Admixtures And Special Concretes

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Lecture -71

Special concretes - High-density concrete - Heavyweight aggregates, design, case study

Factors affecting aeration in aerated concrete

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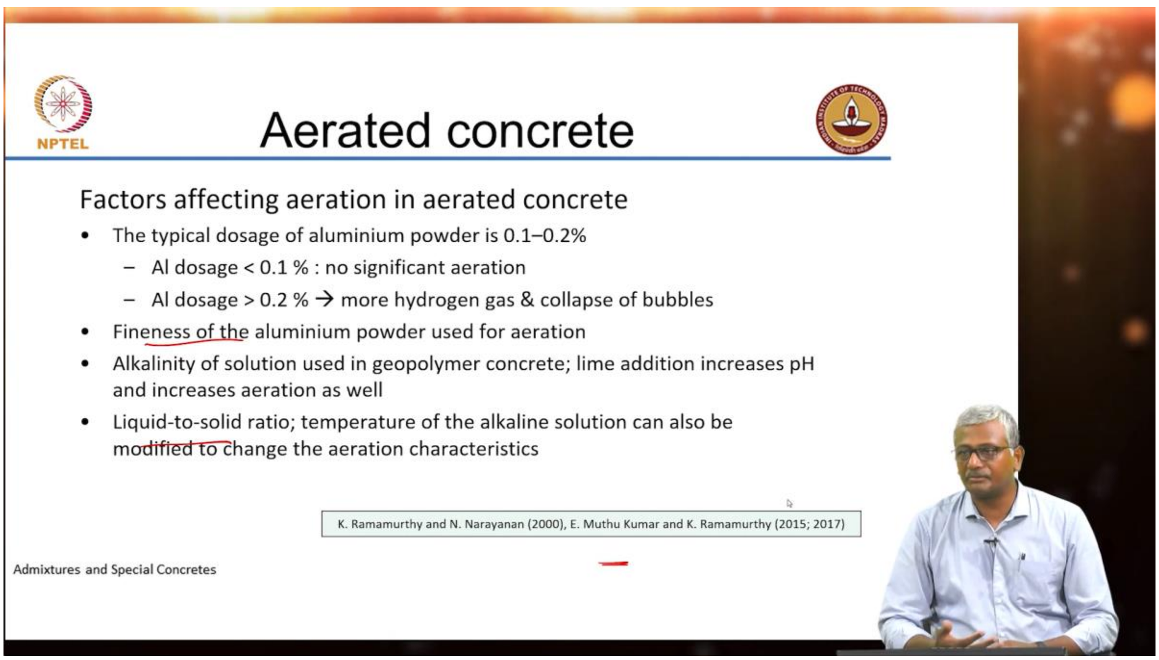

We were talking in the last class about lightweight concrete which could be produced by different methods. One is the use of foam; the other is the use of lightweight aggregate, and finally by aeration. Aeration is caused because of the use of aluminum powder which generates hydrogen gas in an alkaline environment and this gas gets trapped within the concrete structure. I have not covered aerated concrete in much detail because this is a widely available product. You can find several product data sheets of many different types of aerated concrete blocks.

As I said earlier, the curing is almost always done by autoclaving which ensures that you can produce these blocks quite fast. You have rapid productivity, which leads to the production of autoclaved aerated concrete blocks or AAC blocks.

Heavyweight aggregates:

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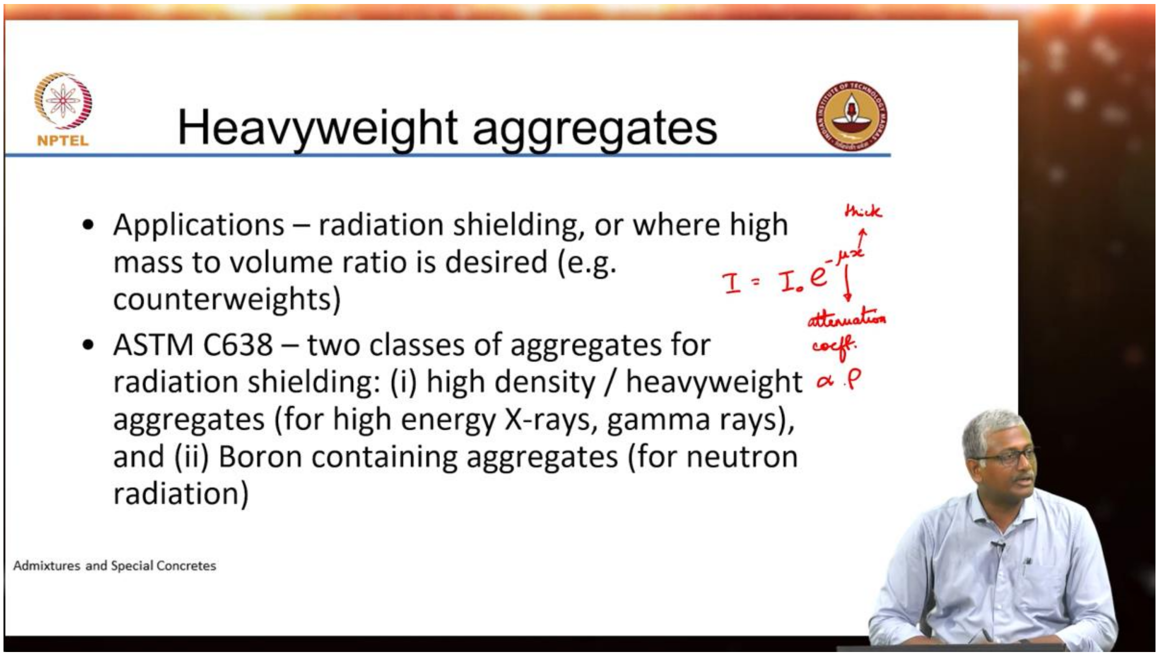

Let us move on to heavyweight aggregate, the other end of the spectrum. Now heavyweight aggregate must be used in applications where you need to make use of the density, not the strength but the density.

In such cases, you can apply heavyweight concrete for purposes of radiation shielding. In nuclear power plants, you know that there is a lot of radiation generated which is harmful to human health. This radiation needs to be stopped from getting out into the atmosphere and this can be done with the help of concrete with heavyweight aggregate. You could also do it with other materials.

What are the metals that are extremely high density? Steel is high but probably not high enough. Lead is a common material that is used for shielding. But of course, using lead is going to be extremely expensive.

So, people usually adopt heavyweight concrete because they can use aggregates within the structure of cement paste and create a composite that essentially has an overall density that is much greater than your typical concrete density. Now if you look at ASTM C638 which talks about the use of aggregates for radiation shielding, they divide into two purposes. One is high-density or heavyweight aggregate which is used for high energy X-rays and gamma rays and boron-containing aggregates for neutron variation. There are certain nuclear reactors based on heavy water where neutrons may be generated. These neutrons are also prevented from getting out into the open by doing an efficient shielding and this is typically done with aggregates containing boron.

Those are not essentially heavyweight aggregates. They have to have the property of restraining neutrons from going out. Whereas heavyweight aggregates like iron bearing aggregates, which are typically used are used to stop high energy radiations like X-rays and gamma rays. I assume you all remember your electromagnetic spectrum. So where do gamma rays come in the electromagnetic spectrum in terms of wavelength? Smallest, largest, medium? Wavelength implies the inverse of energy.

So, the higher the wavelength the lower the energy. So, gamma rays obviously will have high energy so they are at the end of the spectrum with low wavelength. Gamma rays and X-rays are at the spectral end which has a very low wavelength. What is on the other side? What do we use for long-range? Infrared is close to the visible range. It is just above the visible range.

What do we use for long-range signaling and satellite communications? We use radio waves for long-range communications. Microwaves are slightly less than radio waves but we use radio waves for long-range communications because the wavelengths are of orders of several tens of meters. Here we are talking about wavelengths of the order of angstroms. That means the energy is extremely high and to stop this you need to have a proper high-density material that can stop. So essentially the intensity of electromagnetic radiation as it is passing through a dense material attenuates with respect to the thickness of the material.

So generally, if you have an intensity at any given point, I is equal to the original intensity multiplied by e to the power minus mu X where X is the thickness and mu is the attenuation coefficient.

$$I = I_0 e^{-\mu x}$$

I = Intensity at any given point

I_0 = Original Intensity

μ = Attenuation coefficient

x = Thickness

This attenuation coefficient is dependent on density. So, the higher the density the greater will be the attenuation coefficient and the greater will be the decrease in intensity of electromagnetic radiation as it passes through a certain thickness of the material. So, you must choose your material carefully and high-density aggregate is used to make heavyweight concrete of densities which are typically much more than 3 g per cubic centimeter or 3000 kg per cubic meter.

Desired properties of Heavy Weight Concrete

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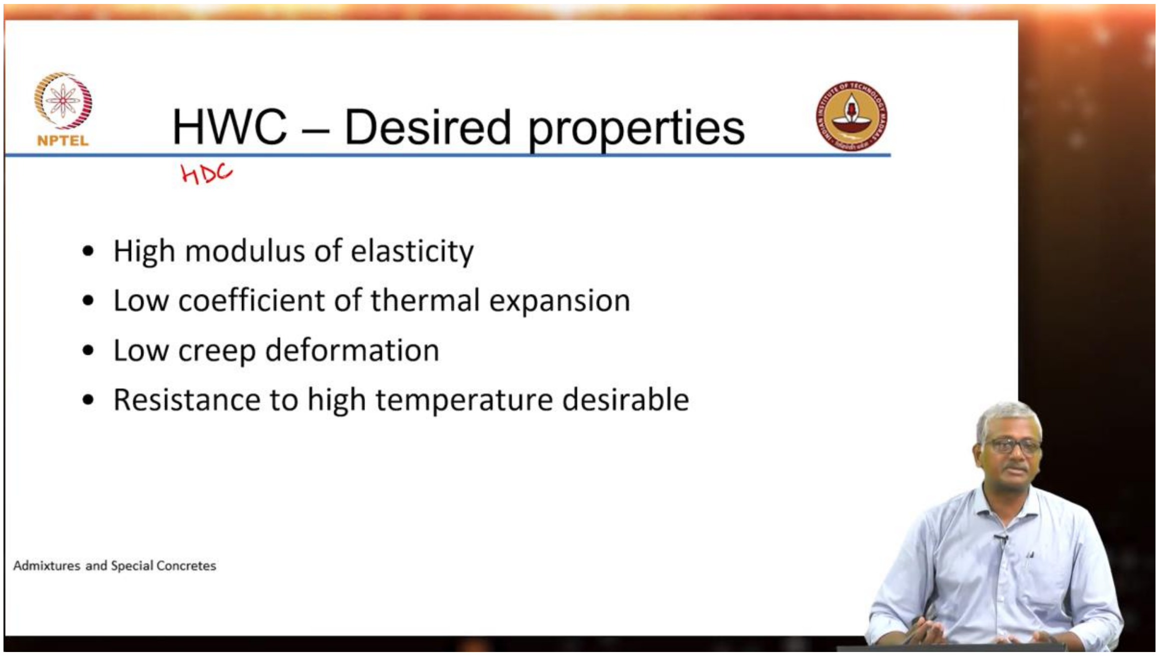

HWC is heavy-weight concrete. Sometimes it is also called HDC high-density concrete. Heavy-weight concrete or high-density concrete are used interchangeably but both mean the same thing. You desire from these materials a high modulus of elasticity and a low coefficient of thermal expansion. Why? Because in radiation there is a large amount of heat is also getting transmitted. So, stopping the transmission of heat effectively also is important.

But usually, the radiation shielding materials are not intended to stop heat too much. You have cooling systems in nuclear reactors which are essentially able to bring down temperatures of the vault, and outer temperatures of the vault. The nuclear reactions proceeding inside are generating extremely high temperatures, so concrete is going to get subjected to very high temperatures because of this you need a low coefficient of thermal expansion and low creep deformations with respect to your sustained loads. Your material should be able to resist creep for a longer period. Most heavy-weight aggregates have high stiffness because of which they can resist creep to a large extent. And again, as I said resistance to high temperature is desirable for any material that you put inside nuclear vault.

Different types of Radiation Shielding Aggregates:

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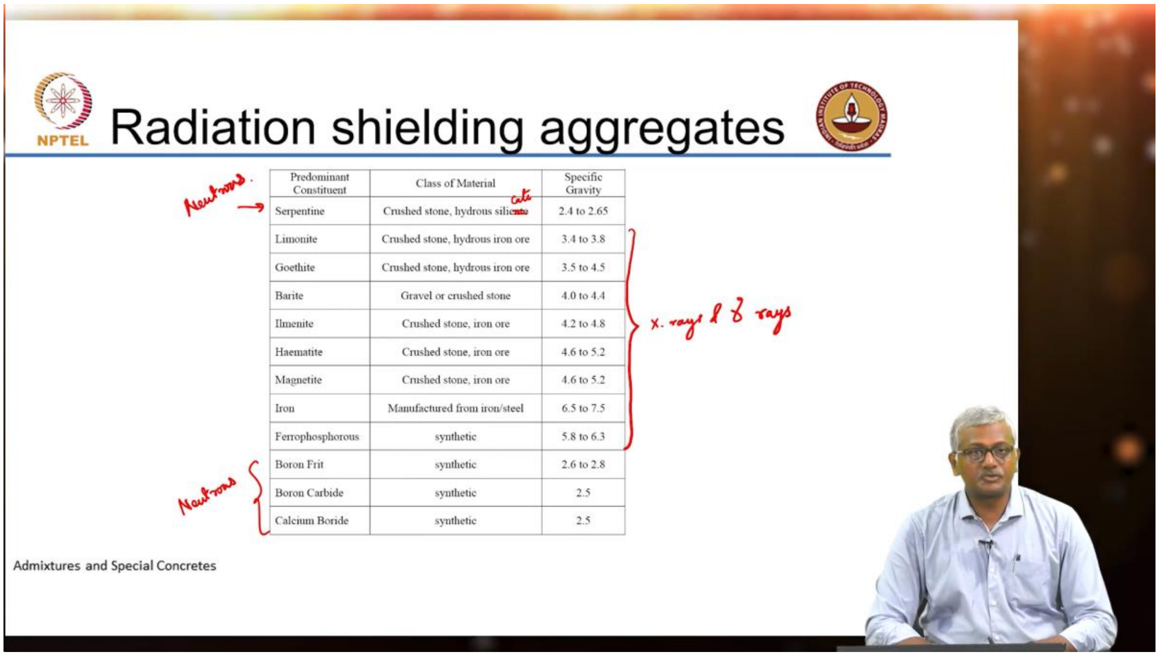

Now what I was talking about earlier is that you have the boron-bearing aggregate (Boron Frit, Boron Carbide, Calcium Boride) which could be used for neutron radiation shielding. You can also use Serpentine a hydrous magnesium silicate and that is also able to reduce the intensity of neutron radiation. But all these other aggregates which are higher density than normal aggregates are used for x-rays and gamma rays. As you can see most of the iron-bearing aggregates are the ones that we use as material for high density concrete.

Placement considerations for High Density Concrete

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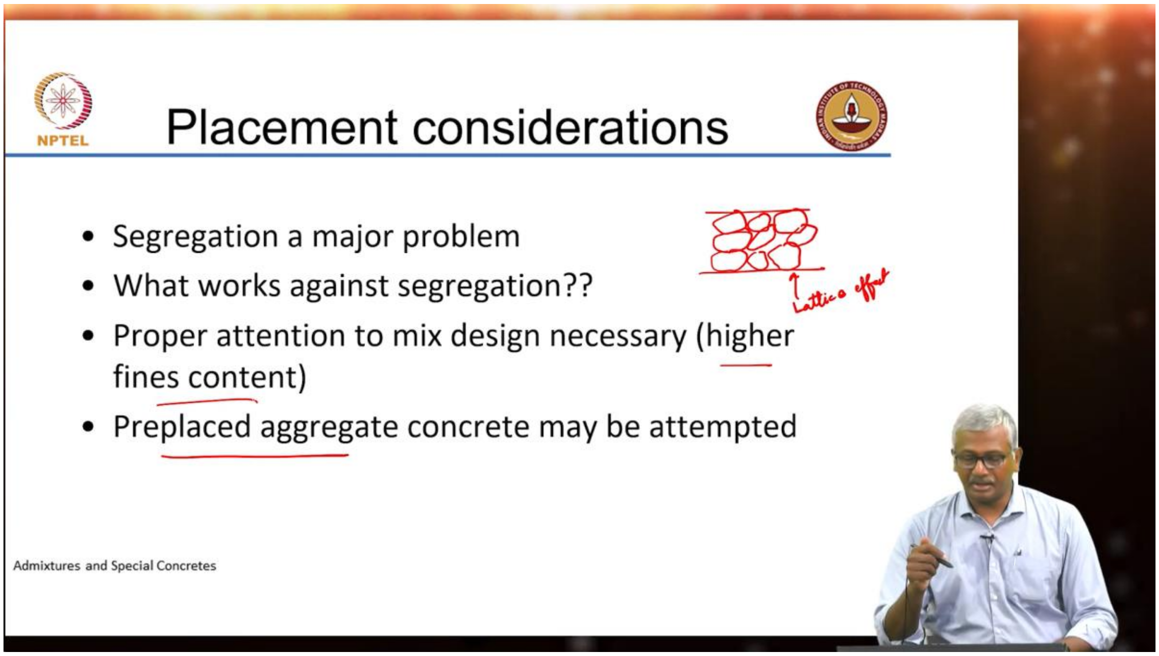

So here when you deal with high-density concrete, you are dealing with the risk of extremely high segregation because your aggregate phase is now very heavy as compared to your paste phase. So, it is quite easy for the segregation to happen. Now what may work against segregation is that if you have designed your system with a lot of aggregate let us say this is your slab (Refer to the illustrated figure in the slide) for instance and you have a lot of coarse aggregate present in your system.

So, what works against segregation is the fact that you have a three-dimensional network of aggregate that is sort of preventing the collapse of or settling of coarser aggregate. So, in other words, we call this the lattice effect. So, you make a three-dimensional lattice of several aggregates that are working against each other to keep the concrete mass uniform without allowing for any settling to happen. So, one thing you need to think about is that you need to design your concrete with enough amount of aggregate. So here again aspects of particle packing may be quite useful because then you can maximize the amount of aggregate in your system so that they work to prevent a collapse or settling of the aggregate when the paste is added.

The other possibility is using preplaced aggregate concrete. That means in your formwork you place the aggregate first and then pump in the slurry. It is not very easy but it can be done. Now of course you need to ensure that you have a high enough fine content to have a stable structure without collapsing or settling.

So, because of that, you need to design against segregation. You have to remember that here the fines or fine aggregate are also going to be heavy-weight aggregate. So, you are going to be crushing the hematite or magnetite aggregate whatever you are using, the coarse aggregate is going to be crushed to fine sizes. So even the fine aggregate is going to be extremely heavy weight.

Study at IITM- for IGCAR- Design of M30 & M45 Heavy Weight Aggregate Concrete

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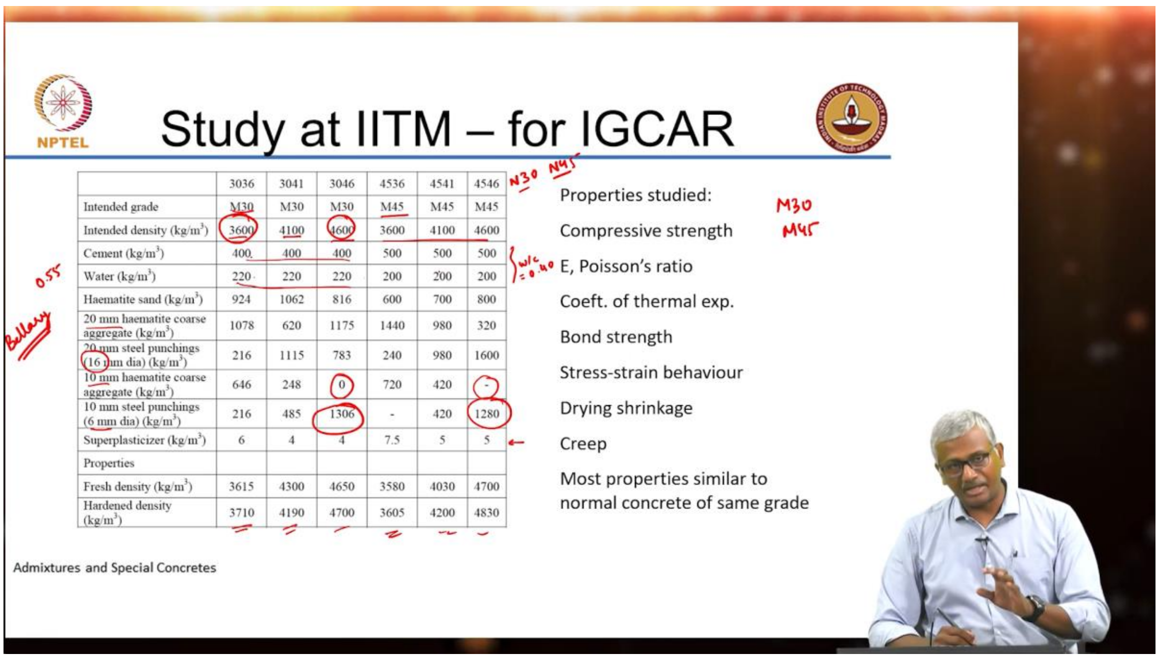

I will give you an example of a study we did at IIT Madras for Indira Gandhi Centre for Atomic Research where we were looking at creating a database of structural properties of heavy-weight aggregate concrete.

They had been doing radiation shielding concrete for a long time. They were able to understand how best to look at the radiation and intensity decrease as it passes through concrete of different densities. However, they did not have a clear understanding of how to design for a particular strength. Like what would be the engineering properties like the modulus of elasticity for a particular strength? Can we still use the IS 456 relationships in the case of modulus or do we need to change our outlook?

So here in this project, we designed concretes of 2 grades M30 and M45. As you can see M30 and M45 grades with 3 densities 3600, 4100, and 4600. The same 3 densities were also repeated for the M45 concrete. So as compared to the density of regular concrete which is 2400, heavy-weight aggregate concrete has a density of 3600. So, a normal concrete was also done for 30 MPa and 45 MPa.

So, there was a normal concrete also done with normal aggregate to compare the properties of the heavy-weight concrete. So, refer to the table in the slide to see how the design has been achieved. The cement content was kept fixed at 400 in the case of the M30 concrete mixes. The water content was also kept fixed at 220. So that means the water-to-cement ratio of 0.55. You may assume that this water-cement ratio seems to be too high for an M30 concrete. In most laboratory studies you can design optimally to get high strength with even higher water-cement ratios. So, in this case, the idea was to keep the concrete mix as simple as possible and yet achieve the required strength. So here the water-cement ratio is kept at 0.55. In the case of the M45 mixes the water-cement ratio was 0.4.

The aggregates were a combination of hematite sand. Hematite aggregate was obtained from Bellary in Karnataka. There are a lot of mines in Bellary. Most of your steel works like Jindal Steel and so on are also located. They get their iron ore by extracting iron ore from hematite or magnetite, mostly hematite from Bellary. But you can also use that as a heavy-weight aggregate. So that is the other problem with these heavy-weight aggregates. First of all, they are not easily available.

Second, they are going to be more profitable to extract iron from. Why would you sell the aggregates to make concrete when you can extract iron from it? You have to have a balance and ensure that. That is why all these nuclear projects are government projects which will create a necessity to supply these projects. For private purposes, one cannot easily get high-density concrete. The other application of high-density concrete is as a counterweight. You can produce much more denser counterweights as opposed to normal concrete. You can reduce thickness and still have the same mass for as regular concrete which requires a very high thickness.

In our case, hematite coarse aggregate was used in two sizes 20 mm and 10 mm, and apart from that we also had to add 16 mm diameter steel punching of length 20 mm. That means we took 16 mm bars and cut them into 20 mm length sizes and also smaller steel punching (6 mm diameter steel rods that were cut into 10 mm sizes). So, all this was done to ensure that we were able to get the required density.

So, you can see for instance when we go to the 4600 kg/m^3 density, we did not use any 10 mm hematite aggregate but we entirely used 10 mm steel punching otherwise, you cannot get that density. Same here in the M45 mix with 4600 kg/m3 density, there is no 10 mm coarse aggregate there are only steel punchings to fill up the remaining volume. So super plasticizer had to be used to make the mix compactable. We were not looking primarily at pumping-related properties because imagine, pumping of high-density concrete is extremely difficult.

Later in a study that is about to be concluded now, there is an engineer from Ajaykar who had also partially taken me on as a co-guide where he has worked on pumping high-density concrete. And that is going to speed up a lot of construction if you can efficiently pump high-density concrete. So, he has also developed high-density concrete that is pumpable. That is a lot more challenging but it can be done. So here super plasticizer also has been used to achieve a certain workability as you can see very clearly in terms of densities, the required densities were easily obtained.

We have achieved a hardened density of 3700, 4200, and nearly 4700 for M30 concrete. So almost 100 more than what was required was achieved and it is almost perfect in terms of densities in the case of M45 concrete. So again, you need to do this design carefully. So here the approach adopted was that we just fixed the cement and water contents first.

So, if 3600 is the unit weight of the concrete. You remove the weight of the water and the cement. The remaining weight needs to be distributed amongst the aggregate. You distribute it in such a way that you maximize the packing. You can maximize packing typically by introducing a little more coarse aggregate than fine aggregate and then based on the densities of these individual phases you can select the amount of material so that the volume corresponding to the balance mass can be filled up by the aggregate.

So, that is how the design was done in this case. Cement and water were fixed first and from the remaining mass that was aggregate mass a distribution of aggregate was chosen in such a way that packing could be maximized and at the same time the exact specific gravity of the aggregates was taken in for the calculation to get a true volume of 1 cubic meter. Whenever you design concrete, you have to keep that in mind that you have to design for that 1 cubic meter purpose. It is often very easy to design for the mass which means to design for 2400 kilograms.

You can often do that quite easily. You know that for M30 concrete you may need so much cement and so much water. The remaining part you subtract from 2400, whatever is remaining is the mass that you need to distribute amongst the aggregate and it is easy to just do a random design of 60% coarse and 40% fine. The problem is if you do not take the true specific gravity of the materials, the total volume of all the ingredients will not add up to 1 cubic meter and that is when your concrete mixes are not yielding properly. Yield means when you design for 1 cubic meter you produce 1 cubic meter. Concrete mixers are said to be under yielded when you design for 1 cubic meter but you get less than 1 cubic meter.

So that is because you have not done a proper calculation of the densities of the aggregate. Alternatively, it also may mean that you have got too much air in your system. Mix design has to be done carefully to ensure that your yield is always 1 cubic meter. So here different properties are studied compressive strength, modulus of elasticity, Poisson's ratio, thermal expansion, bond strength, stress stream behavior, drying shrinkage, and creep. Most properties were found to be similar to that of normal concrete of the same grade.

Stress-Strain Data

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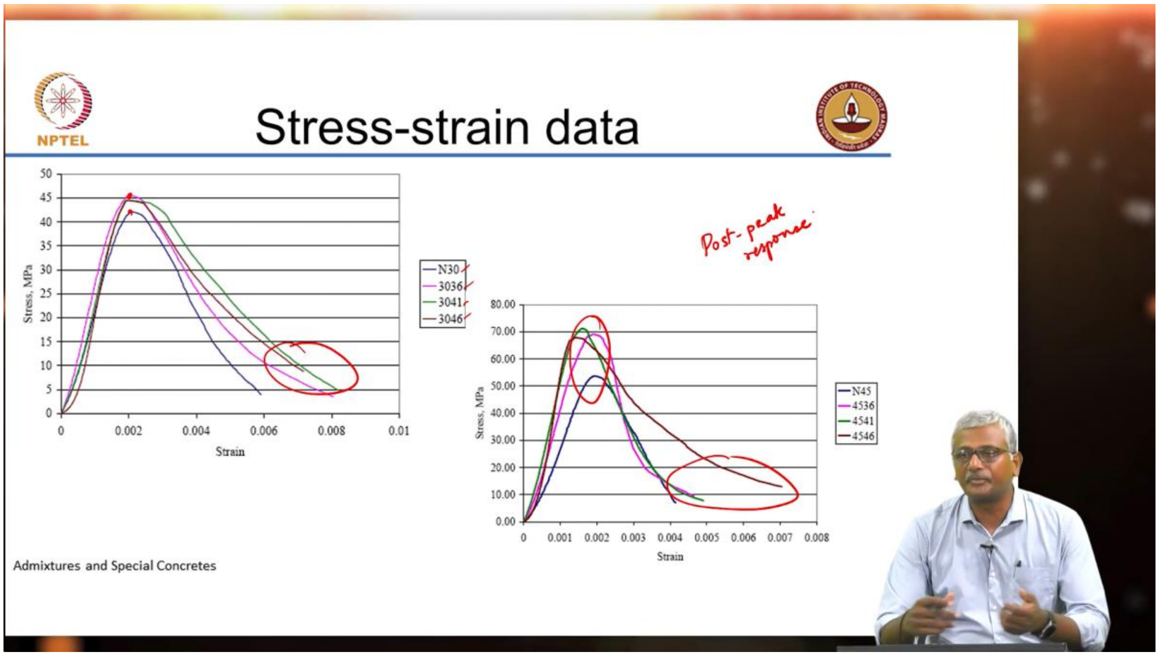

What I will just show you briefly is the data for the stress-strain curves that were generated in the study. So here you have normal concrete with 30 MPa and different density concretes with 30 MPa (Refer to the left chart in the slide). So, what you see is the peak stress is significantly higher than 30 MPa so you get more than 40 itself but the strain at peak is more or less similar. So, there is not much difference there in terms of the strain at peak. Similarly, even for these the strain at peak which we assume typically as 0.002 seems to hold quite well. What you do see is different is the tail of this curve which means the approach towards failure. Why does this strain-softening behavior come about in concrete? Why does the structure not collapse all of a sudden? Why is there no collapse? Why is it a slow failure? We have discussed this before. At peak what happens? All the cracks start coalescing. Beyond that, the concrete must fail but you know that there is sufficient inter-particle friction caused by the aggregate, and that prevents the rapid failure of the system.

It gives some degree of ductility. See we call this a post-peak response. And it seems to be getting better when we employ steel aggregates in the system. In this high-density concrete when we put the heavy-density aggregate or steel aggregate in the system it seems to be increasing the friction that causes the crack to slowly open up and reach an unstable size. At that point, the failure actually happens but then the crack slowly opens up and then you get some benefit because of the added steel aggregate.

Proposed Model for Modulus of Elasticity (E)

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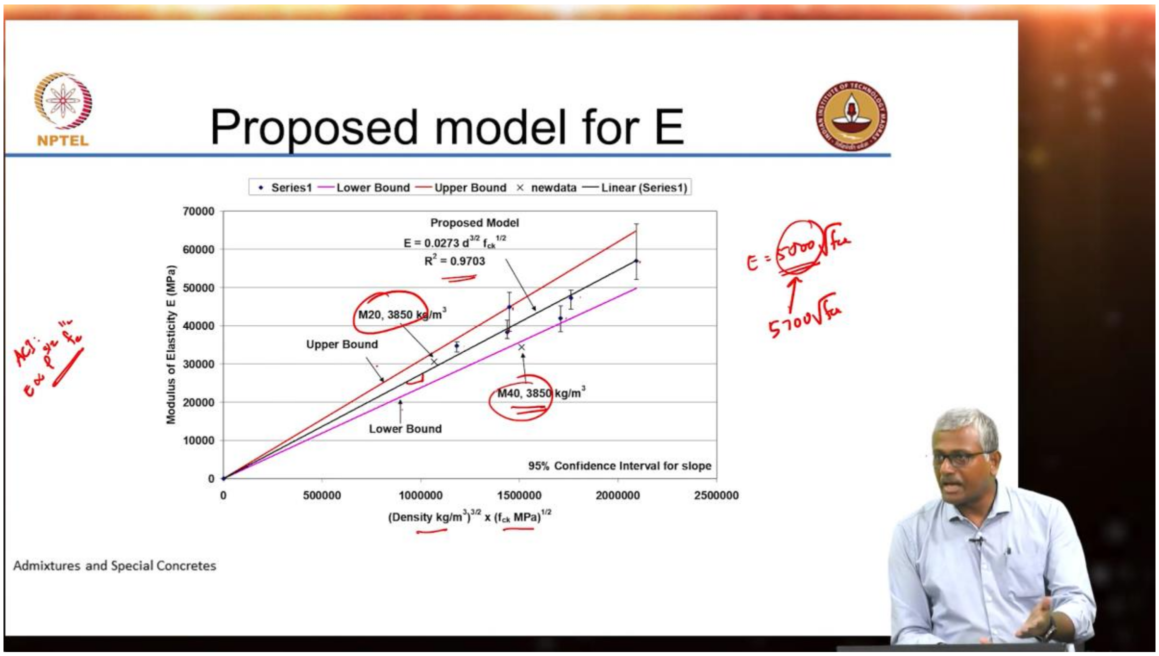

Now what about the modulus of elasticity? We know that IS 456 gives you a relationship of E equal to 5000 square root of f_{ck}.

$$E = 5000\sqrt{f_{ck}}$$

E = Elastic Modulus

F_{ck} = Characteristic compressive strength

Now one thing that you have to ask is where does this 5000 come from? Why 5000? Is it just data fitting or is it something else? If it is data fitting again, they could have fit the data against linear data with f_{ck}, why a square root data? Square root because as you keep on increasing the strength the modulus does not increase linearly there is a lesser increase in the modulus. That is one thing that you see but why this 5000 has come about? This 5000 comes about because of the consideration of a normal density aggregate. The original ACI relationship has E as a function of density to the power 3 by 2 and cylinder strength f to the power half.

$$E \propto \rho^{3/2} . {f_c}^{1/2}$$

That is the original relationship and when you put in the density of normal concrete there you get a relationship that ultimately when you convert back to SI units it ends up in this range.

The previous expression that was used in IS 456: 1978 used to be 5700 square root of f_{ck}. It was later changed when enough data was produced with experiments done on modulus to the relationship that is currently there. This is going to change again in the next IS 456 revisions. Some normalization is being done for the fact that when you go to extremely high strength this is not the data that is getting followed. What we did was if we use this, we are really not getting a proper prediction of the modulus from the strength values that is what we saw in our data.

Then we went back to this original equation. What if we assume this form and plot the modulus against density to the power 3 by 2 multiplied by the square root of compressive strength? Of course, f_{ck} is characteristic compressive strength. Here we have just used the mean compressive strength that we get at 28 days. We have not used characteristic strength.

So here when you plot this modulus data it is quite interesting. So, 6 mixes were tried (refer to graph in the slide). If you plot a linear relationship through that you get a good relationship with a regression coefficient of 0.97 indicating that the degree of fit is quite good. And even if you do a confidence interval for the slope, so this is the slope and the confidence interval means with 95% confidence you can state that the slope is the true slope for this relationship.

And this 95% lower bound and upper bound are given here and you can very clearly see that all data are nicely covered within that. Additional data were also produced with other densities and other strengths which were not from the same set. M20 with 3850, M40 with 3850 kilograms per cubic meter and you can see that these are also close to the suggested data range. So, this implies that you can now have an engineering relationship between modulus, strength, and density when you design high-density concrete, and that can then be used for structural design purposes. Because not always do you have the opportunity to test the modulus of elasticity but nevertheless it is always important to do a proper test for modulus before you can determine that and use it in structural design.

So instead of blindly using IS 456, you can now create a different relationship based on this data and that will apply to most high-density concretes.

References:

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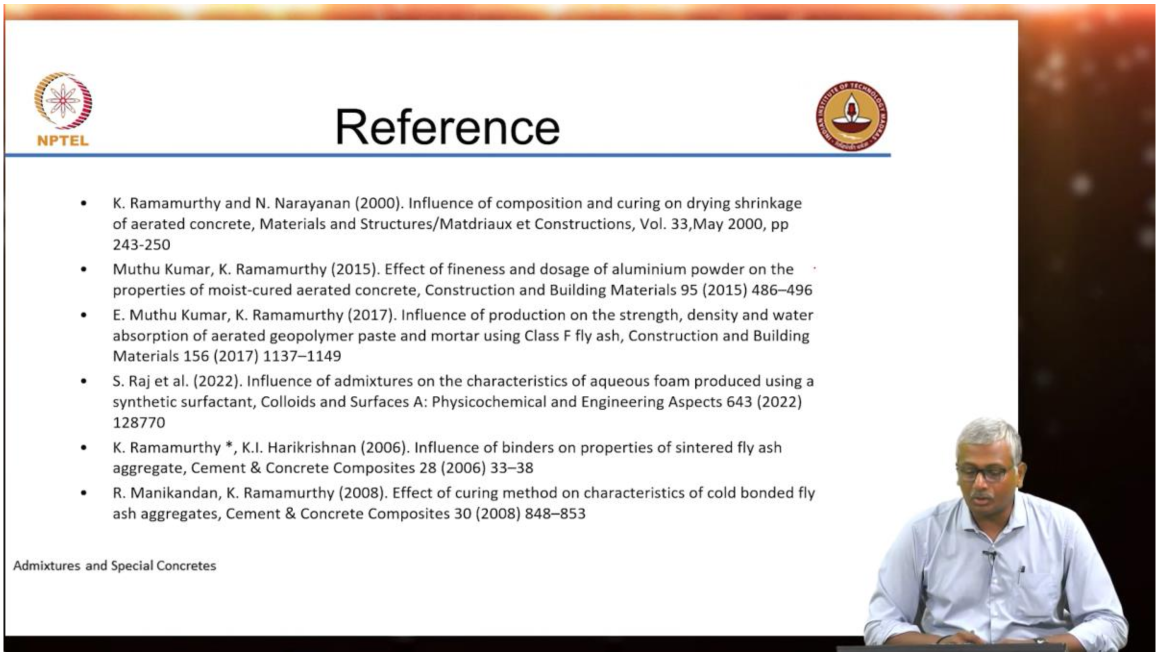

So, there are several references, most of these are of course references for your lightweight concrete. I will also put in a few papers from high-density concrete in your Moodle page so that you can get a good idea about what kind of work has been done and how these are able to produce the data that we have talked about just now in this class. As you can see most of these papers are dealing with work done by Professor Ramamurthy's group as I said that is perhaps the most, perhaps a leading group I would say in the entire world which looks at lightweight concrete.