**Admixtures And Special Concretes**

**Prof. Manu Santhanam**

**Indian Institute of Technology Madras**

**Department of Civil Engineering**

**Lecture -53**

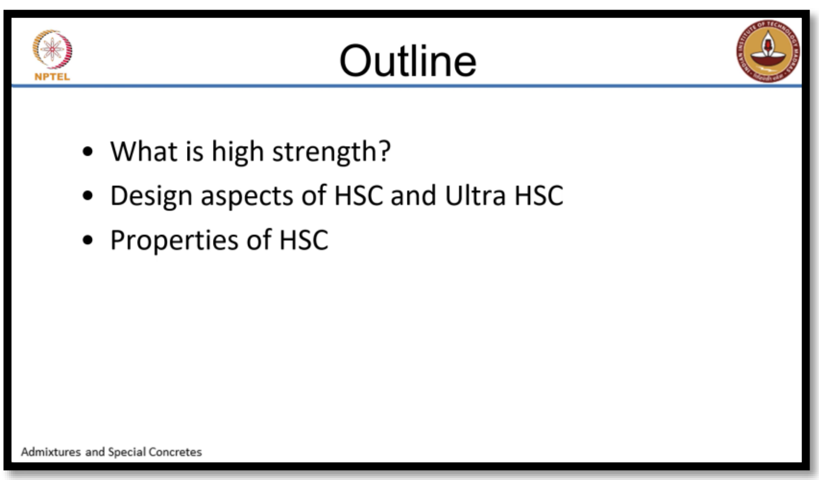
**Special concretes - High strength concrete - Definition, design and concept of particle packing**

## High Strength concrete:

So today we'll begin our discussion on special concretes. We'll start first with high strength concrete.

### Outline

(Refer to slide time: 00:29)

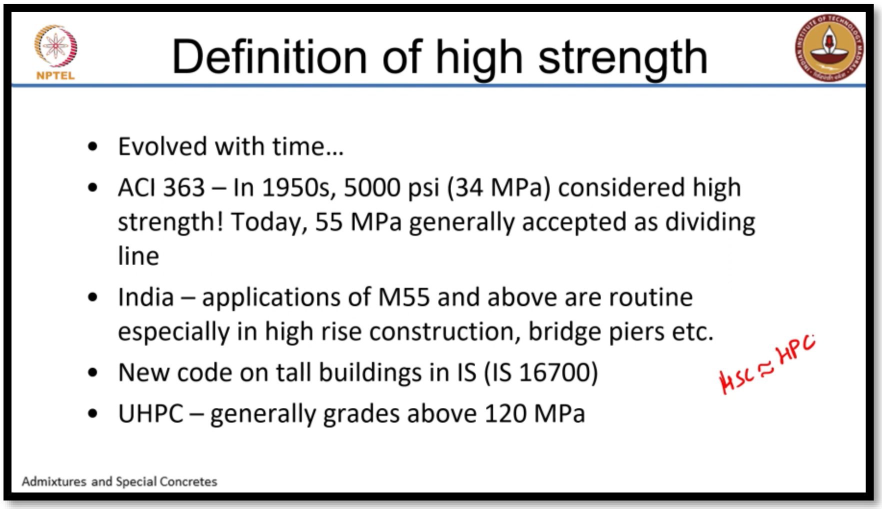



Now, first, we'll go about defining what exactly is high strength. What do we mean by high-strength concrete? What are some design aspects? How do we lead to successful design of concretes that are high in strength? And also ultra-high strength concrete, which reaches strength levels of more than 120 megapascals.

Then we'll look at some properties of high-strength concrete. How do we need to be careful about designing for these kinds of characteristics?

**Definition of high strength concrete:**

(Refer to slide time: 00:54)




Of course, the definition of high strength has evolved with time. In the 1950s, as per ACI 363, there is a committee on high-strength concrete, a 5000 PSI or a 34 megapascal concrete was considered high strength in 1950s. So, 34 megapascal, which today is actually a day-to-day kind of concrete, was actually high strength in 1950s.

Today, of course, we are using routinely 55 megapascal and above as high-strength concrete. But even 55 has become really a low number as far as the kind of strengths that we are achieving today in concrete are. Today concretes are being used at least for high rise buildings with strengths of at least 80 to 90 megapascals. For bridges, you can have 45 to 60 is more typical for bridges. Now, high-rise construction often has special demands for concrete, which we'll discuss about later.

But in general, we at least in India, the accepted definition is more than 55 MPa is high strength. There's in fact a new code or tall buildings IS 16700, which was recently formulated, I think about four years ago. And this is specifically brought out because the requirements for concrete in tall buildings are quite different as compared to requirements for concrete in regular structures, regular buildings. When you consider tall buildings, there are issues obviously of wind and earthquake effects being quite dominant. And because of that, you need extremely high stiffness for the concrete, at least in the lower stories.

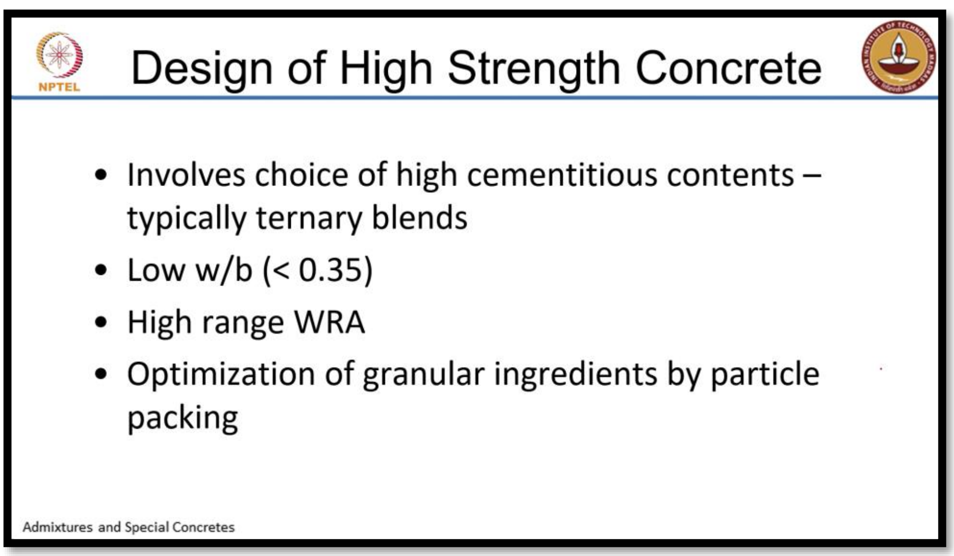
So you have to design adequately for that. And it's not enough to go with the codal recommendations for determining creep and shrinkage based on the strength of the concrete, you need to actually determine these characteristics every time that you come up with a design for a new concrete. Ultra-high performance or ultra-high strength concrete is generally grades above 120 megapascals. And in research, even grades up to 800 megapascals have been actually formulated. But in reality, people have not used more than 250 to 300 megapascals.

But let's look at how we can actually achieve that level of strength also. And sometimes HSC- high-strength concrete is used interchangeably with high-performance concrete. But what don't necessarily mean the same. High performance need not be high strength. Okay, performance could be another characteristic also like flowability.

So when we have self-compacting concrete, it is actually a high-performance concrete but not necessarily a high-strength concrete. So high strength and high performance are not necessarily the same thing. But in literature, you'll see one being referred to as the other because in general, high strength involves low water-to-cement ratios. And generally with low water-cement ratios, you'll also get better durability. So high performance also is obtained from high strength.

**Design of high-strength concrete:**

(Refer to slide time: 03:49)




Now, for obvious reasons, we will have to use cementitious blends that are high in overall cementitious content. We want to use, we want to maximize the usage of cementitious material to get the advantage not just from the hydration reaction, but also from the packing that comes about because of the use of such fine materials. When we discuss, when we do ordinary concrete mix design with only cement, we are not really utilizing the lower end of the particle sizes well enough. That's why when we start using fillers as replacement of aggregate, we are trying to fill up the smaller particle regions. And when we replace cement with finer mineral additives, that also helps to some extent in actually filling up the gaps in the smaller particle sizes.

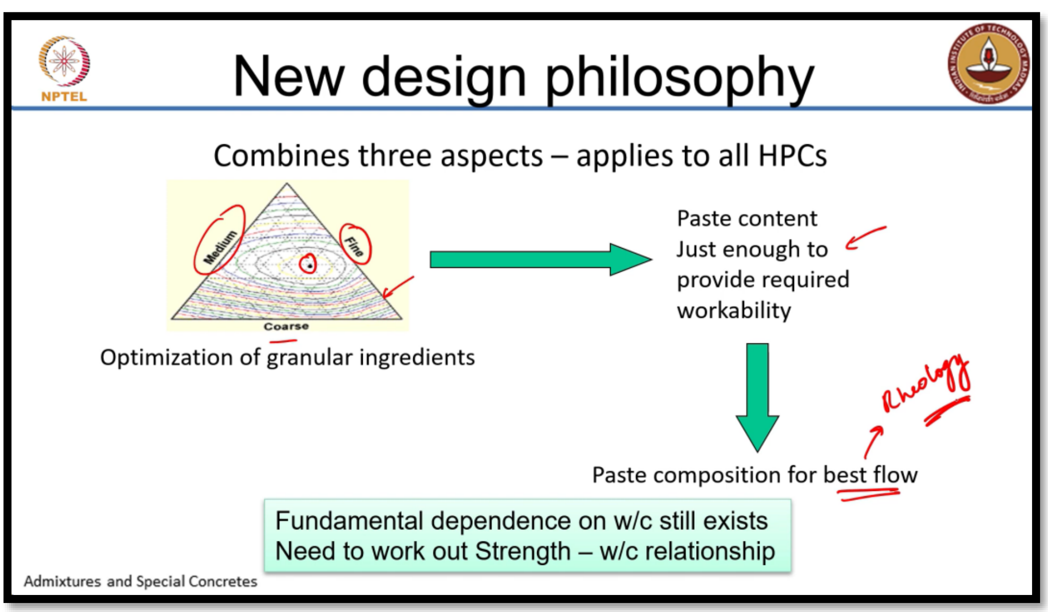
So in general, with high-performance concrete or high-strength concrete, we are looking at blended cementitious materials of very high content. Low water-to-binder ratio, typically less than 0.35 is chosen for high-strength concrete. We have to use a high-range water-reducing agent because you can't get workability at that water-cement ratio if you don't use a high-range water reducer. And you can also opt for optimization of your granular particle skeleton by a process called particle packing.

The idea is simply to arrive at a strategy to maximize the packing of solid ingredients so that you minimize the voids. Because if you want to increase the strength, you need to minimize the voids. So you have to evolve the strategy with which you can minimize the voids. One of the examples we saw previously was in one of the approaches when we discussed biomass ashes, they were looking at applying compaction during setting. When you apply compaction during setting, you are obviously overcoming this issue of void creation by suppressing the voids from forming.

And that is one way of increasing the strength of your material. We look at that also when we discuss ultra-high strength concrete that compaction during setting process is often a strategy that is used to get the best out of the concrete, even at strengths which are not really achievable.

**New design philosophy:**

(Refer to slide time: 06:06)



So the new design philosophy that we need to apply for high-strength concrete combines three aspects. Now it's not just for high strength, it may be applicable to all high-performance concrete, not just high strength. So, what we do is we optimize the granular ingredients.

For instance, when we have coarse and fine aggregate, we can also have some medium aggregates, let's say 20 mm, 12 mm and sand, there are three different sizes of aggregate. We choose the blend or ratio in such a way that we minimize the voids. Now this is not very difficult to find out, right? You can randomly choose proportions of your sand 12 mm and 20 mm aggregate, mix them all together, put them in a cylinder which has a known volume and then you try to measure the mass of the materials that has gone in and convert that mass to volume because you know the densities of these materials. You subtract the total volume of the ingredients from the volume of the container, you will get the volume of voids. And you do experiments until you achieve the minimum volume of voids.

But all this has to be done with a caveat because you can't obviously choose material combinations that have too much in excess of one type of aggregate over the other. For instance, in concrete, you will not choose a mixture which has only 10% fine aggregate. That's not a decision that you will make. You will not choose a mixture that has only 20% fine aggregate. You will choose a mixture that has significant amount of fine aggregate to avoid any problems of segregations that may happen in the concrete, right? So your choices with respect to the material combinations are not going to be infinite when you do this experimental evaluation of the mix that gives you the lowest voids content.

So you can, based on your understanding of concrete mixture design, arrive at a lesser number of combinations of the ingredients to get you the desired voids content. Nevertheless, it has to be an optimization exercise. This is of course a much more sophisticated exercise where contours of equal packing density are plotted. I will discuss what is meant by packing density later. And then there is a single point at which you get the maximum packing or minimum void content of your mixture.

Now what is the advantage of having a minimum void content in the granular combination? Now granular combination not only includes aggregates. It may also be given to include your fines that are coming in from cement, from your mineral additives and so on and so forth. So you are optimizing the sizes and fractions in such a way that you minimize voids. But now what is the advantage of minimized voids? Minimized voids you get better strength no doubt. But then you need to get workability also. How do you get workability? You have an initial estimate of the voids content that means you need at least that much amount of paste or water to provide you some workability.

But then that may not be enough. You may want to put water or paste in excess of that void content to really get you the desired level of workability. You will see this application later when we talk about self-compacting concrete that because of the determination of voids content now we can figure out exactly how much paste we need to put into the system. So, paste content should be just enough to provide the required workability. Now again this is stemming from the fact that we want to maximize the aggregate in concrete.

Why do we want to do that? Because aggregates are not providing strength in concrete. Please remember that. Strength is obtained from the binding ability of the cement paste. It is not from the aggregate. What are aggregates providing to the concrete? What is the primary contribution of aggregate to concrete? Bulkiness means volume.

No that's not I mean that anyway you can fill up volume with anything but why aggregate is important to concrete? Can I make concrete with just cement paste? No. Why? I don't get dimensional stability. Aggregates are absolutely essential for dimensional stability. You need more aggregate to have more dimensionally stable concrete and the aggregate phase as compared to the paste phase is going to be inert in most circumstances so you will get better durability if you have good aggregate combinations.

But one more important aspect. Why do we want to maximize aggregate? Which is a very practical aspect. Cost. We want to minimize the cost of concrete. So more aggregate means less cost. So you want to have maximal aggregate from many perspectives.

Now when we go for higher and higher grades of concrete you don't have that luxury of putting in lot of aggregate in the system because you need the paste to get you the packing. You can't get that by just using aggregates alone. But nevertheless paste content should be just enough to provide adequate workability. You don't want to have excess paste in your system unless you want flowing properties which we will discuss later in self-compacting concrete. Now the paste itself can be designed for the best flow and that's why an understanding of the rheology of the paste.

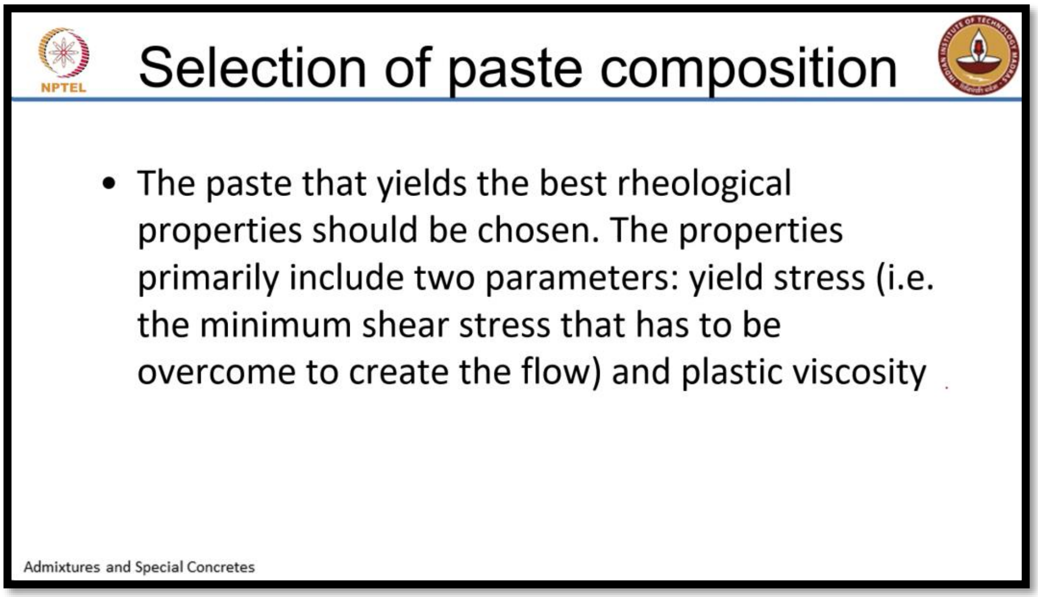
And that's what you have looked at earlier as to how we can use rheological parameters to control the characteristics of paste to obtain certain performance parameters. We talked about yield stress, we talked about viscosity, we talked about shear thinning, shear thickening. Those kinds of characteristics are brought in by a suitable design of the cement paste. The paste is essentially carrying the aggregates along and the paste rheological composition or rheological properties of the paste will determine how the concrete workability is governed. So, these are the three characteristics that you need to solve to do any high-performance concrete mixture design.

One thing of course is the fundamental dependence of strength on water-cement ratio still exists. The higher the water-cement ratio, the lower the strength. So that has to be established for any concrete based upon the kind of ingredients that you have in any geographical location. As we had discussed earlier, the requirement of water-cement ratio may be different for a concrete in Chennai as compared to a concrete in Delhi.

The aggregates are quite different. The extent of packing you can get from these aggregates is also quite different. So all of that will lead to differences in the way that you design concrete in different geographical locations. It may be the same grade of concrete, but the design may be quite different.

**Selection of paste composition:**

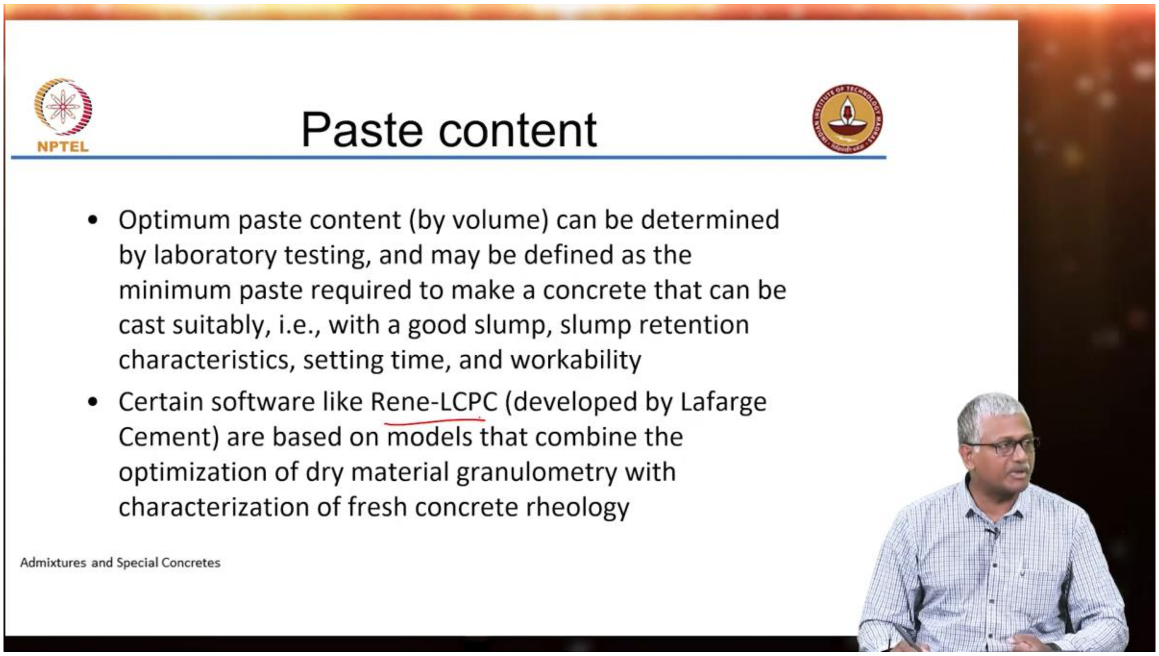
(Refer to slide time: 12:55)




So, the paste rheological parameters need to be measured- yield stress and plastic viscosity. We talked about yield stress as being the minimum shear stress that is we overcome to create the flow and plastic viscosity is when the concrete is flowing, the resistance to that flow is the viscosity.

**Paste content:**

(Refer to slide time: 13:18)



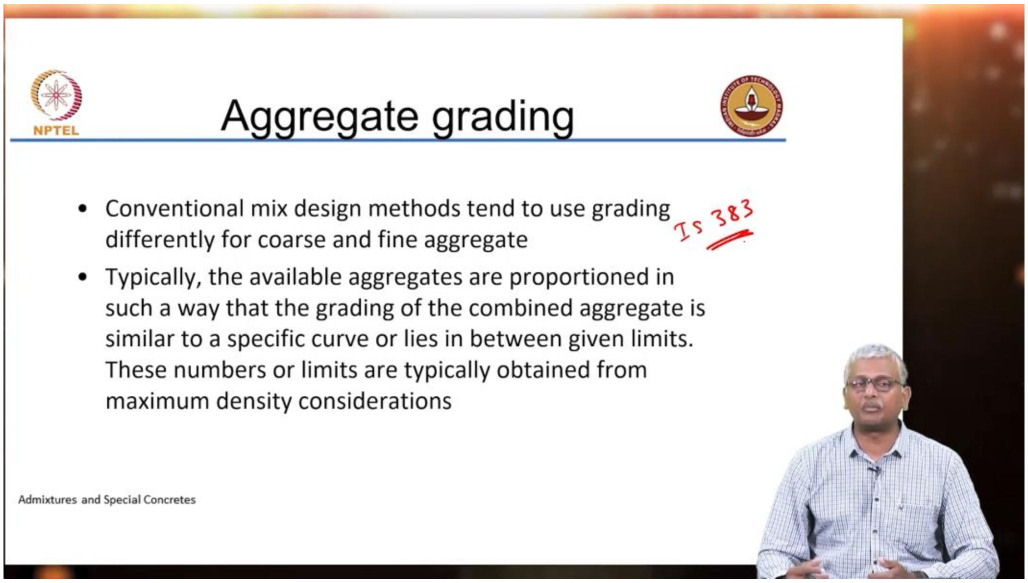

Now, as I said, we can do testing of aggregate combinations to determine the void volume and decide the paste content based on that. Or you can just do a random laboratory testing and arrive at a mixed design which gives you the right level of workability, strength and so on. But that's a little too cumbersome. You need to have a good starting point. It's very good to have a starting point which deals with determination of voids content and then determining a paste volume based on that voids content.

This can be done by a look at particle packing approaches and these particle packing approaches can be done with or without the consideration of rheology of the paste. Now there are some models like this Rene LCPC model developed by Lafarge Cement that is based on models that combine optimization of the material packing with the rheology of the concrete. It's a little complicated to understand this model. Most models would tend to either look separately at the dry material packing and the concrete rheology.

But this model combines both these aspects. But I will talk about some simplistic models which can be used for understanding the dry material granulometry and optimizing it to obtain the minimum voids content.

**Aggregate grading:**

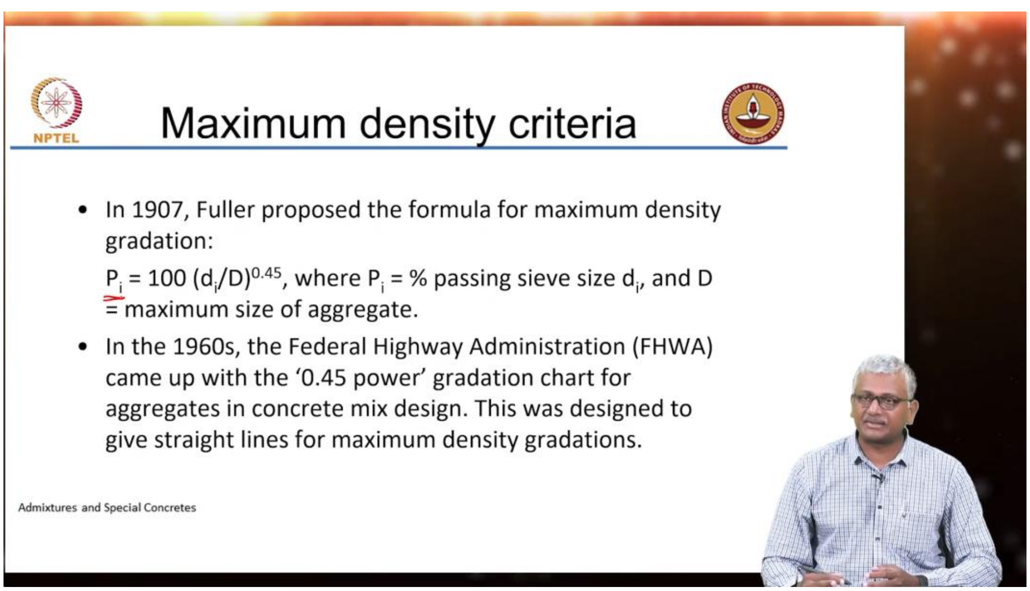
(Refer to slide time: 14:28)




Now in regular concrete mix design, aggregate grading is not really given too much importance. There are prescribed gradation limits in your IS 383. If you look at IS 383, it talks specifically about the gradation limits for coarse aggregate and fine aggregate and also a combined aggregate gradation that needs to be followed for the concrete. But this is based on rules that were formulated many many years ago.

**Maximum density criteria:**

(Refer to slide time: 14:58)

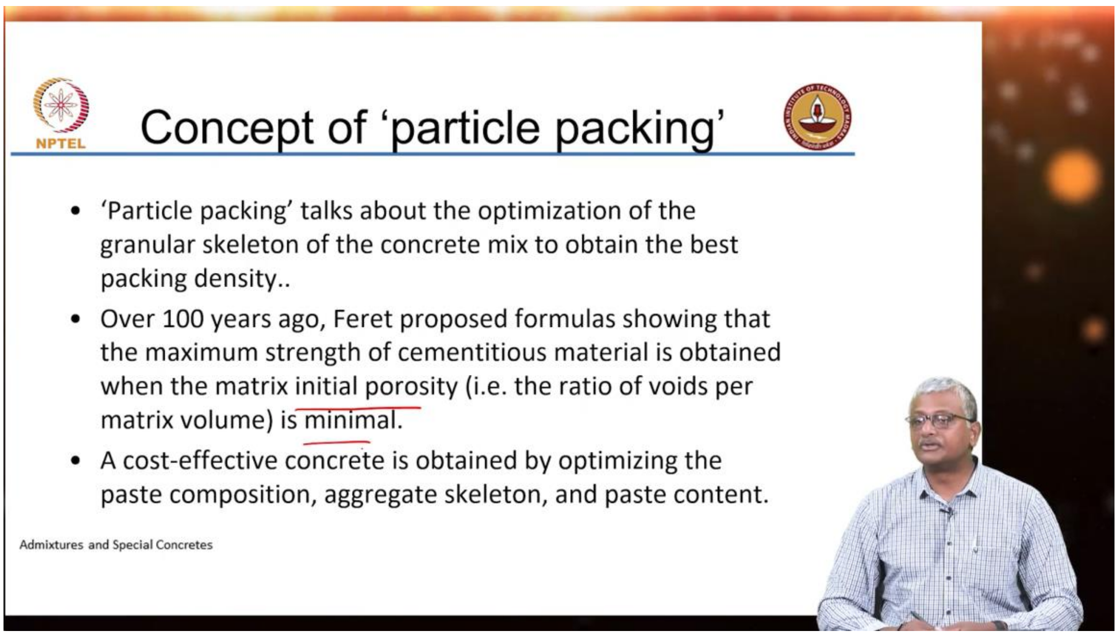


Now if you look at the rule, it is basically loosely following the 0.45 power law which is dating back to nearly a century ago. This is the fuller gradation curve where particle or percentage finer than Pi is given as 100 into the specific particle size divided by maximum particle size to the power of 0.45.

And this 0.45 power rule simply got adopted for all concrete mix designs. It was earlier used for pavements but later it followed for all concrete mix designs and has been used ever since. We have not really revisited this aspect of packing that can be brought in when using aggregates of different types especially when we start using filler materials inside the concrete. The mineral admixtures bring in a completely different dimension. So people have started looking at what can we do to modify this to really get an estimate, a better estimate of particle packing.

**Concept of 'particle packing':**

(Refer to slide time: 15:56)



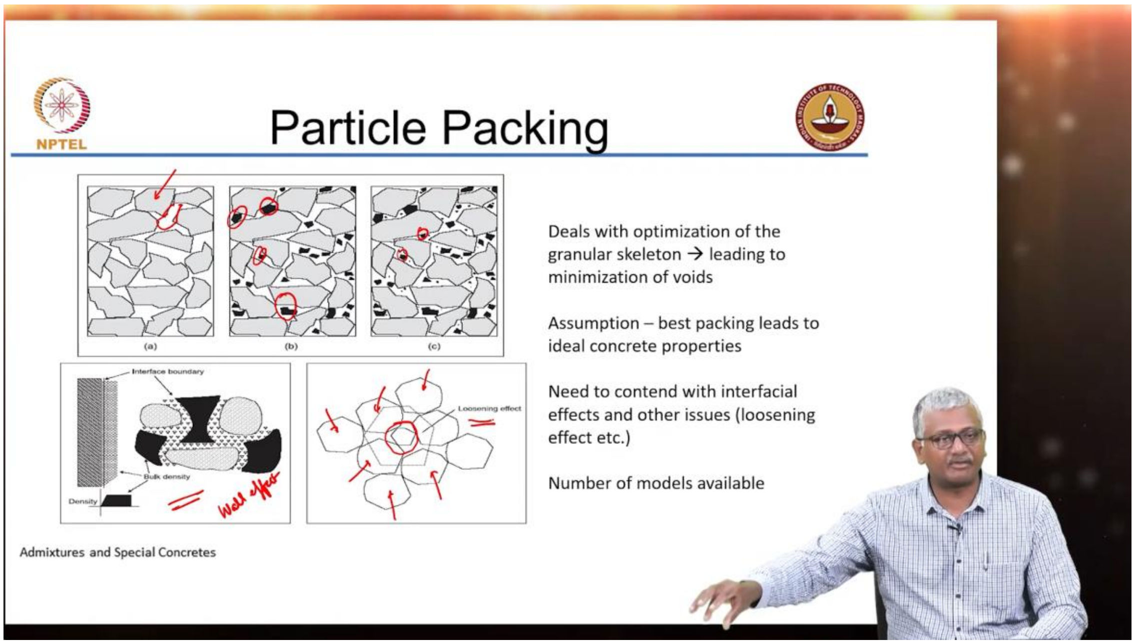

So, particle packing is basically the optimization of granular skeleton to obtain the best packing density. Now again please do not confuse this density with the actual physical meaning of the word density. It does not mean that we are producing concretes of more than 2.5 g per $cm^3$ density.

Within that 2.5 we are packing as much of the aggregate well as possible so you get the minimum voids content. So, density will still be around the 2.4 to 2.5 but obviously a packed material will have a slightly higher density as compared to a less packed material.

But we are not fundamentally altering that density. So, again it is discussed by many different scientists including Feret who said that when the matrix initial porosity is minimum that is when we get the maximum strength. So it is not just for optimization of strength but for also minimization of cost that you want to increase the extent of granular materials in your system.

**Particle packing:**

(Refer to slide time: 16:55)




And for this people have looked at various ways in which you can start filling up a volumetric container with sizes of materials that are progressively reducing. Let us say you fill up with coarse aggregates first, you have gaps between these coarse aggregates, you choose your next particle size in such a way that you can start filling up these gaps. And then you still have gaps after you choose that material.

You fill up those gaps with even smaller particle sizes and so on and so forth ad infinitum. So, the idea is that you progressively keep on filling up your volume with smaller and smaller particles so that you get a maximal filling up of the particle space. There are some considerations here, which you need to think about.

One is called the wall effect. This is the wall effect. The wall effect essentially says that the packing near to the boundary of the container is going to be less than the packing away from the boundary of the container. So, let us take a cylindrical container, you try to pack your aggregates in that cylindrical container by doing some compaction by the tamping rod. The packing which is close to the walls is going to be poorer as compared to the packing that is away from the walls. So, wherever you are coming to interfaces the packing gets affected and this is something that you see in your definition of ITZ also. You have more porosity in the ITZ also as a result of this wall effect.

You do not get as efficient a packing of your cement paste or cement mortar around the aggregate as you get slightly away from the aggregate. So, wall effect is something that you need to be aware of while designing particle packing. The other is loosening effect. Now you have these larger particles which you put into your system. If you choose the size of particles smaller than that in such a way that the size is slightly larger than the gap that is available between the particles.

Alternatively, if you choose so much of the small particles that they now do not have sufficient space in that gap they will start pushing out the larger particles. So, this is called the loosening effect. So if you do not choose an appropriate proportion of smaller particles they do not have sufficient space to fill up the gap. So, they will start pushing out the coarser particles to fill up the gap. Now that can be detrimental to the overall packing of your system.

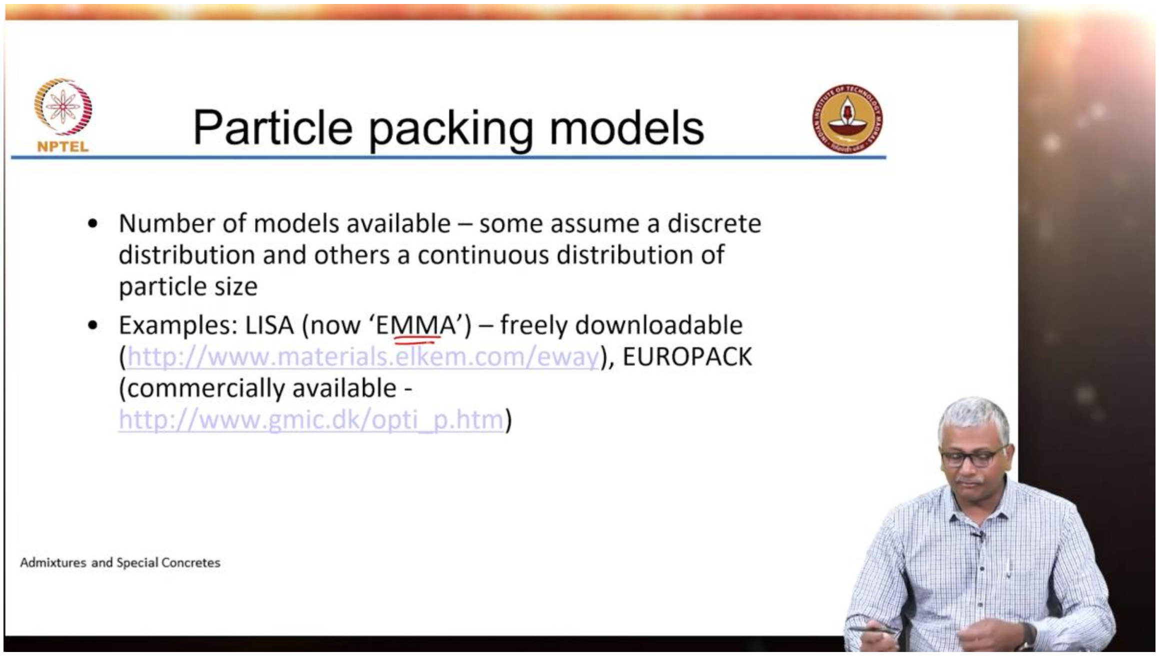
Now, think of it in such a way that let us say I am choosing to replace cement with silica fume. Silica fume is much smaller particle size. But if I use too much of it what is going to happen is that is going to get between the space given by the cement particles and it may tend to spread out the cement particles further thus disrupting the packing that you have got for the cement particles. So you cannot keep on choosing more and more quantities of finer ingredients to fill up a space.

That is the idea of the loosening effect. You need to have an optimal level available in your system so that you get the filled-up space as practically well as possible. Now a system like this obviously can be defined with several different mathematical models. There are several models available. Some of these are based on discrete approaches. Discrete means you have uniform-sized particles that are filled up in each step.

Let us say only 20 mm, only 10 mm, only 5 mm and so on and so forth. Alternatively, you can also do this with a continuous particle size range. That means each particle, each system of particles has a gradation, a continuous gradation and then you can use that towards your model.

**Particle packing models:**

(Refer to slide time: 20:46)




Now one of the popular models which adopts this continuous particle size distribution is the EMMA model. Now this website may not be working now because I think it has since been removed ever since Elkem got taken over by a different company.

Elkem is the manufacturer of silica fume. So they got taken over by a different company and this software may not be as easily available but looking at the model and the equation you can use that to actually design in Excel itself. You can use Microsoft Excel to do the same thing as what is done in this software. But I will just take you through the software anyway just to show you what it can actually do. There are of course also commercial models available like EUROPACK for which you need to pay a fee to buy the model. The model is again giving you an optimization of granular materials based upon the given particle size of the ingredients.