Admixtures And Special Concretes

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Lecture -58

Special concretes - Ultra high performance concrete - Design principles, strength, durability

Ultra-High Strength concrete

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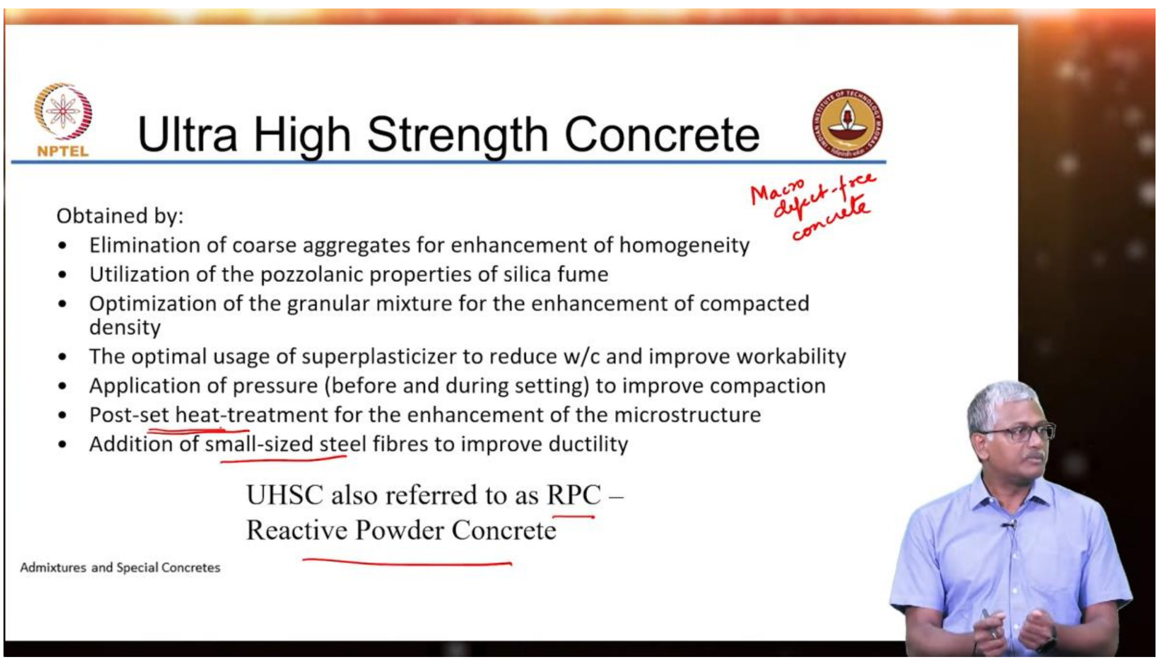

So, let us just shift a little bit to ultra-high-strength concrete and then talk somewhat about how to design such a system. It is not that complicated to think about how to design the system but actually achieving the results in the lab is a different story altogether. So what you want to do with ultra-high strength concrete is make the concrete as homogenous as possible. I was saying earlier that when we shift from normal concrete to higher strength we generally tend to reduce the aggregate sizes because now the paste matrix and the ITZ have become so strong that the cracks tend to pass right through the aggregate. So if you have more aggregates on the way of the crack, the crack has to go through all those aggregates to really cause the failure. So that is why we want to make the concrete as homogenous as possible.

Now in that case why do not we simply use cement paste? We cannot use cement paste because? Before cost there is a technical reason why we cannot use cement paste. Cost is definitely a problem but a technical reason why we cannot use cement paste. Strength you can achieve with cement paste nothing wrong that is why it is homogenous you can achieve strength. Dimensional stability- without aggregate you do not get dimensional stability in your concrete.

So, you have to use aggregate but the idea to achieve higher strength is to ensure that you pack your aggregates very well first of all. Second, you ensure that the particle sizes of aggregates are reduced to an extent that the concrete almost has a homogenous appearance. So eliminate coarse aggregate for enhancement of homogeneity. In fact even the fine aggregate is restricted to a certain maximum size as we will see in the examples later. You have to utilize very fine mineral additives like silica fume it is absolutely essential and optimize your granular mixture to ensure you have the best packing density just like what we talked about with regular high-strength concrete mix design that is one of the important steps to use.

You have to obviously use a superplasticizer without which you cannot get a low water-to-cement ratio or water-to-binder ratio. In some instances, you may want to apply pressure during compaction we saw that in example with biomass bricks but the same thing can be also thought of for high-strength concrete. When you apply pressure during setting what happens is you start eliminating the voids that come inside. The voids inside are eliminated and when you do that it is almost like a defect-free concrete. In some papers, you may also have a reference to macro defect-free concrete.

That is concrete in which you have done the processing in such a way that large defects like cracks and voids inside the system have been completely closed because of the pre-setting compaction that you give to such concrete. Then the other thing is that post-setting heat treatment for enhancement of microstructure can be also taken up for ultra-high strength concrete that further increases the strength. I will show you some examples later and using small-sized steel fibers to improve ductility. As we saw earlier when you increase the strength of concrete it becomes more and more brittle. It loses whatever little ductility it can have.

You want to enhance the ductility but yet achieve a very high strength that can be done with the help of fibers. Why because what do fibers do? They bridge the cracks and prevent the cracks from opening up. When the fibers used are extremely small sized they will also be very effective in bridging cracks that are extremely small. You know that cracking initiates in concrete with the micro cracks that are generated first and if you have fibers to bridge the micro cracks you will further enhance the strength of the concrete. So ultra-high strength concrete is also referred to sometimes as RPC or reactive powder concrete because you have so much of your cementing material inside the system that it is almost like a powder.

So let us look at what happens here. Again, we are talking about water-cement ratios of 0.2 and below. So where is hydration going here? What is the role of hydration? In all high-strength concrete we are always talking about water binder ratios of less than 0.35 or 0.3 sometimes.

What is happening to the hydration? Will it hydrate much? Probably not. It is not going to hydrate much because there is first of all you have so much powder in there that there is no space for the hydration to happen. But yet obviously you cannot just take the powder and compact it. It is not going to work.

So, hydration is still necessary to an extent to ensure that you have a skeletal framework that is created which can bind the particles together. So, some minimum level of hydration is absolutely important and to enhance that hydration further you can do this post-setting heat treatment that further enhances the hydration characteristics without really compromising on the overall long-term strength. So, it is a little bit contradictory to what we have been taught before. We have always been told that the more you hydrate the better the strength. But you have to think about it differently.

Ideally, strength is related to the porosity of the concrete. The minimization of porosity is the maximization of strength. So how do you minimize porosity? By ensuring that you have a compact packing of all the materials that are available. But at the same time, you need some minimal hydration level to ensure that the skeletal framework is formed. Otherwise, the particles will be loose. Some minimum level of hydration is absolutely important.

Principles of UHSC Design:

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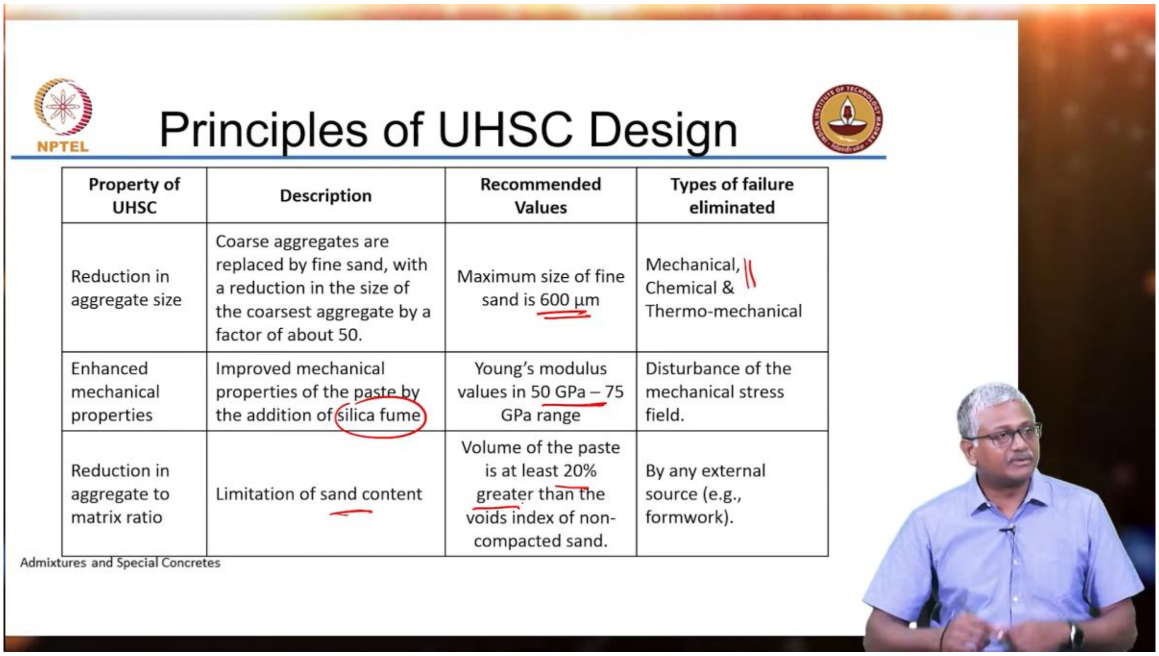

Now, generally aggregate size is reduced all the way to about 600 microns. So we are talking about using fine sand, extremely fine sand as aggregate. So, you are generally trying to avoid failures such as mechanical, chemical and thermo-mechanical. Of course mostly mechanical when you are trying to reduce the aggregate size more and more.

You can enhance mechanical properties by addition of silica fume and achieve stiffnesses which are way beyond your regular concrete 50 to 75 gigapascal is what you can obtain with reactive powder concrete. Aggregate to matrix ratio is also reduced. You have more cement paste in this case. You can limit the sand content to achieve that. The problem is when you try to fit in more and more sand you are not going to get the effective packing that you need with the smaller scale or smaller sized materials.

So, volume of the paste is at least 20% greater than the voids index of non-compacted sand. So if you take a container and put non-compacted sand inside, determine the amount of voids that are present, the paste that fills up that void plus an additional 20% is what is required to make this microstructure feasible.

Reactive Powder Concrete- Ingredients:

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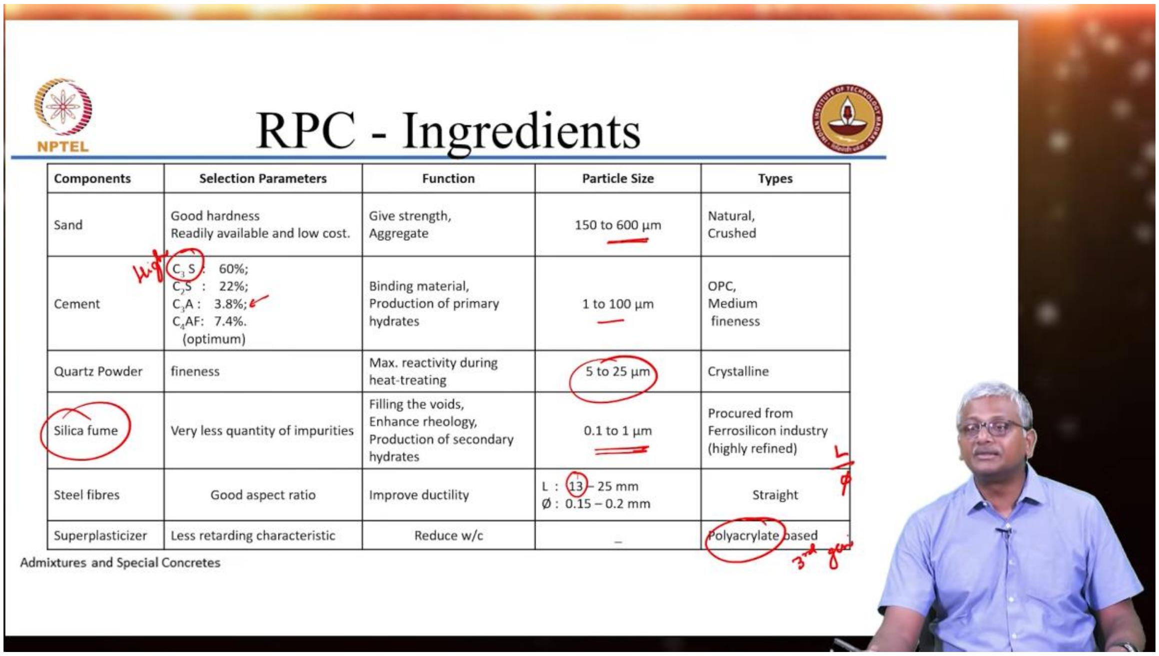

So, ingredients typically sand as I said less than 600 micron, cement we want to choose cements that are high in C_3S. Of course, this is not necessarily true C_3S of 3.8% happens only in sulphate-resistant cement which we typically would not get such low C_3S in normal cement.

So, you want very high C_3S and of course particle size of cement is about 1 to 100 microns with an average particle size between 15 and 20 microns. Quartz powder can be used as a filler to provide additional fines. It fills up this sort of a size range of 5 to 25 microns. The bulk of the particles are around 10 microns so slightly lower than cement. So, you see the idea, you have sand particles followed by cement particles, quartz powder then you come with silica fume or micro silica which fills up the even smaller spaces 0.1 to 1 micron.

And then steel fibres which are high aspect ratio and low length. So, you want steel fibres of around 13 mm and aspect ratio is basically length by diameter. So, if you divide 13 by 0.15 you will get an aspect ratio of nearly 80 to 90. So aspect ratio needs to be high.

Now fibres are used for crack bridging. So how should fibres fail to obtain ductility? How should the fiber-reinforced concrete fail so that the system is still ductile? Should the fibers fracture? No, they should not. Then how should they fail? As the crack opens up the fibre is getting pulled out of the matrix. So, you want to maximize the extent of pull-out that actually happens. So, when you have a high aspect ratio it leads to failure by pulling out.

At the same time if you keep on reducing the diameter, you can also fracture the steel fibres. So you need to choose the aspect ratio carefully. So, you want to maximize the pull-out that happens in the system. And super plasticizer you have to use a generation 3 because otherwise, you will not get the required water-cement ratio reduction.

Water demand and packing:

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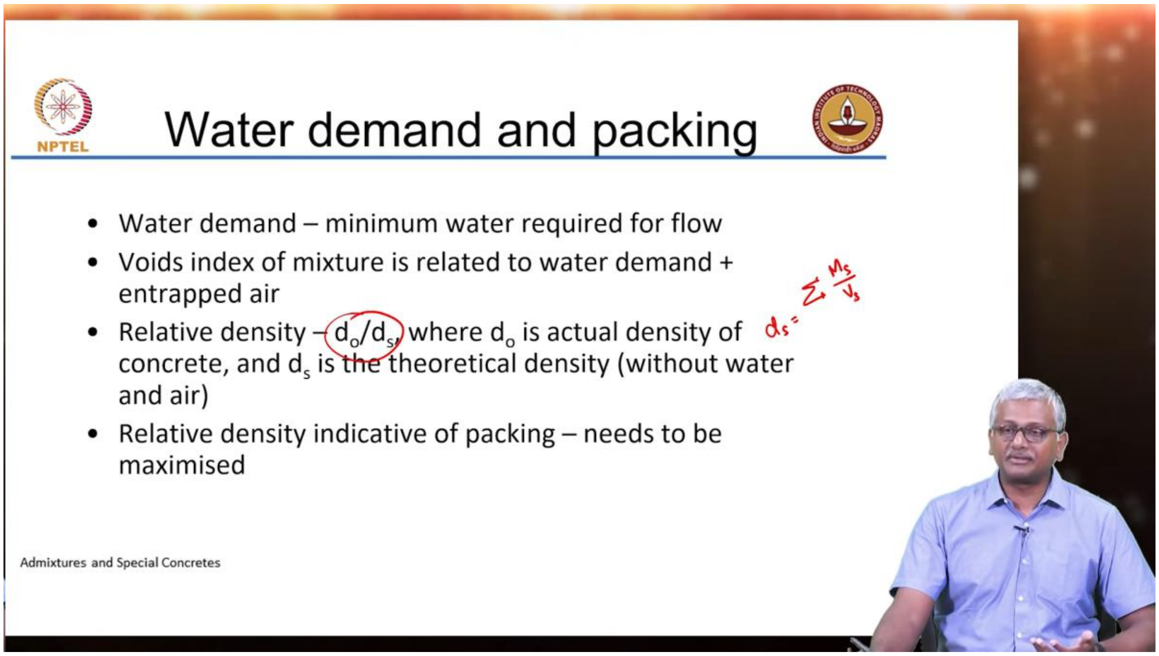

So, as I said again you are employing concepts of particle packing where you can define a parameter such as relative density d_0 by d_s where d_0 is the actual density of the concrete which is achieved after compaction and d_s is the theoretical density without the consideration of any voids.

$$Relative\ density = {}^{d_0}/_{d_s}$$

$d_0 - Actual\ density\ of\ concrete$

$d_s - Theoritical\ density\ (without\ water\ and\ air)$

So, mass of the solid ingredients, so sum of ds is the sum of mass of the solid ingredients (M_s) by their volumes (V_S)

$$d_s = \Sigma \frac{M_s}{V_s}$$

So that is essentially coming from your aggregate, cement, quartz powder and silica fume and d_0 is the actual density that you measure after compaction into a cube or something. So, what you need to do is minimize voids so maximize the packing density. Same concept as what we discussed earlier.

Additional measures:

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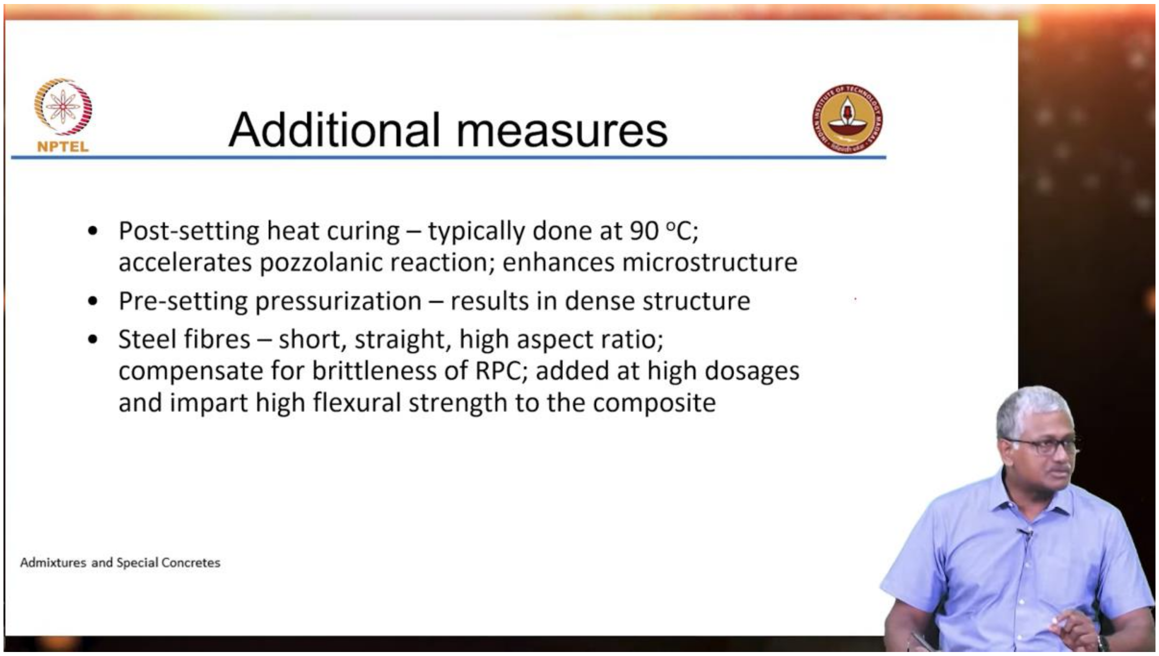

Post static heat curing typically done at 90 degrees Celsius. It is a very high temperature, 90 degrees is a very high temperature, it cannot be sustained for a long period of time.

You can sustain it during the initial steam curing period like in most precast factories. It accelerates the pozzolanic reaction, it makes silica fume contribute something at the early stages and also enhances microstructure. You are further increasing the rate of cement reaction whatever hydration takes place now takes place much faster. The other strategy which we discussed earlier pre-setting pressurization. So, you do not allow voids to form and compact the concrete while it is setting.

So, it results in a dense structure. As I said steel fibers essentially providing ductility to the system and because they are able to bridge microcracks they are also able to increase the strength of the concrete. Generally, in normal cases the use of fibers cannot increase strength or does not increase strength. It increases the extent of deformation achieved by the concrete before failure. How do we define flexural strength of concrete? We define it as modulus of rupture.

Even when you use fibers, modulus of rupture is basically seen whenever the first crack appears. You do not change that at all when you use fibers. But beyond that point how soon does failure happen is governed by the use of fibers. If you do not have fibers as soon as the crack appears the concrete splits. But if you have fibers it will sustain the deformation for a long period of time and you will see major deflections of your beam before actual failure happens.

So here the fibers are actually small enough that they start bridging the micro-cracks and that enhances strength of the system also.

Typical RPC mixture designs:

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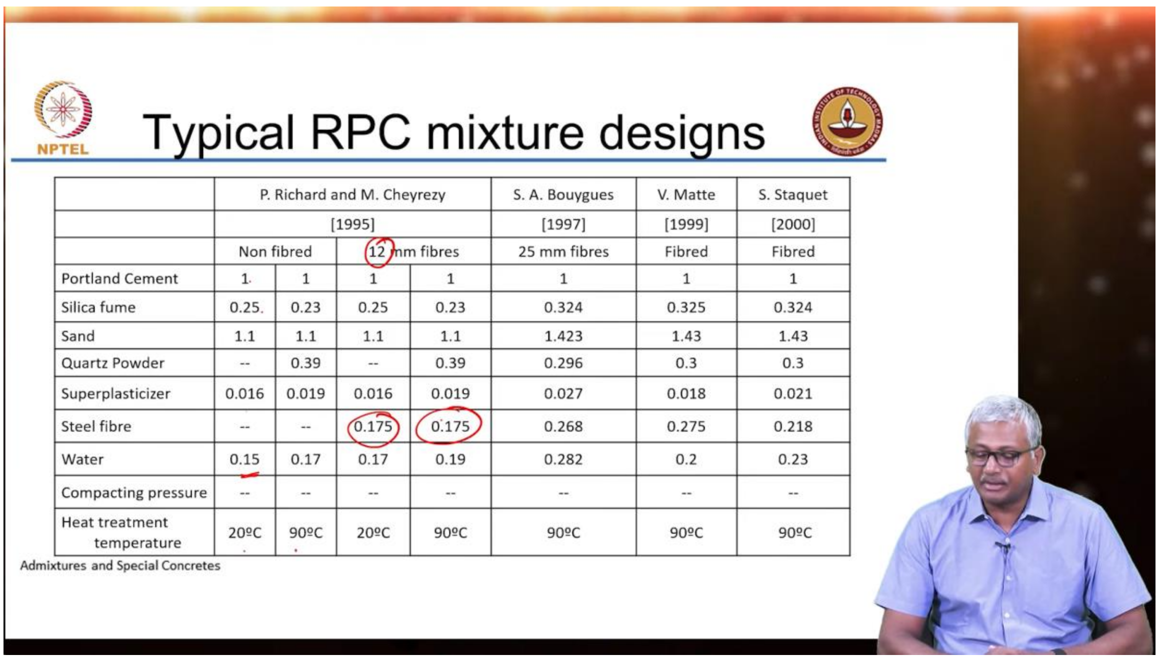

	P. Richard and M. Cheyrezy				S. A. Bouygues	V. Matte	S. Staquet
	[1995]				[1997]	[1999]	[2000]
	Non fibred		12 mm fibres		25 mm fibres	Fibred	Fibred
Portland Cement	1	1	1	1	1	1	1
Silica fume	0.25	0.23	0.25	0.23	0.324	0.325	0.324
Sand	1.1	1.1	1.1	1.1	1.423	1.43	1.43
Quartz Powder	--	0.39	--	0.39	0.296	0.3	0.3
Superplasticizer	0.016	0.019	0.016	0.019	0.027	0.018	0.021
Steel fibre	--	--	0.175	0.175	0.268	0.275	0.218
Water	0.15	0.17	0.17	0.19	0.282	0.2	0.23
Compacting pressure	--	--	--	--	--	--	--
Heat treatment temperature	20ºC	90ºC	20ºC	90ºC	90ºC	90ºC	90ºC

These are some examples of mix designs from literature. Of course, I am sorry that this is not up to date this is up to 2000. But nevertheless, more or less you still have similar designs adopted even today. As you can see here the designs are presented in terms of fractions.

One being cement and all the other quantities are presented in terms of how much they are in terms of cement weight. So for instance here one part of cement- 0.25 parts that means silica fume is to cement is 0.25 is to 1 that is how you need to look at this design.

Sand to cement ratio is 1.1 is to 1 or if you take sand is to cement plus silica fume it is 1.1 is to 1.25. So you can imagine you reduce the sand significantly but you still have quite a bit of sand available in the system. Superplasticizer water-to-cement ratio is 0.15 extremely low water-cement ratio and heat treatment temperatures that were used by these researchers in 95 were 20 and 90 degree Celsius. They also made the same system with 12 mm fibers as you can see the fiber dosage was significant- 0.175 per 1 kilogram of cement, you have 175 grams of fiber that is a fairly high dosage. Considering there are about 800 kilograms of cement in the concrete in this case.

So, imagine you need to multiply this 0.175 by 800 how much does that become? Let us say 150 kilograms the density of steel is about 8000 kilogram per cubic meter. So you are talking here about significantly large amount of steel fiber in your system and that is going to cause tremendous problems with your workability. When you put fibers in your concrete it is going to create problems with workability. So that is why super plasticizer becomes even more important in such a case. So, as you can see most of the systems have similar sorts of mix design except that in some cases there is more silica fume used and so on.

Mechanical properties of RPC:

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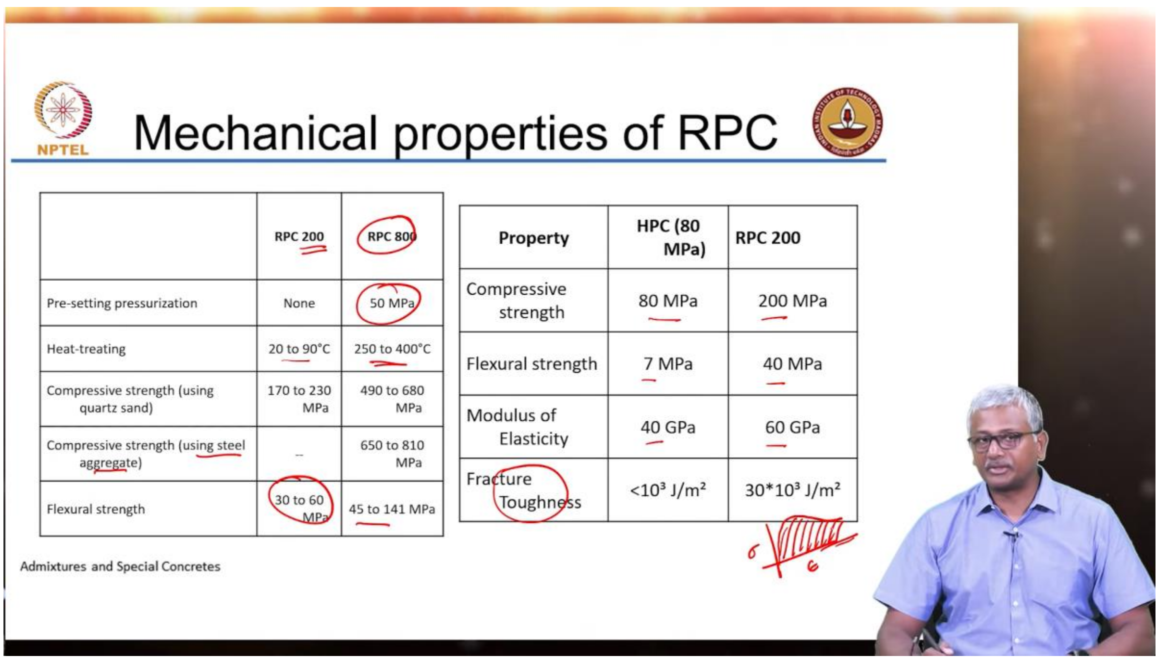

So, from all those papers one thing that you can work out is essentially when you want to produce reactive powder concrete or ultra-high strength concrete of 200 MPa grade. Generally, there is no pre-setting pressurization done here. Heat treatment can be from 20 to 90 degree Celsius from those papers that I reviewed, the compressive strengths are about 170 to 230 MPa. So you do get extremely high strengths.

Flexural strengths 30 to 60 MPa. So now we are talking about a concrete which could be used in some applications without any steel reinforcement. You may not need steel reinforcement in some of the members that we want to design. For instance, when we are talking about designing columns when you use ultra-high strength concrete in columns you could perhaps do without steel reinforcement. In flexural members, it is very difficult to achieve the ductility that you want without really using steel reinforcement. When in compression members you can certainly obtain a very good performance especially when you do not have too much danger of bending by this kind of a concrete.

Now people also attempted 800 MPa concrete. Here, the idea is to use steel aggregate. So you are strengthening your system so much that now you use steel balls in your system as aggregate and you are reaching strength levels of 650 to 800 but nobody is going to do this in reality because your concrete is going to be completely different here. Heat treatment is done at very high temperatures. Your pre-setting pressurization is also 50 MPa stress. So extremely high compaction stresses are applied to obtain that level of strength.

Flexural strength is 45- 141. This is just a research study. It is just not going to have any practical applications where you will find steel aggregate anyway. So just a comparison of properties of high-performance concrete or high-strength concrete and RPC. Compressive strength 80 to 200, flexural strength 7 to 40, modulus 40, 60 so about 1.

5 times more. The fracture toughness, what is the fracture toughness? If you draw the stress-strain curve, fracture toughness relates to the entire area under the system. The entire area under the system is related to the fracture toughness.

Durability of RPC vs HPC:

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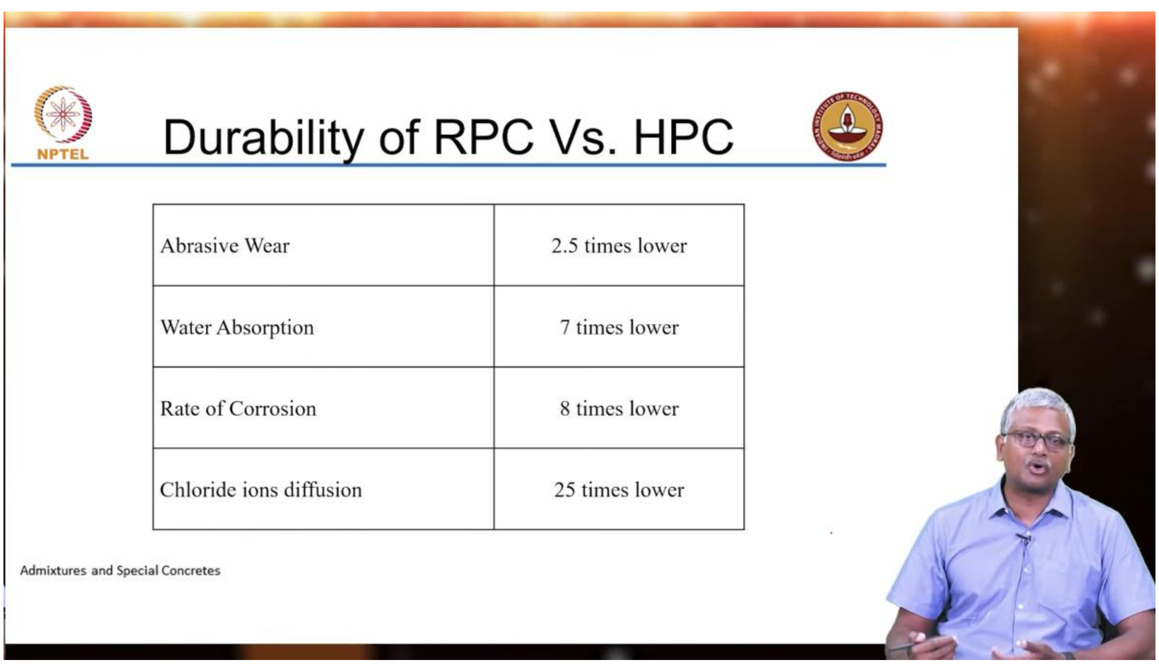

Now in these research papers, they also looked at durability of RPC versus HPC. The abrasion resistance is significantly higher for obvious reasons because you do not have any major difference in particle sizes anymore.

So, you have to actually abrade the material without dislodging the larger particles. See in rocks also, if you think about rocks, each rock has minerals of different sizes, grain sizes are quite different. So, when you cause abrasion of the rock if the grain sizes are too large it abrades easily. So, when you go for grain sizes that are small abrasion happens slowly. So, same thing here in RPC the abrasion resistance is much better, water absorption is much lower because your water-to-cement ratio is too low, rate of corrosion, chloride ion diffusion all of these are going to be extremely low in the case of RPC with fibers.

Now, the interesting part is if you do a test which is based on electrical measurement like rapid chloride penetration test, if you do an electrical based test what do you expect will happen with RPC with fibres? It is not going to be a good result because the fibers are going to conduct the charge. So, you have to choose your test carefully to really show the effectiveness of the system. You cannot choose an electrical test when you have fibres in your system because it is going to show the effect of conductivity of the fibre which is not really going to cause a poorer durability in your system.

UHPC- Stress-strain comparison:

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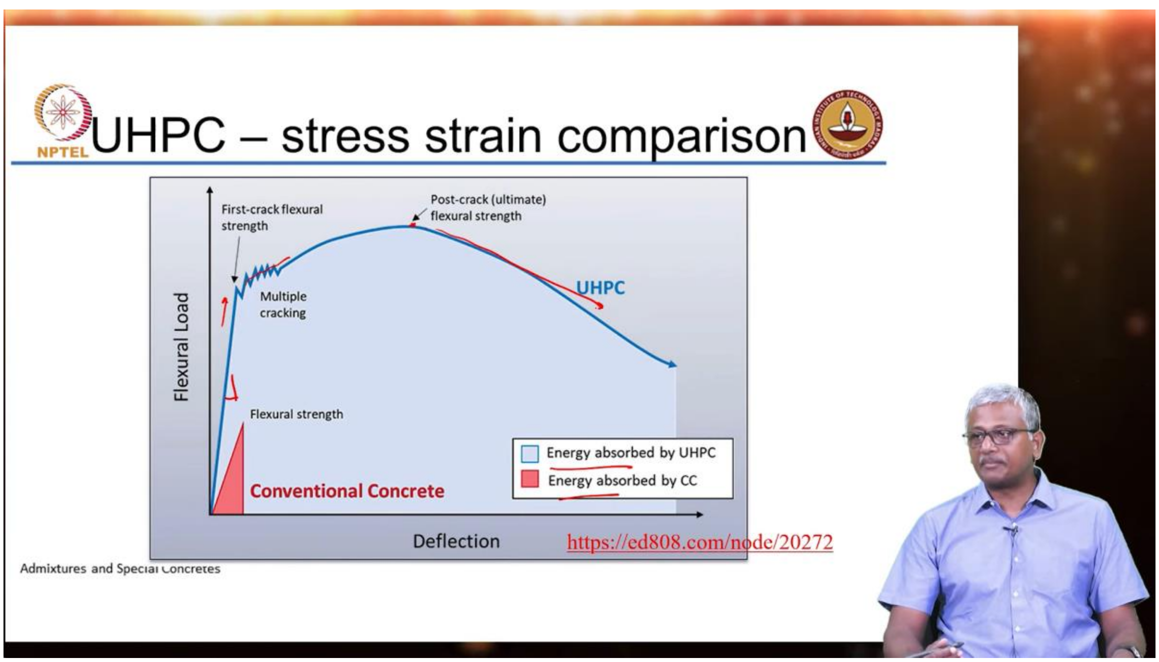

So, this is what I was talking about the fracture toughness is also related to the energy absorbed before failure. So, this is conventional concrete of course this is done in flexure, in flexure conventional concrete almost has a linear stress-strain behaviour.

In flexure, it is almost linear you do not really see the levels of non-linearity that you see in compression. Why because as soon as the crack appears there is immediate failure. But in the case of concrete with fibers and especially in the case of ultra-high strength concrete you are increasing the strength significantly of course modulus is also going up you are getting multiple cracks because of the fibers then you get post-peak deformation which extends for a long period of time and if you look at the overall area under the load-deflection or the stress-strain curve you will see that this kind of concrete has much greater fracture toughness as compared to conventional concrete.

UHPC Benefits- Reduction in section:

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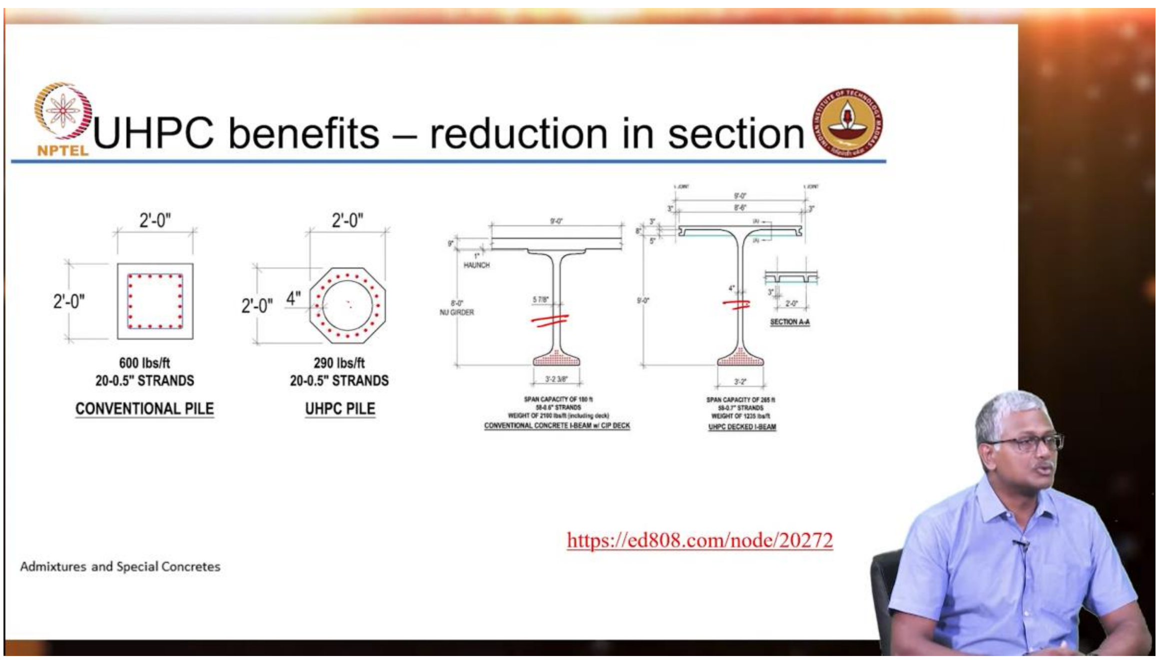

One of the obvious reasons of using high-strength concrete is to lower the size of members you see here examples have been given with a conventional pile of 2 feet by 2 feet I am sorry the numbers are in feet this is an American example so that is why the numbers are in units that are archaic. So here you can see that you have a conventional pile which is 2 feet by 2 feet. The ultra high-performance pile in this example is an annular pile is an empty space inside it is just an annular pile you have reduced the area significantly.

But in girders you can even achieve much better performance this is a conventional concrete, I-beam you can see the it is a pre-stress beam so you still need the pre stressing obviously but look at the size reduction that you have in your system you can really reduce sizes you can make your structures a lot more elegant all these metro structures that we make we can actually make them lot more elegant with the use of higher strength concrete. But it comes with its bag of problems as we discussed earlier if you are not aware of those problems you can create more trouble for yourself.

Limitations of RPC:

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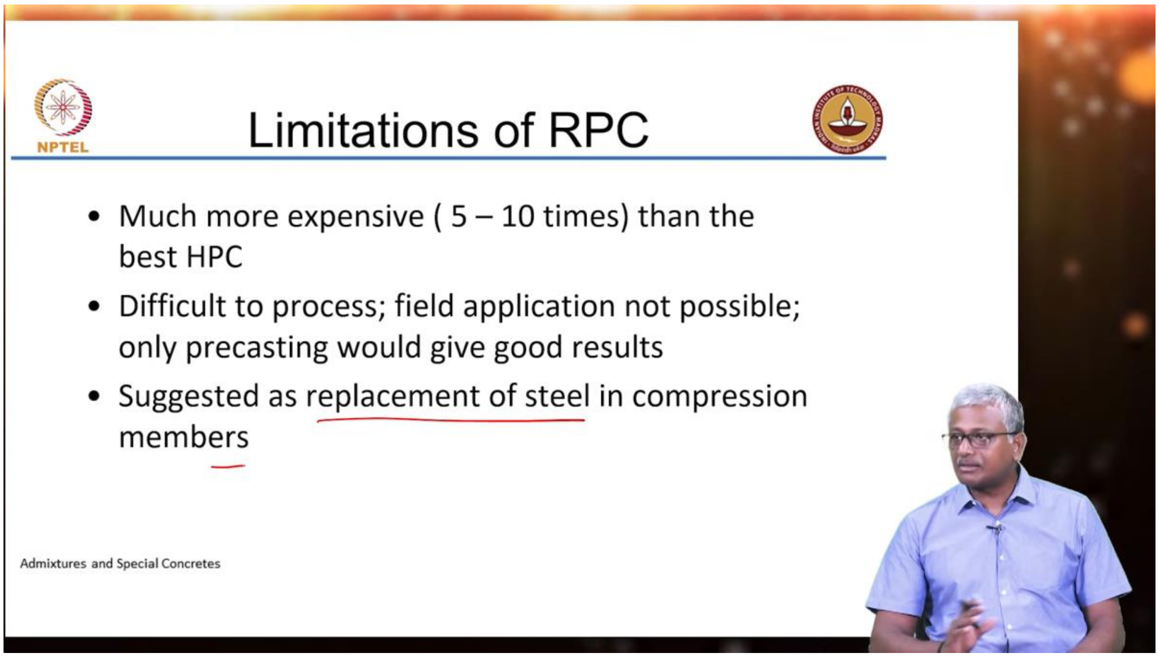

Now, obviously it is quite expensive to use reactive powder concrete it is 5 to 10 times more expensive than high-performance concrete. Processing is extremely difficult imagine working with 0.2 or less water-cement ratio and in Mumbai if they ask you for 3 hours workability retention you can tell them to go to hell it is not going to happen. So, that is why such concretes are possible mainly in precast factories where you have some control and where you do not really need long workability retention.

So precasting would be a good solution for use of relatively high ultra-high strength concrete. Now you can think about using them as replacement of steel and compression members and that could be a very good application because steel has to be protected significantly against corrosion here if you can avoid steel altogether you only have steel fibers do steel fibers corrode? They could but is that a problem? May not be a big problem steel fiber corrosion because there is no connectivity in steel fiber further the amount of aspect ratio is so small that the part that is corroding is not really going to be able to stress the concrete significantly and already your moisture penetration into high strength concrete is so low that you are not really going to sustain that reaction for too long. If you have exposed steel fiber they can corrode but mostly what happens is the steel that is used for these fibers, high strength steel fibers they have much lesser corrosion potential as compared to your mild steel that is used for reinforcement. So, if you go on our road that goes from Mandakini hostel to the research park the slabs are all with fiber-reinforced concrete. In fact, you can actually see some steel fibers on the top surface they are not corroding.

There is no corrosion there. So, depends on the material of the steel fiber the high-strength steel fibers which are typically used in such applications they generally have a very low tendency of corrosion.

Applications of RPC:

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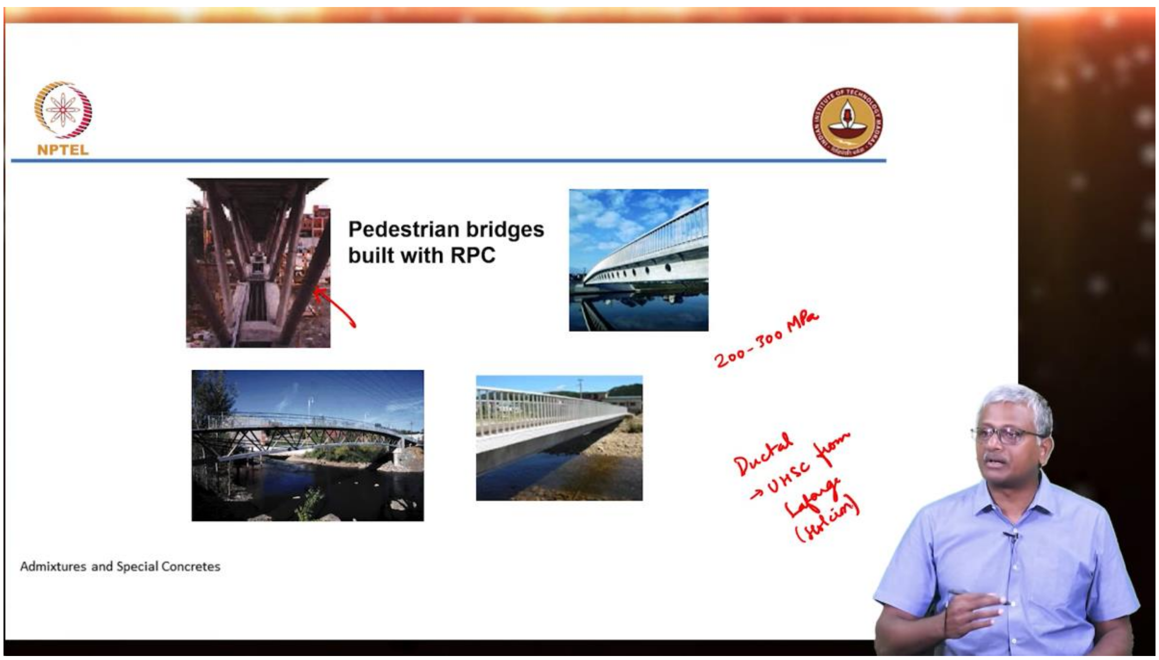

So, there have been applications such as pedestrian bridges where concrete strengths of 200 to even 300 MPa have been obtained. In this case, these tubes were actually filled with concrete so that confinement with the tube further enhances strength of the concrete to 300 MPa. Now, obviously people are not brave enough to risk an entire roadway bridge without the use of reinforcing steel. So, it will take a long time before somebody can convince to use concrete with just fiber reinforcement even in members that are subjected to flexure that will take some time.

So, that is why these are all pedestrian bridges you do not really have applications of actual road way bridges. But post-tension bridges why not you can definitely do it there is no problem at all. So, you can look at this material called Ductal is the ultra-high strength concrete from Lafarge. Now it is Holcim. There is also a company in India which deals with ultra-high strength concrete it is based out of Pune and they do a lot of work with use of high-strength concrete in various different applications.

Experimental study at IIT Madras:

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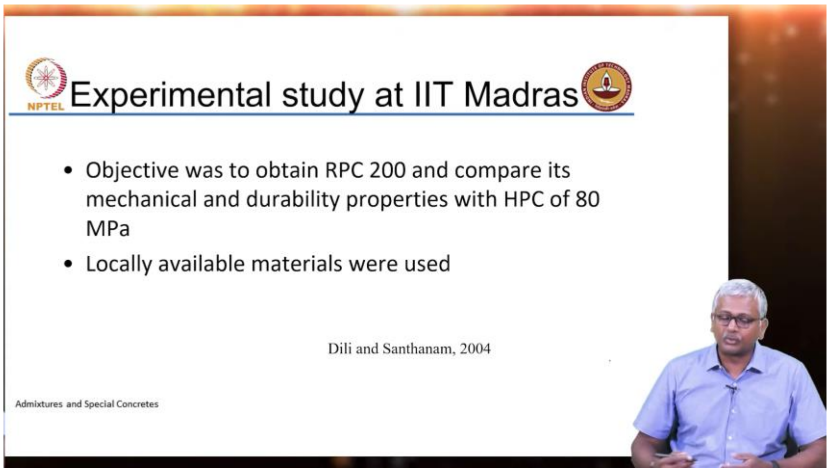

So, I am going to leave this last part for you to study on your own basically it is from this paper which one of my master students worked on. I will have that paper also uploaded for so that you can understand the details of this.

Materials Used:

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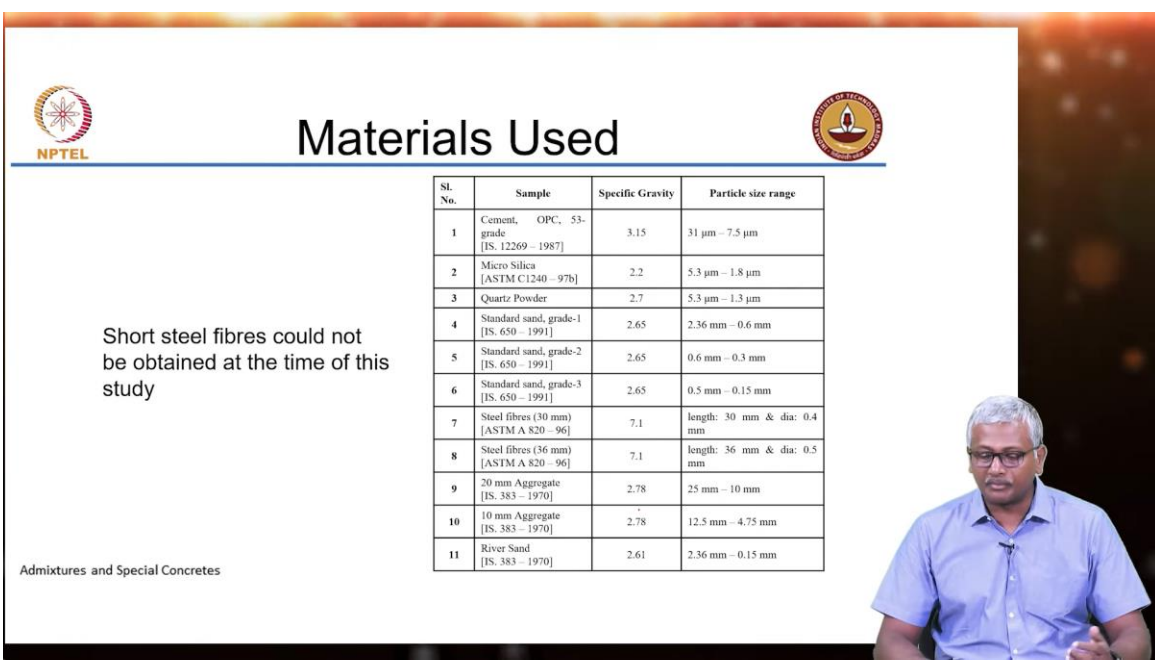

So here it just talks about the mix designs more or less similar to what you already saw from my examples in literature. The problem here was the fibers could not be obtained at that point of time the microfibers so we worked with conventional steel fibers that was a major limitation of the study.

Mixture Design:

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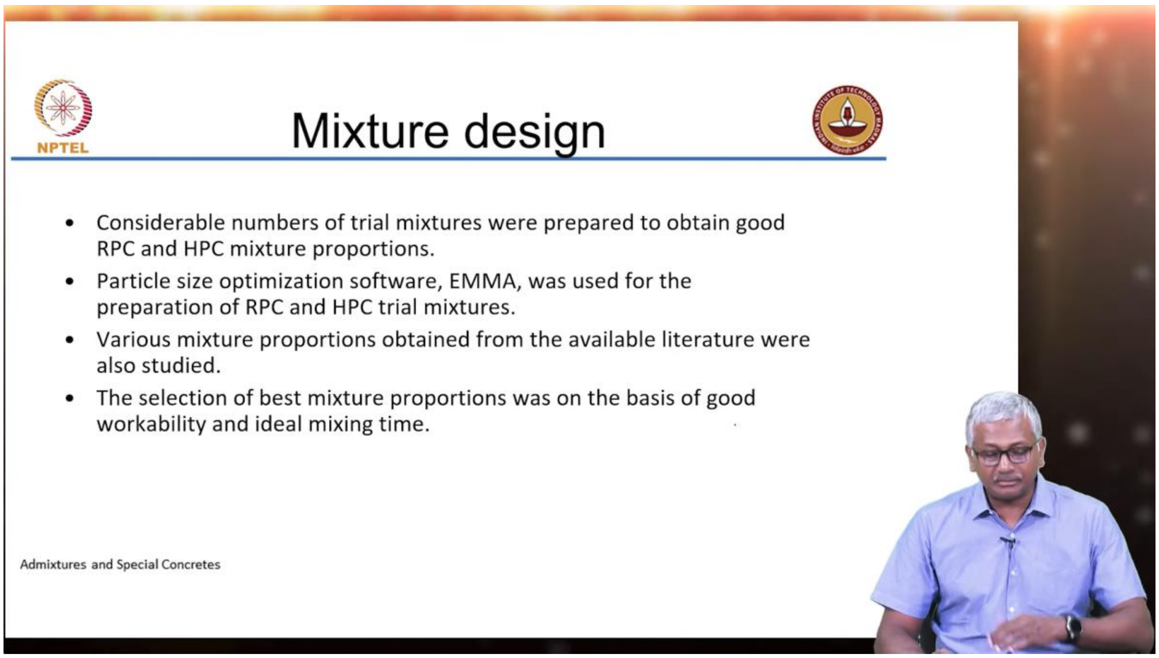

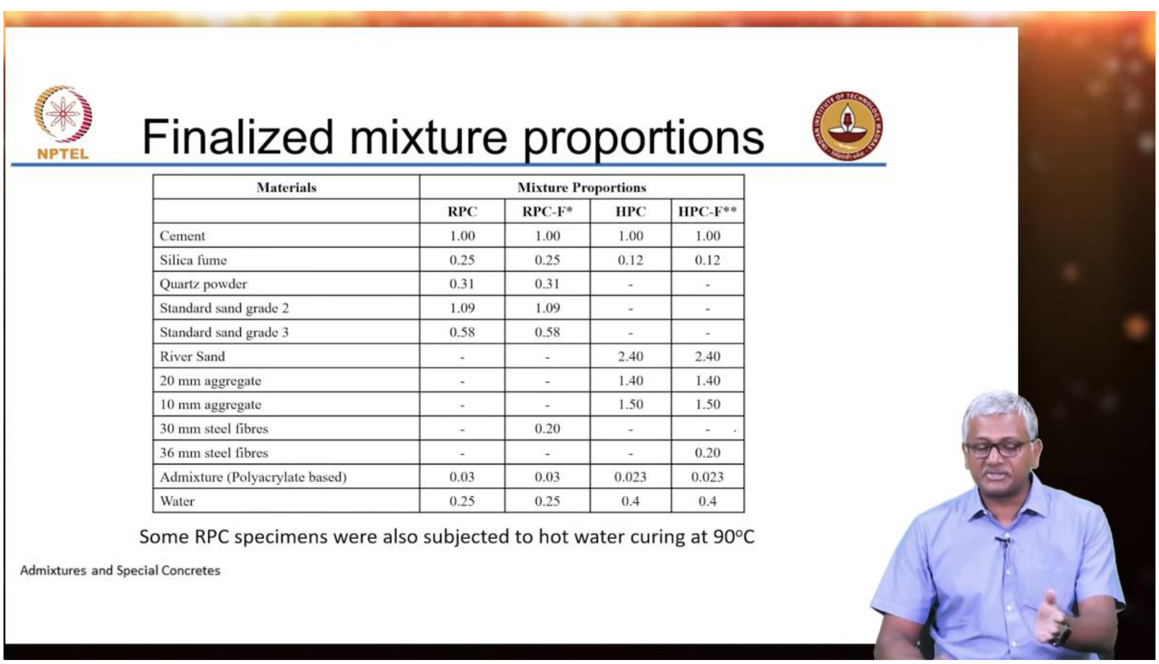

And again RPC and high-performance concrete were compared in this and you can see the mix designs also given there.

Fresh concrete properties:

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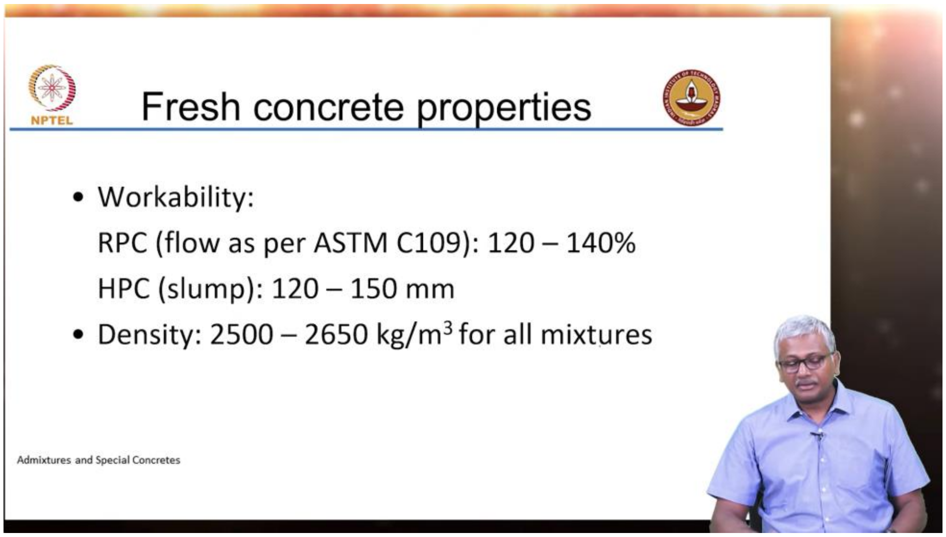

The range of workability that was desired was in terms of flow in reactive product concrete and slump in high-strength concrete or high-performance concrete.

Results:

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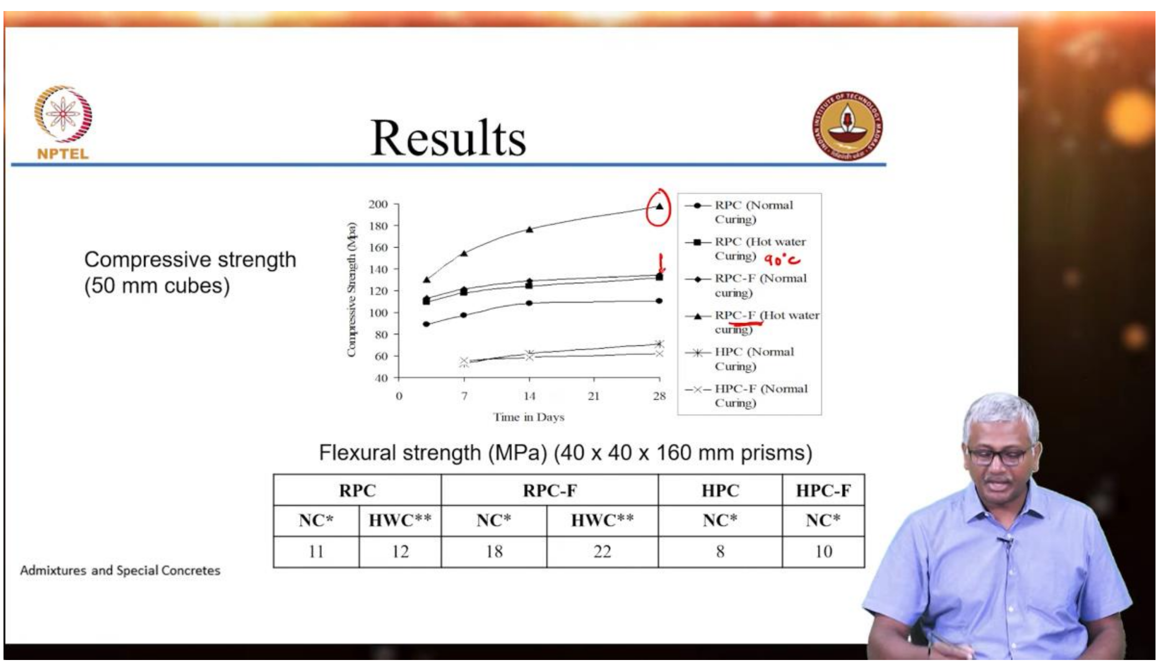

RPC		RPC-F		HPC	HPC-F
NC*	HWC**	NC*	HWC**	NC*	NC*
11	12	18	22	8	10

So, the results you can see that with hot water curing at 90 degrees Celsius at 28 days we could achieve close to about 200 MPa strength. The same concrete without any hot water curing so this is the RPCF that means the RPC with fibers in hot water curing. So with normal curing the strength was about 130 MPa so it is still significantly high but you do need that heat treatment to enhance the strength significantly. And flexural strength you can see we could achieve with hot water curing with fibers of up to 22 MPa not as large as what was shown in literature again because the limitation of the fiber lengths we had long fibers in this case.

Rapid chloride permeability test (ASTM C1202)

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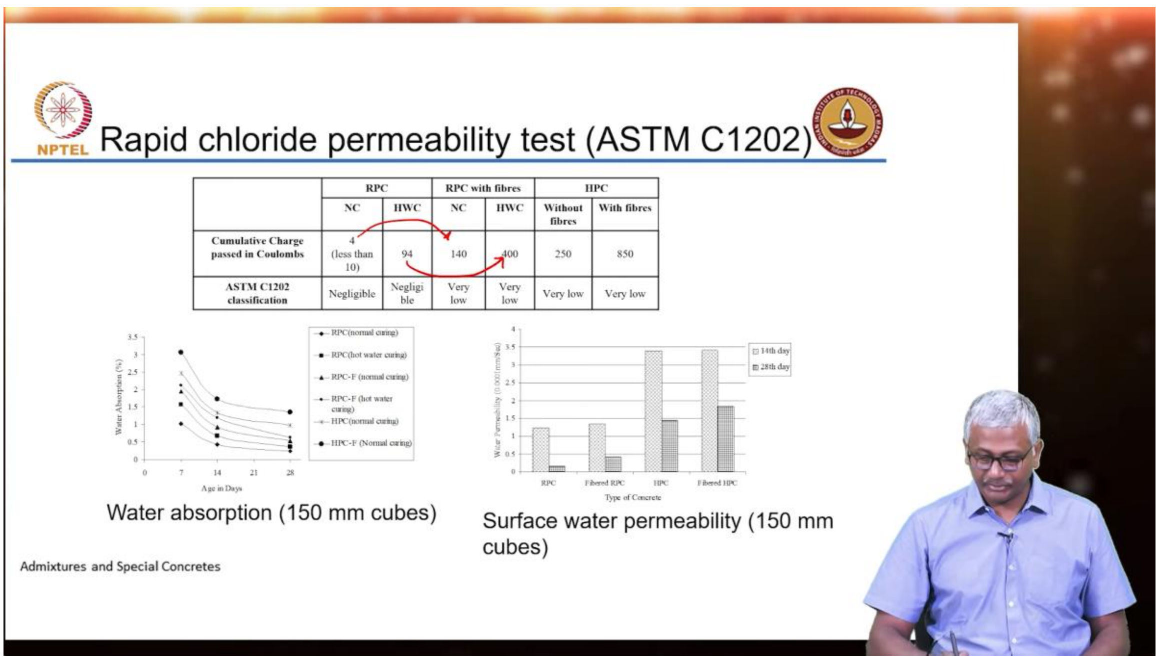

So, again durability as you can see very clearly water absorption and water permeability were very low but interestingly again cumulative charge passed in coulombs you can see with fibers the number went from 4 to 140, 94 to 400. You can see the effect of the conductivity of fibers brought in into the RPC with fibers.

Conclusions from experiments:

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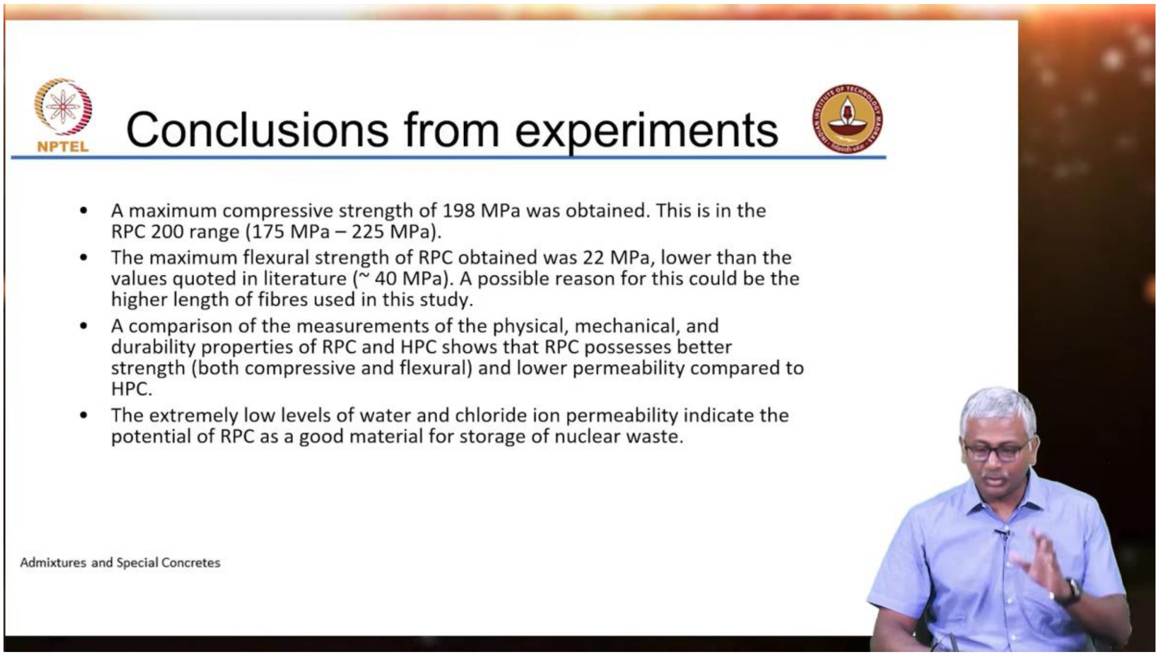

References:

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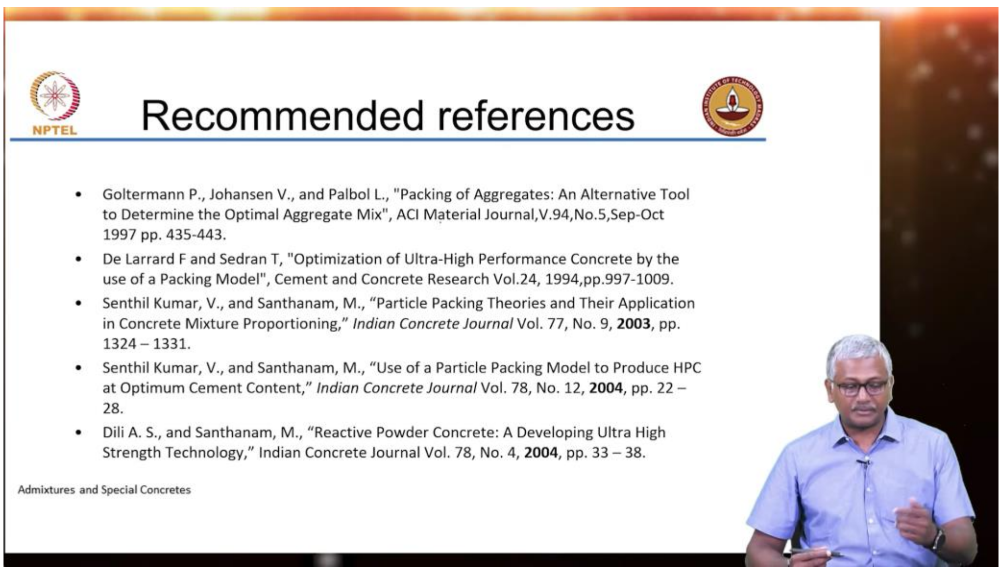

So, I will stop with that there are several references that I have used in this chapter primarily dealing with particle packing and how to design concrete with lower cement contents by the choice of particle packing and also the RPC paper which I will also have uploaded to the Moodle system. Thank you.