 10% lower than the plain cement mix, still reasonably good. When you are replacing with micro silica, your strengths are shooting up to about 78, so strengths are going up quite significantly and we expect that with micro silica.

because your curve is not closer to the ideal gradation, interestingly when you work with this DM1, you get nearly 82 mega Pascal's with the same system, mind you there is only 270 kilograms cement present in this case, so you have saved 150 kilograms of cement, of course you are using micro silica, your cost is not going to be very low but still you are saving a cement usage and you are still getting a strength which is far superior to the plain cement mix at 150 kilograms less of cement.

Similarly, micro silica and fly ash mix together, is still giving you excess of 70 mega Pascal's, and that again tells you that you are replacing cement in a very large quantity because here it is only 240 kilograms cement, you have saved 180 kilograms cement and the last one is the optimise mix with respect to strength with respect to the particle size, where there is only 300 kilograms of cement.

And please see that the strength level is not all that much different as compared to the plain cement mix, so this seems to be fitting in our assumption quite well, the assumption was as long as you pack your particles well enough, you should be able to get a positive effect on the strength, we are seeing that, with flexural strength also, there is not much difference, the same trends are seen with flexural strength also.

DM1 is the one which has mixture of micro silica and quartz powder, DM3 is the one with quartz powder, so DM3; the philosophy was how much maximum can we remove cement with a filler keeping almost the same particle gradation, so there is not much difference between the two.

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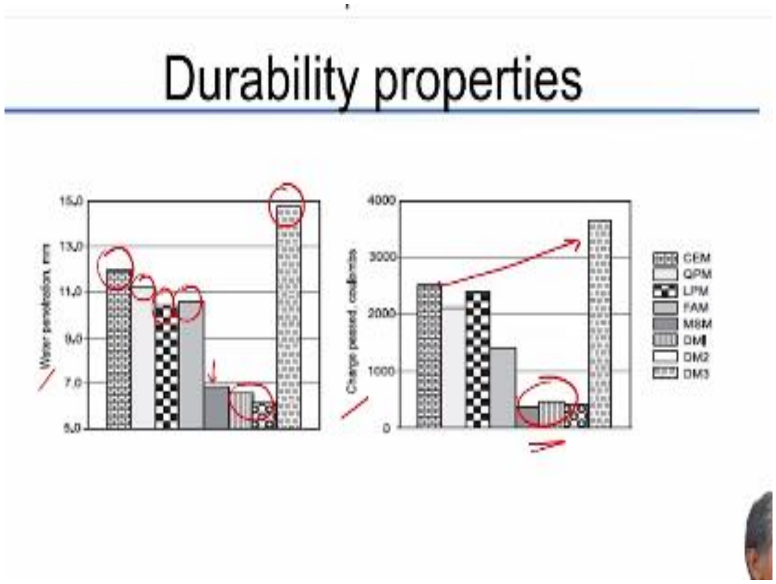

Now, in terms of durability, some interesting trends here, so this is; we did two tests in durability; one is a water penetration test under pressure, the other is a rapid chloride permeability test of course, the lowest numbers are those with silica fume that you can understand quite well, nevertheless even in the water penetration test, you can see that the plain cement mix was around 12 millimetres water penetration.

Of course that is also a very good performance, high performance concrete, your general specifications around the world say that if your water penetration is less than 30 millimetres, your concrete is a very good quality, so here it is only 12 millimetres water penetration, when you replace it with quartz powder and lime stone powder, you are making the water penetration characteristics get better.

With fly ash again quite similar in terms of performance, when you start using micro silica in the mix, there is a distinct benefit to reduction of the water penetration interestingly; the best performance again is achieved from DM1 and DM2 which have much lower cement contents. Now, look at what is happening with DM3, the water penetration is actually more than the plain cement mix although, we were able to utilise the substitution of cement with a plain filler to produce the same strength but we are not able to produce the same durability level.

Same thing happens in the case of rapid chloride charge passed also, you have a greater charge passed, when you have quartz powder in a larger amount replaced in the system, but again with all the other systems especially the ones which incorporate micro silica you are able to cut down on the charge passed significantly.

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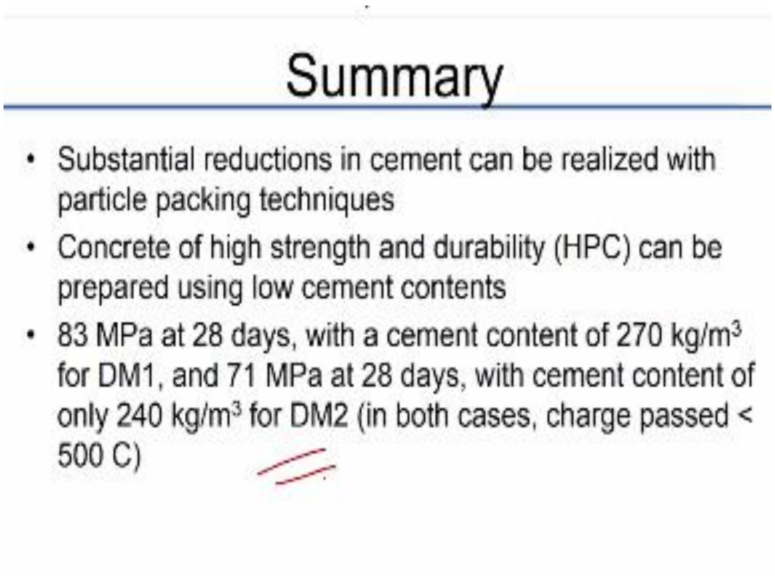

So, what this is telling us is; you can bring about substantial reductions in cement with particle packing techniques and again, these are just giving you the numbers that we talked about previously, one aspect that you need to understand is whatever is done in this procedure is not going to be a substitute for trial mixing, what it simply doing is; helping you cut down the number of trials, especially for high grade concretes.

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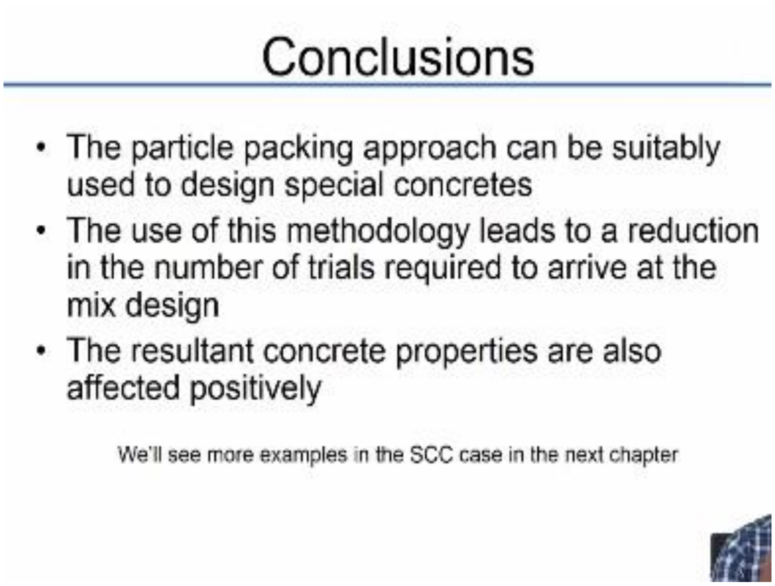

And for concretes incorporating multiple mineral additives, you do not need as many trials as you would need, if you just do a trial and error based method. So, in conclusion generally, particle packing can be suitably used to design special concretes, especially high performance concrete again, you can reduce the number of trials and resultant concrete properties in terms of strength and durability are optimised or maximised with the combination of ingredients that you can have.

So, we will see more examples, when we actually look at self-compacting concrete design after we discuss the fresh concrete properties, you will see how we can actually combine the granular packing along with rheology to optimise the design of self-compacting concrete mixtures.

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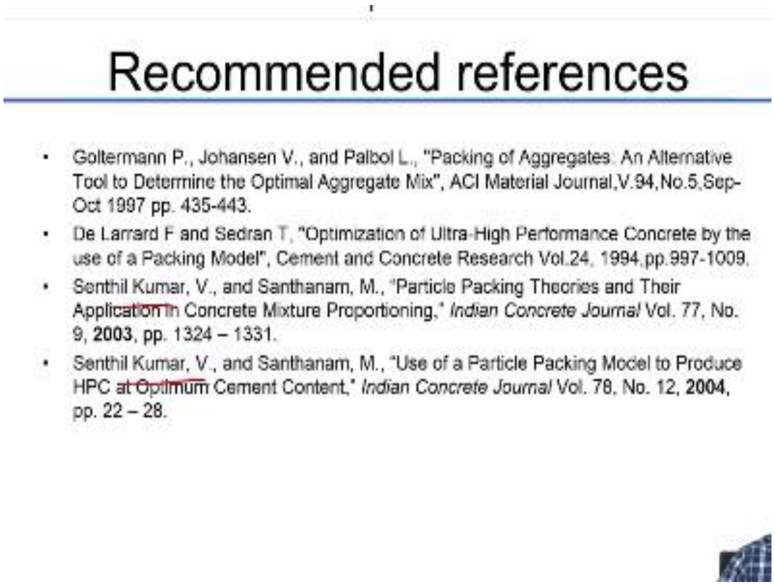

So thanks, there is a lot of recommended references and these were the 2 papers that were produced as a result of the student's work, both are in Indian concrete journal and you can definitely look at these to get a little bit more of an idea about different types of particle packing methodologies and this same result that I described to you just now, the details of the technique and all the results are there in the paper. Thank you.