Hydration, Porosity and Strength of Cementitious Materials

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Lecture – 28 to 30
Mineral Admixtures

Hi good morning to one and all. I am K V Harish assistant professor department of Civil Engineering IIT Kanpur. You are watching MOOC lecture course on hydration porosity and strength of cementitious material. Today we will see lectures 28 to 30.

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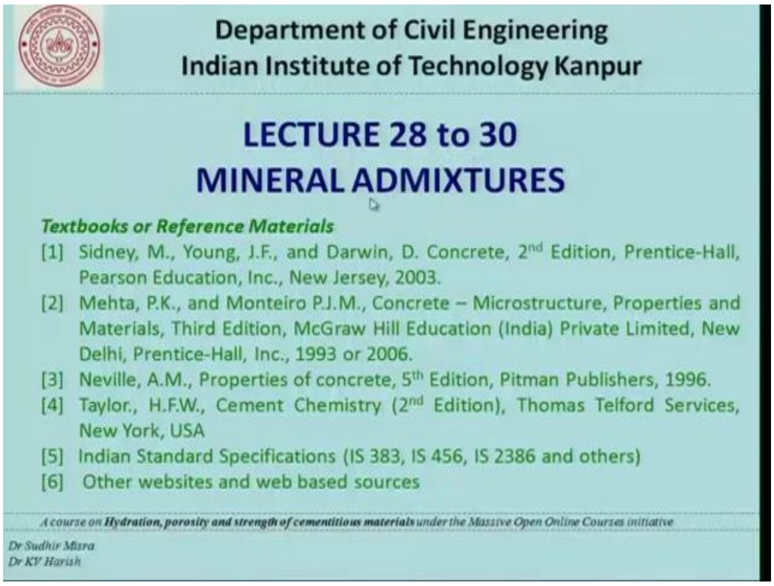

Remember that in this in this lectures 3 lectures are together combined 28 29 and 30 together. And the main topic is mineral admixtures and in the previous topics we have extensively seen production and properties of fly ash and how the properties of fly ash actually influence the properties of Portland cement based paste systems.

In this lecture we will see a largely about a silica fume and slag. And we will initially goead with silica fume and see a similar to fly ash how each of those properties get affected because of the addition of silica fume. And then we will go on to slag and then compare the performance of all the different pozzolans or with respect to control mixtures. Now for this lecture the textbooks or reference materials are shown.

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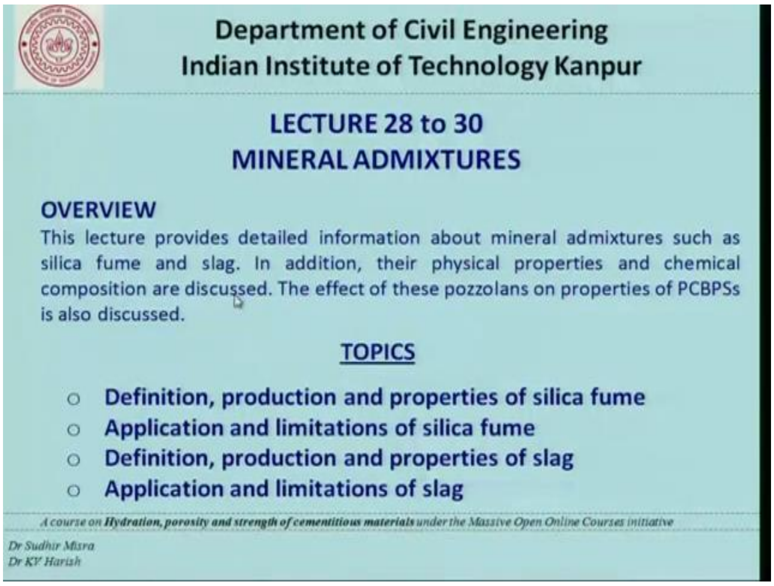

So, the overview of the lecture is as follows this lecture provides detailed information about mineral admixtures such as a silica fume and slag. In addition, their physical properties and chemical composition are discussed. In the previous lectures we have seen fly ash extensively primarily the physical properties chemical composition. In addition to how the influence properties of Portland cement Portland cement based paste systems. And in this one we will see the chemical properties and physical properties of silica a fume and slag and the effect of these pozzaolans on properties of Portland cement based paste systems is also discussed.

So, under silica fume what we will see is what is the appropriate definition of silica how silica fume is produced and what are the properties of silica fume. And what are the applications of silica fume and any limitations with pozzolan. Likewise, we will see similar top topics for slag also.

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So, we will now start with silica fume. So, production of silica fume first of all definition what is meant by silica fume. Silica fume is a byproduct of the smelting process in the production of silicon metal and ferrosilicon alloys that contains more than 75 percentage silicon. So, by definition silica fume is a byproduct in the production process of silicon metal and ferrosilicon alloy.

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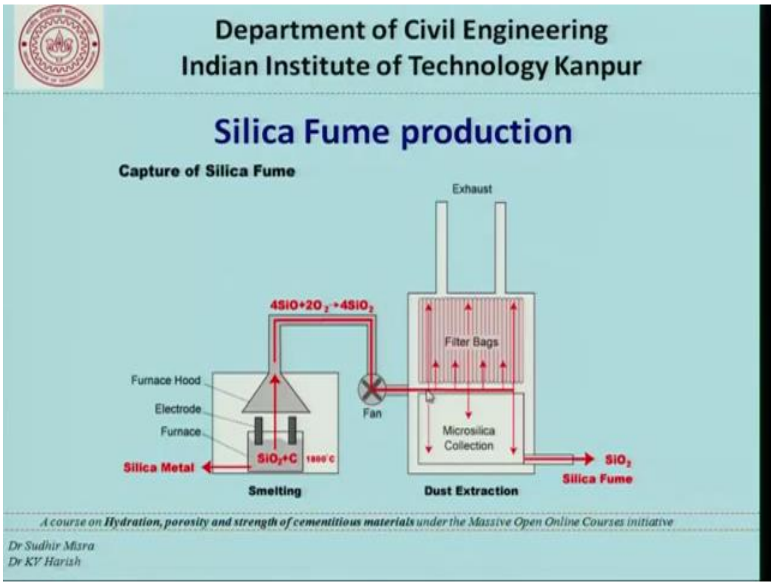

Now, if you get into the production of silica fume, basically you have 2 different process one is the smelting process the other one is a dust extraction. And what usually happens that this smelting process involves heating to 2800 degree Celsius and basically the silicon and the carbide that is present in the in the metal, in the metal ores they basically get heated and SiO plus O2 gives for SiO 2 which is silicon dioxide and the other silica fume which is actually fine particles they are actually captured in filter bags before they get off to the exhaust. And those particles which actually fall down which is actually called as the microsilica they are called as silica fume. So, many time silica fume is also known as microsilica

So, typical the size range of silica fume is extremely smaller. So, we will again when we go to physical properties we will see what is the fineness and particle size and other information. So, what you get out of the smelting process is primarily the silicon metals. Because the ores which contains impurities primarily the carbide they gets they get removed and the setup shown here involves some electrode and furnace and other such arrangements are used in the production of silicon metal.

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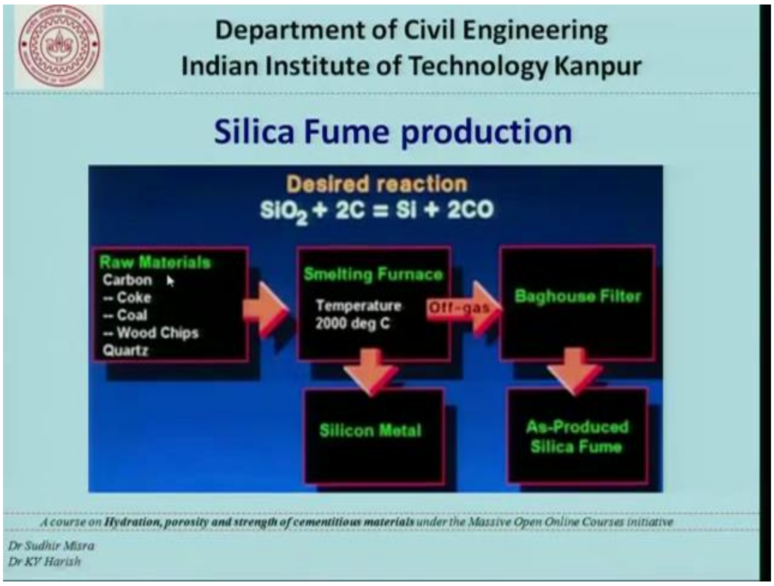

Now, more information about what are the raw materials that are used in the silica fume production and others. Raw material such as carbon and quartz are used and the primary source of carbon is coke coal or wood chips. And primarily they are subjected to very high temperature a this melting furnace usually it ranges from 1800 degree Celsius to about 2000 degree Celsius.

Sometimes the furnace temperature is not the temperature used in the smelting process is not a very precise in some cases they use 1800 in some cases they use 2000, but it is much higher than the conventional temperatures that are used in the coal production process or others. And in in the process as we have already seen you have a filter bags that is one the other one is the silicon metal which is extracted, and remember that silicon metal is actually the main element which actually comes out and silica fume is actually byproduct from the silicon metal extraction.

So, finally, what you have is a silica fume and the reactions which we have seen previously is again once again shown for easy understanding. Basically the silica SiO 2 reacts with carbon to form pure silica and the carbon monoxide that forms gets out into the atmosphere.

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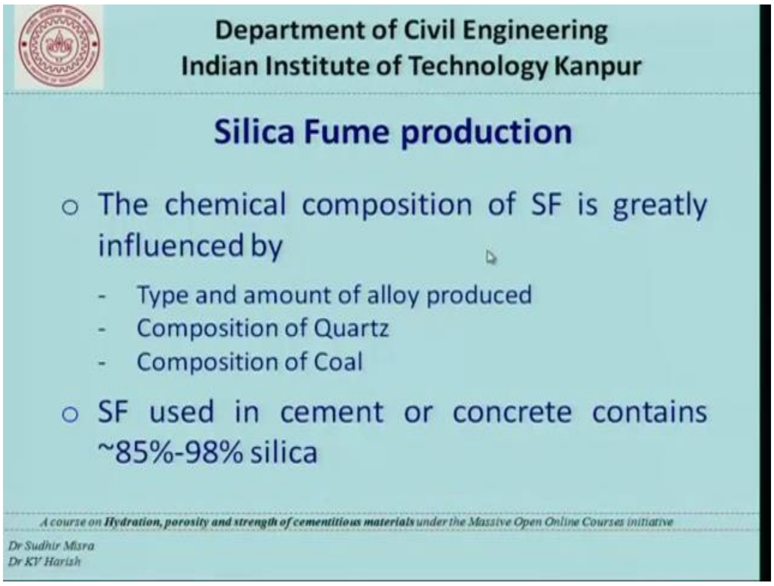

Now, very many information about the production of silica fume is not required for this course, because what is more important for this course is primarily the physical and chemical properties of these material and how it influence the properties of Portland cement based paste system. So, production primarily is important only from the standpoint of what are the temperatures that are used and what types of reaction takes place and what are the raw materials used and such things. Now having seen the production of silica fume we should also know that the chemical composition of silica fume is highly influenced by several factors number one, the raw materials that you use and hence their composition also, like for example, you use quartz you use coal which is source of carbon and hence their composition also has immense effect on the composition of silica fume.

In addition to that the type and amount of alloys that are used also has substantial effect on the chemical composition of silica fume. We will see the chemical composition little later, but these are important factors from the production plant which can actually influence the properties of silica fume. Now typical is silica fume used in cement or concrete applications ranges between 85 percentage to 98 percentage silica.

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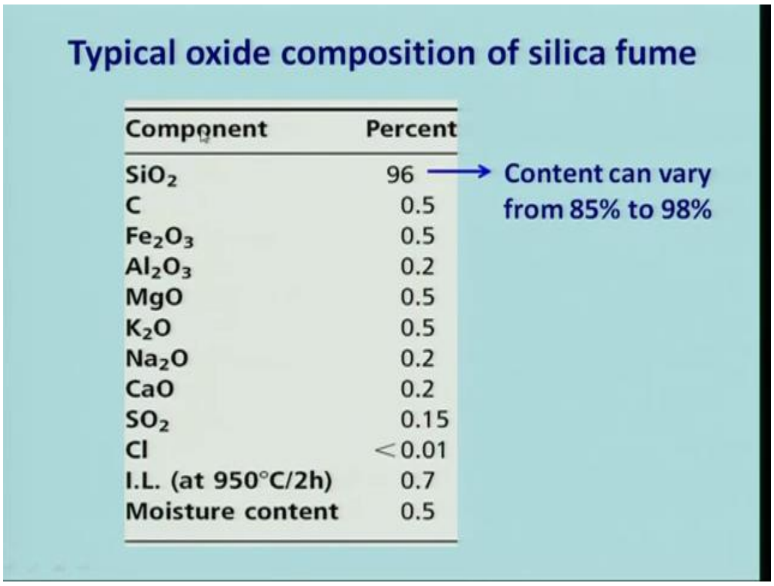

Typical oxide composition of silica fume

Component	Percent
SiO_2	96
C	0.5
Fe_2O_3	0.5
Al_2O_3	0.2
MgO	0.5
K_2O	0.5
Na_2O	0.2
CaO	0.2
SO_2	0.15
Cl	$<$ 0.01
I.L. (at 950°C/2h)	0.7
Moisture content	0.5

So, now we will go to the typical oxide composition of silica fume, and what is shown in this table is that here you have component where the oxides are listed. And at the bottom you have some information about chloride moisture content and others. And here what is presented is the percentage of oxides and what we find is that the silicon dioxide is typically 96 percentage whatever is shown in this figure, but remember that silica fume could actually range from 85 percentage to 98 percentage depending upon all these factors.

So, one should not directly take 96 percentage as a very stiff value to understand the percentage of silica fume that silica that is present in silica fume. So, and if you take the remaining oxides, if you take carbon or iron aluminum or magnesium all other oxides are typically present in very low amounts. And remember that the carbon is a very important factor for this particular case alone what we can see is since the silicon content is extremely high the carbon content is a lower, but if the production process does not have refined a system, in the capturing process of a silica fume what tends to happen is carbon in the raw material will stay in the silica fume.

So, in such cases the carbon content will be much higher and the in for the same cases the silicon dioxide content will be much lower. So that is where the importance of this range comes into picture now all other oxides in any cases are usually at very low amount. So, they are not a very big factor in it. So, primarily the 2 things that comes in the picture is a silicon dioxide and carbon.

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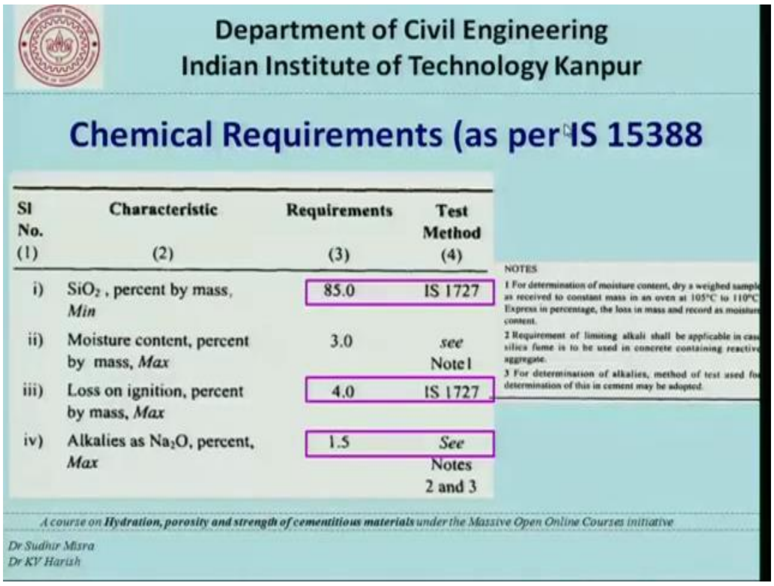

Now, when it comes to chemical requirements, as I have already mentioned in a couple of lectures before for a pozzolanic materials like silica fume we have IS 15388, which primarily gives more information about the chemical requirement.

So, what is specified in the code is actually shown here. So, if you take a silicon dioxide content. So, if you want to use silica fume from a particular source. We have to make sure that the minimum amount of silicon dioxide should be 85 percentage. If you have much lower than that it actually does not qualify to serve as a pozzolone in cement based paste system. So, what is has specified is that the minimum quantity should be 85 percentage. And the other specifications are also given and the probably the other most important things or the loss on ignition which is 4 percentage maximum. And alkalis which is 1.5 percentage maximum. So, these all other important thing sometimes these limit is could be substantially higher. And remember that loss on ignition is a function of the carbon content. Higher the loss on ignition usually indicates the indicates that the carbon content in the pozzolone is higher.

So, is has safely mention the maximum limit of 4 percentage for loss on ignition. Likewise, if alkalis are actually present in excess amount that is also a problem primarily from the standpoint of alkali silica reaction. Because in alkali silica reaction distress the internal sources of alkali can cause can react with the reactive aggregates present in the Portland cement based paste systems and they can form alkali silica reaction gel which will eventually leads to lead to cracking of the system. So, from alkali silica reaction standpoint it should be restricted it should make sure that the alkalis are restricted to 1.5 percentage, but remember that alkali silica problem. Alkali silica reaction problem will exist only the aggregates or reactive in nature, if the aggregates are a non reactive in nature still if the non if the aggregates are non reactive in nature then the issue of alkali silica reaction does not come into picture. In that case even higher amounts of alkalis is fine with the system.

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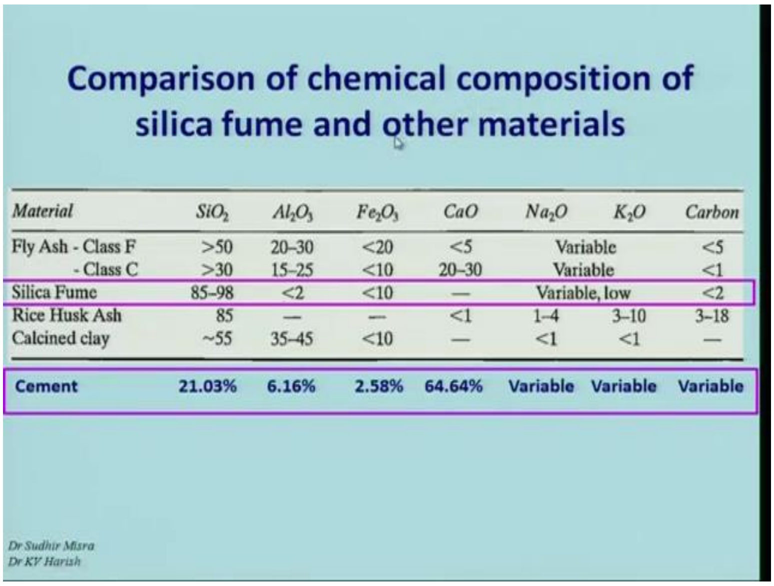

Material	SiO_2	Al_2O_3	Fe_2O_3	CaO	Na_2O	K_2O	Carbon
Fly Ash - Class F	>50	20–30	<20	<5	Variable		<5
- Class C	>30	15–25	<10	20–30	Variable		<1
Silica Fume	85–98	<2	<10	—	Variable, low		<2
Rice Husk Ash	85	—	—	<1	1–4	3–10	3–18
Calcined clay	~55	35–45	<10	—	<1	<1	—
Cement	**21.03%**	**6.16%**	**2.58%**	**64.64%**	**Variable**	**Variable**	**Variable**

Now, coming to the chemical composition of silica fume and comparing it with the other mixtures and primarily what we are doing is comparing with the cement. So, what we find is that the silicon dioxide typically is 80-85 to 98 percentage and it is a substantially higher compared to cement. While the cement has higher calcium oxide content the calcium oxide content typically in silica fume is either 0 or it is very little quantity. And these the silicon dioxide and calcium oxide are primarily the oxides which are actually comparable with the cement. All other things that are not much limit is that are provided and it could actually vary depending upon the production process and several others. And not only that all the other oxides are also less in quantity compared to silica and calcium oxide.

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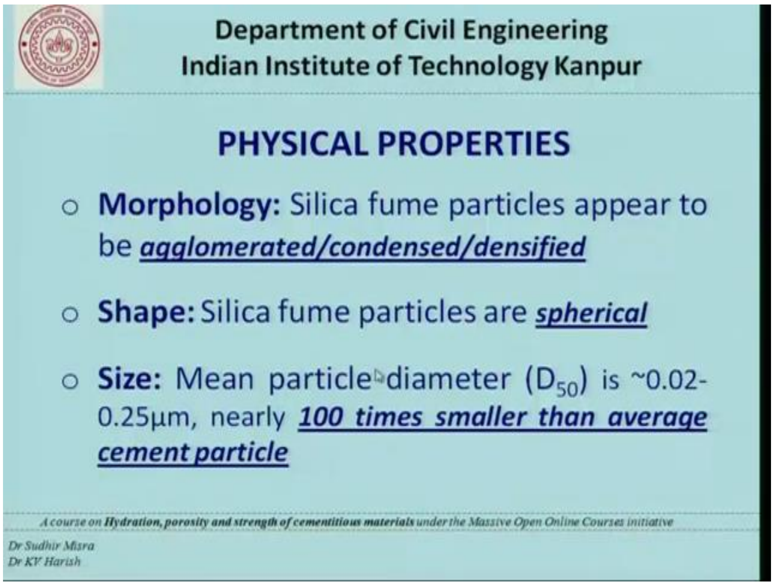

Now, coming to the physical properties of silica fume some of them are discussed one is morphology. So, silica fume particles appear to be agglomerated or condensed or densified; that means, silica fume practices are not present as a individual particles. They basically stick with each other and they are generally found in the densified or condensed form this primarily happens because if there are moisture that is present in the atmosphere. They attend to a they tend to have they tend to attract the moisture and all the silica fume particles generally agglomerate with each other.

Now, the second one is shape the silica fume particles are generally found to be spherical in shape. Remember that we have also seen fly ash which are actually spherical in shape. So, like fly ash we cannot also see the spherical shape of silica fume in our naked eye primarily because the silica fume particles are very fine in very high fineness or the particle size is too small to see in the naked eye. So, the shape of silica fume particle is spherical like fly ash. How are if you take cement the particles are angular in shape. So, if you compare the shapes of different materials that we use in Portland cement based paste systems, you find that some maybe angular some maybe a spherical. So, maybe some maybe some other shapes so, but the shape can actually substantially affect the properties or it can also improve the properties.

So, let us see how you whether shape is a important factor for silica fume or not in affecting other properties. Now if you go to the size of a silica fume particle are the mean particle diameter d 50 is approximately in the range of 0.2 0.25 micron meter. So, this if you can imagine this is something like hundred times smaller than the average cement particles. So, if you get back to the fly ash lectures that we saw in the previous 3 to 4 lectures what we will find is that the particle size distribution of cement is similar to the particle size distribution of fly ash. And many times the fly ash can have particles size 12 to 45 micron when I say particle size I am talking about d 50. So, it can be between 10 to 45 and many times it can also be lower than 10 microns.

Typically, the average particle size of cement is in the range of 10 to 30 or 40 micron meter. So, fly ash and cement as similar particle size distribution, but when it comes to silica fume the silica fume particles are hundred times smaller than that of the cement particles. And what is specified here is the range is 0.2 to 0.25 microns. So, that that is a very small size in terms of when it comes to using it as pozzolone in Portland cement based paste systems. The morphology of silica fume particle as I already mentioned the shape cannot be seen through naked eye.

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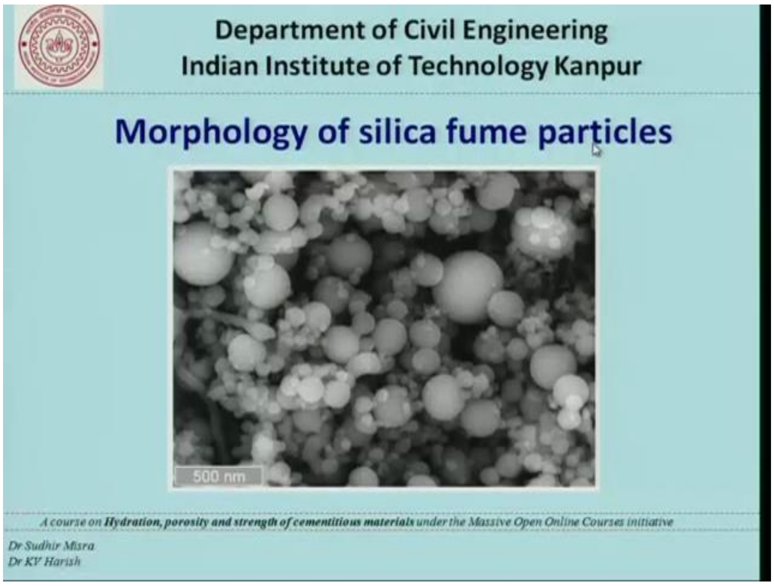

So, a scanning electron microscope image is shown where you can see that at a 500 nanometer level we can see that the shape of the silica fume particles are spherical. And remember that this is 500 nanometer is 10 power minus 9 meters. And what we also see is the agglomeration that is few particles together join I mean particles together join with each other and they are generally seen as agglomerated or condensed or densified form. So, that is what is can be observed from this figure.

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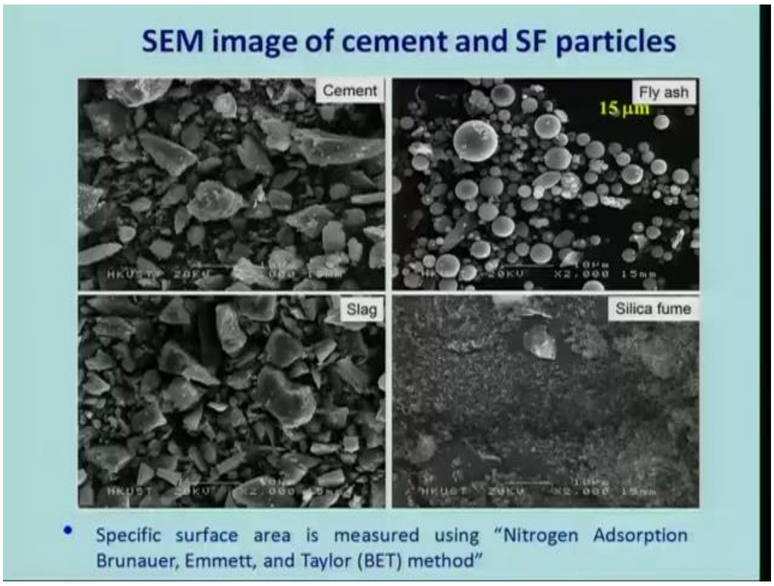

Now, if we want to have a comparative image of say cement and silica fume particle along with fly ash. Remember that slag is also included here, but we will slag as little later. So, if we want to compare all these materials together at the microstructure level and remember that we are talking only about the dry powders. So, in the case of cement you find that the particle size are typically angular in nature. So, we cannot simply assume cement particles to be spherical in shape it is it is not appropriate. So, at the micro level it is purely angular in shape and in the case of fly ash you find that it is more or less spherical in shape and of course, you have again cenospheres fluorospheres and several things and again cenospheres you do not have anything inside it whereas, fluorospheres you have multiple balls inside this. So, largely fly ash contains more amounts of fluorospheres compared to cenospheres.

So, these are some of the images typical images that we see for fly ash. And if you have a look at silica fume you are not even able to see the particular size or shape of silica fume. Remember that all these figures are taken at same magnification. So, if you carefully look into the figure there is a magnification level that is indicated. In all these figures the magnification level is 10 micron meter. So, if you typically look at a 10 micron meter you will be able to appreciate the shape of fly ash appreciate the shape of cement and appreciate the shape of slag whereas 10 micron level the silica fume particles cannot be visualized cannot be even seen cannot be observed. Because the particles are one by hundreds of the size of the cement particles as we just saw couple of slides before.

So, remember that the slide that we discussed in the previous slide this is at 500 nanometers which is much higher magnification compared to this 10 micron meter. So, at the same level we cannot see what is the shape of silica fume and still higher magnifications are required to understand that it is also spherical in shape. Now other information about slag even though we are not dealing slag right now, we will deal little later, but the slag is generally angular in shape similar to cement. And usually slag is available as the particle size distribution of slag is much higher than cement and fly ash and silica fume and hence many times grinding process is used in order to make the slag finer.

So, we will again discuss about all these things when we come to slag. As of now what we can see in the end at a comparative magnification of say about 10 microns the silica fume particles are typically not visible all that you can see is only small clusters of silica fume particles densified together.

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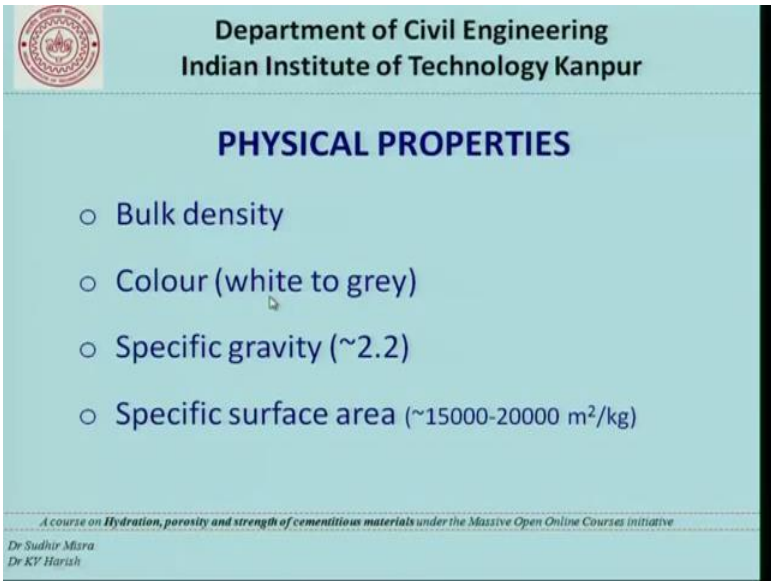

Now, other physical properties may include bulk density color. And the when it comes to color you have to understand that the color could be between white or grey either it could be white also it could also be grey depending upon the percentage of iron and carbon present in the silica fume. If carbon is present in very low quantities, then the silica fume will appear to be white. Usually the iron content is very less in silica fume unlike in Portland cement. And the third one is specific gravity and the specific gravity of silica fume is approximately 2.2 and usually the specific gravity does not change very much like what we have seen with fly ash because with fly ash we typically the specific gravity ranges from 2 to 2.8 we do not find that much variation primarily because the oxide composition of a silica fume largely contains silicon dioxide and you do not have much oxide much other oxides. And the with respect to specific surface area typically it is found to be in the range of 15000 to 20000 meter square per kg.

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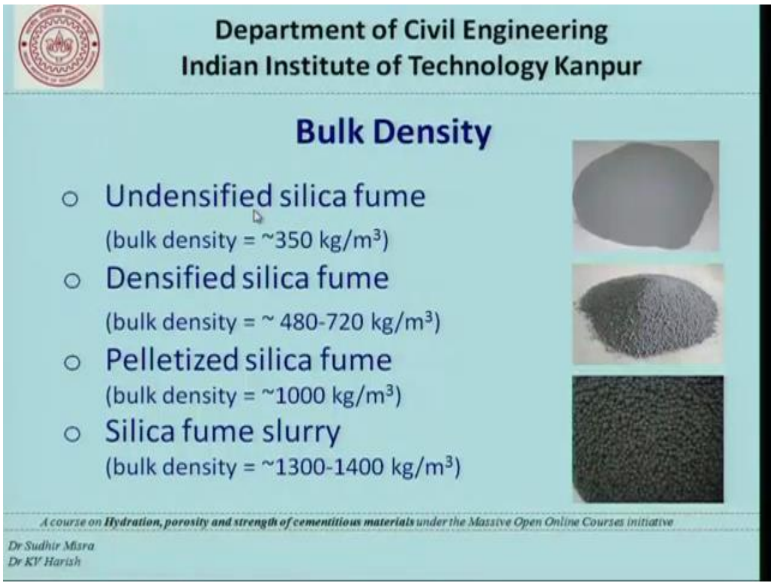

So, this is the very important value. Now we will get into some of the physical properties in detail. Now bulk density now there are silica fume may be available in 4 different forms. One is undensified form the other one is densified form the other one is palletized form the other one is a slurry form. So, there are 4 forms of silica fume which we generally find from the power plant one undensified silica fume is when all the particles are completely separated and they are not agglomerated like this. So, the photograph of the undensified silica fume is shown and densified silica fume is shown that you can clearly observed that small particles are combined together in the condensed form. And for better reactivity we always prefer silica fume to be in the undensified form.

But when you have silica fume in the undensified form. And if it is exposed to atmosphere slowly it also comes to the densified form. So, we have to be careful a little more careful in storing silica fume. Now the third one is actually pelletized form in which we can add a little bit of water and make it into bigger globules and those globuse are generally referred as pellet us. So, you can we can have such type of silica fume also. And they can be also used if it is properly produce they can be also used as a fine aggregate replacement or coarse aggregate replacement material.

Now, in addition to this 3 we can also add substantial quantity of water and make it into a slurry form. And remember that in all the 4 forms the bulk density changes because the topic is primary bulk density and we have to know that the bulk density changes depending upon the different forms of silica fume in a case of intensified silica fume approximately it is 350 kg per meter cube. In the case of densified silica fume it ranges from 480 to 720 kg per meter cube. In the case of pelletized silica fume it is approximately 1000 kg per meter cube and when it is in the slurry form it is 1300 to 1400 kg per meter cube.

So, these are some of the ranges that you may have to remember if something is asked in the assignment or examination, and of the 4 forms usually silica fume to be in the densified form which is for which the bulk density typically varies from 480 to 720 kg per meter cube.

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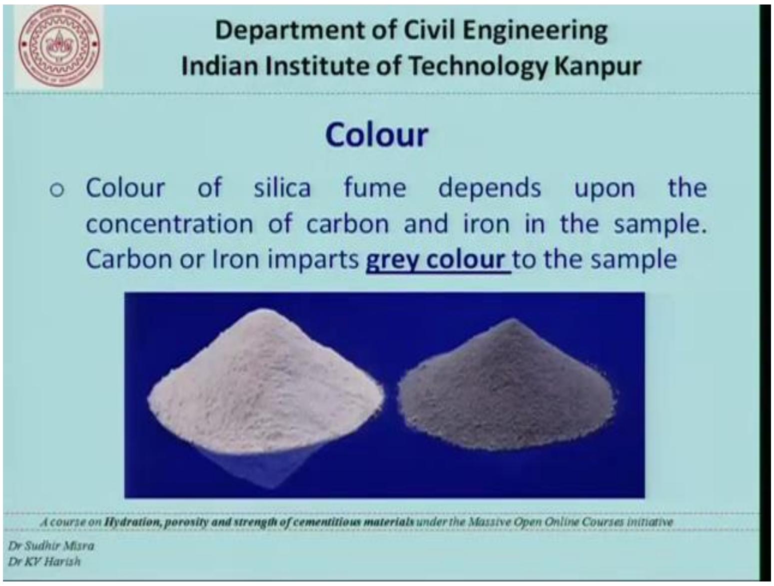

Now, coming to the second one color has already mentioned the color could be either white or grey in color on dark green color, largely we find that silica fume is dark grey in color and that is primarily because of carbon or iron content.

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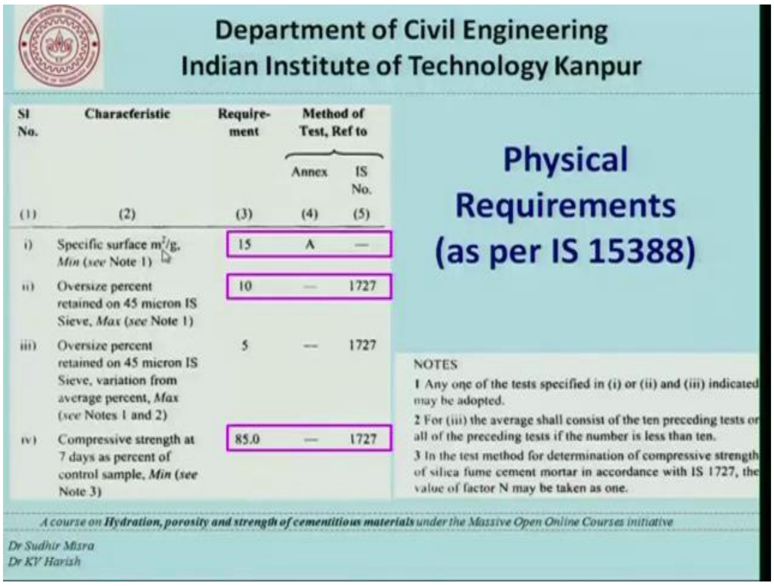

Now, if we get back to what are the physical requirements, because right now we have seen some of the physical properties and if we go to the Indian standard codes to check what are the physical properties that are specified, some are shown here where the specific surface area which is given in meter square per gram is approximately 15, and remember that this is a minimum value, and this is expressed in meter square per gram it has to be 15 meter square per gram at a minimum for any silica fume to be used in Portland cement based paste system, but if you want to express fineness or particle size in term of amount passing through 45 micron, see you like what like how we saw for the fly ash particles that limit is also given here.

So, if you take the oversize percent retained on 45 micron is sieve is only 10 percentage the other way of understanding is that at least 90 percentage should have actually passed through 45 microns is. So, that is a requirement by the Indian standards, and this is maximum. So, maximum 10 percentage should be retained which means 0 to 10 percentage could be retained, but anything about that should not be retained which means 90 percentage or lower should have been passed through these 45 microns. Likewise, if you actually see the compressive strength when we use silica fume in mixtures and you compare it with a reference mixture which do not have silica fume the water specified in the code is that at least 85 percentage of the strength should be 85 percentage of the control strength should be attained by the mixture containing silica fume.

So, and this is said at a 7 day curing period. So, these are 3 important requirements for the silica fume before it is used for any construction or cement based applications.

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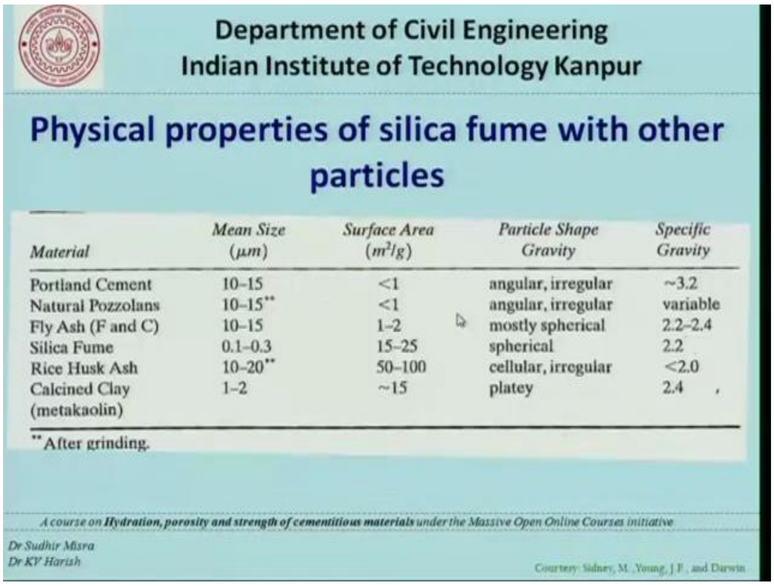

Material	Mean Size (μm)	Surface Area (m^2/g)	Particle Shape Gravity	Specific Gravity
Portland Cement	10–15	<1	angular, irregular	~3.2
Natural Pozzolans	10–15**	<1	angular, irregular	variable
Fly Ash (F and C)	10–15	1–2	mostly spherical	2.2–2.4
Silica Fume	0.1–0.3	15–25	spherical	2.2
Rice Husk Ash	10–20**	50–100	cellular, irregular	<2.0
Calcined Clay (metakaolin)	1–2	~15	platey	2.4

**After grinding.

And some of the comparative physical properties of silica fume with other particles are also shown. So, here what you find is you have the different materials, Portland cement natural pozzolons fly ash silica fume rice husk ash calcined clay. Now right now let us not compare all the things, but right now I just compare only Portland cement fly ash and silica fume because we have extensively gone through these 3 materials. Now if you take the mean size for a Portland cement it is typically between 10 to 15 for fly ash which is usually in the same particle size range of cement that is also found to be 10 to 15. If you take silica fume it is 0.1 to 0.3 that is a very important value and all these things are expressed in micron meters.

So, the mean size for silica fume is substantially lower compare to other pozzoloans. Likewise, if you take surface area in the case of Portland cement it is there is lower than one meter square per gram. In the case of fly ash is it is somewhere between 1 to 2 meter square per gram. In the case of silica fume it is 15 to 25 meter square per gram. So, this also indicates that silica fume particle is much smaller in shape smaller in size. And the particle shape is also provided in the case of Portland cement it is a angular and irregular in the case of fly ash it is mostly spherical, in the case of silica fume it is also spherical. Other the properties provided for other pozzolons are just for information and you can always compare it with silica fume or other materials. And in the case of specific gravity approximately for Portland cement it is 3.2 for fly ash it ranges from 2. 2 to 2.4 silica fume it ranges it is generally 2.2.

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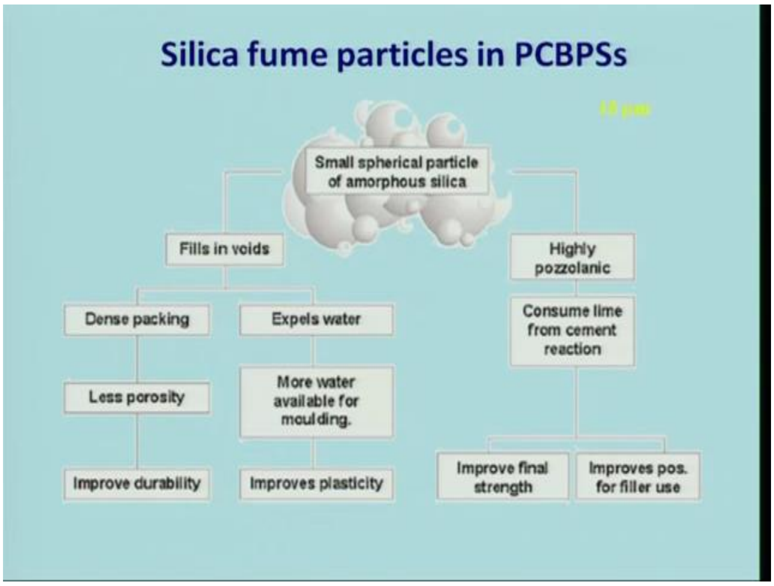

Now, what does silica fume particles do in Portland cement based paste systems. We know that silica fume particles are small spherical particles of amorphous silica. And primarily if you actually recall some 3 4 lectures before when we are discussing about the reactive components that are present in pozzolons, we find that a substantial higher amounts of amorphous silica is present in silica fume. So, the silica content that we have seen ranging between 85 percentage to 98 percentage. Does not indicate necessary that all the silica that is present are reactive, but we can generally understand that more than 50 to 60 percentage will be usually reactive or in other words 50 to 60 percentage will be at a minimum will be amorphous silica. So, though amorphous silica are nothing, but those forms our of silica which are ready to react immediately and undergo pozzolanic reaction.

So, when you have silica fume in the Portland cement based paste systems, and that to has very small spherical particles they are generally ready to react immediately. So, there are 2 types of effects that you tend to find whenever you use silica fume in concrete. One is void filling effect or in other words explained as filling invoice which means if you find any voids in Portland cement display paste systems like for example, we have already seen in lectures between l 11 and l 20 that Portland cement based paste system contains capillary voids the capillary pores gel pores and many others. So, those are basically pores and if silica fume particles are very finer they are effectively capable of getting into those pores and trying to fill and reduce the pore size much lower.

So, one effect that you find is a void filling effect the other effect, that you find is the pozzolanic effect in the sense that they basically react with the calcium hydroxide that is produced from cement hydration even at the early ages and forms calcium silicate hydrate gel having much lower calcium to silicate ratio compared to the primary silicate hydrate silicate hydrate gel that is produced from cement hydration. So, there are 2 effects that comes into picture. One is the void filling affect the other one is a pozzolanic effect. And in the void filling affect again we have a densely packing the voids. The other one is when it packs the voids some voids may actually contain water. So, they will also try to expel the water out. So, if you actually again get back to capillary pores and gel pores which are discussed previously you find that some quantity of water may be present in gel or capillary pores.

So, when you use silica fume these days basic basically occupy the voids or pores. And if water is present in the pores they are expelled out. And the dense packing results in lower porosity or less porosity this will result in improved durability likewise the expelling of water results in more water available for molding. So, that actually helps in molding purpose and that improves the plasticity of the mixture. This is one reason why many times silica fume is used as a potential admixture when it comes to pumpability of concrete. Because pumpable concrete requires mixture to be a cohesive and plastic. So, silica fume helps in making the mixture cohesive and plastic. And it is not just for pumping applications alone even for some applications like tunnel grouting or tunnel shortening where, we need to inject huge amount of cementitious material at a very high velocity, these type of silica fume extensively helps in providing that cohesiveness and plasticity.

So, this is about void filling affect the next one is pozzolanic effect. So, when you have pozzolanic reaction and when you have the secondary calcium silicate hydrate gel that is being formed, it basically depletes the calcium hydroxide and that again leads to higher strength primary, because calcium silicate hydrate gel is the strength forming phase and you tend to produce more and more calcium silicate hydrate gel with the use of silica fume and that improves the strength.

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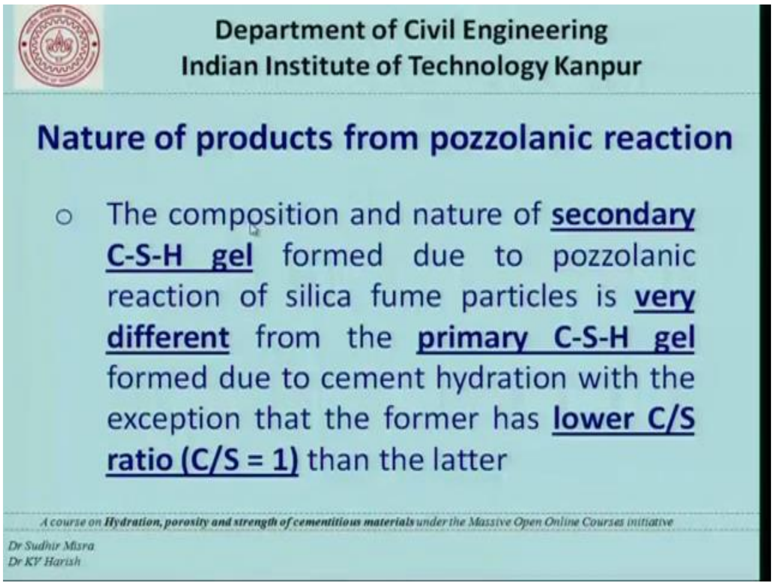

Now, coming on to the nature of a products from pozzolanic reaction. The composition on nature of secondary silicate hydrate gel formed due to pozzolanic reaction of silica fume particle is very different from the primary calcium silicate hydrate gel for formed from the cement hydration process. And in this case the secondary calcium silicate hydrate gel as a lower C by s ratio that actually helps in improving the durability and strength of Portland cement based paste systems usage of silica fume.

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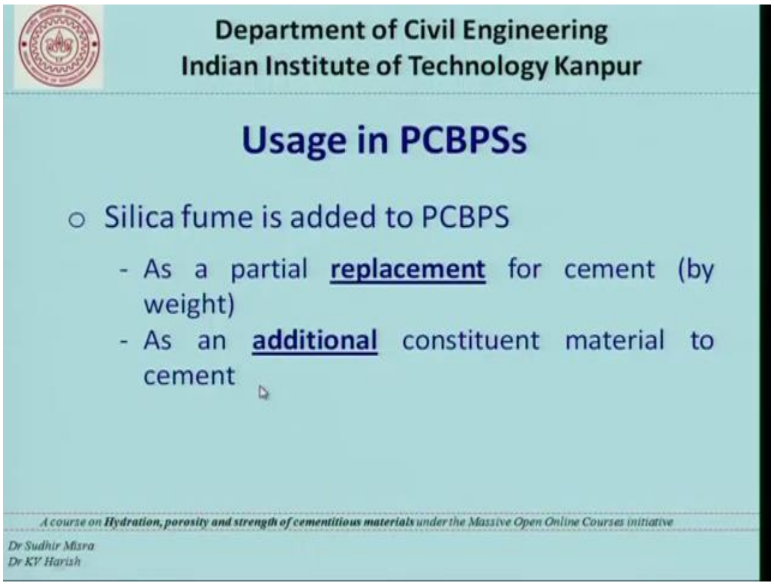

Silica fume is used in Portland cement based applications in 2 different ways as a partial replacement for cement by weight and as an additional constituent material to cement. So, this is similar to what we have seen in fly ash which was dealt in the previous lectures. So, you can use it also has a partial replacement or as a additional element in cement. Now what are the usual effects when we say effects not in terms of properties in terms of properties we will see at a later stage, but immediately when you add silica fume is there any effect with respect to the reactivity is of tricalcium aluminate or others.

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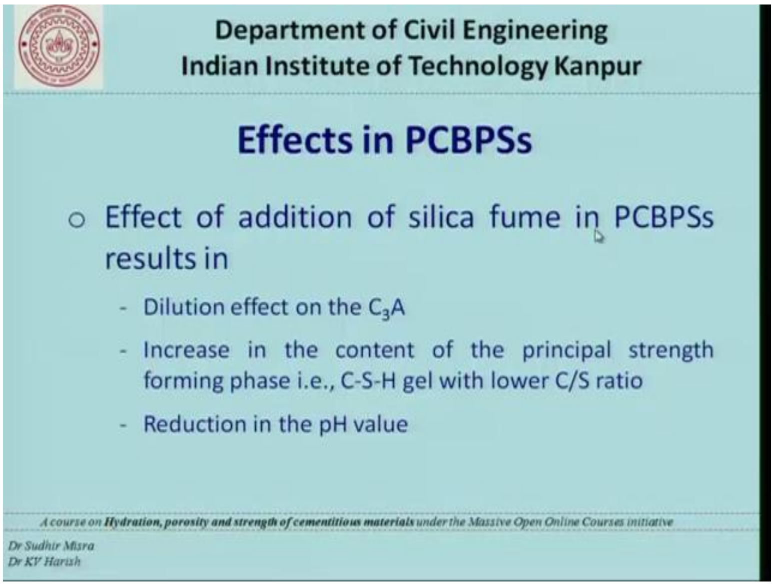

So, that is what is discussed here the effect of addition of silica fume in the mixture results in dilution effect on the C3A. So, remember that C3A stands for tricalcium aluminate and many times when you have silica fume mixture some elements of silica fume can actually react with the tricalcium aluminate.

So, this tries to dilute the C3A primarily because it is expected that a certain amount of water has to react with C3A. When you have silica fume in the in the mixture silica fume basically since it is in the very fine form it will get dissolved in water and it will dilute the effect of water and hence it can affect the hydration of C3A. The second point is increase in the content of the principle strength forming phase.

So, as we have already seen that you have more and more secondary calcium silicate hydrate gel form the net effect will be that you will have very high amounts of calcium silicate hydrate gel in the system. And the third effect is that there is a reduction in the pH of concrete this is primarily because we have already seen that in pozzolanic reaction the calcium hydroxide gets converted to calcium silicate hydrate because of the reaction with the pozzolone. And remember that calcium hydroxide has a higher pH that is one of the advantage that we have because we want concrete to have a higher pH primarily from the standpoint of resisting corrosion.

So, when you use silica fume or for that matter any other pozzolone because of the reduction of because of the reduction in the quantities of calcium hydroxide the pH also reduces, but remember that pH still will be somewhere in the range of 12 to 13 it would not go below twelve, but anything below 11 then the system is a very much vulnerable to corrosion. Somewhere between 12 to 13 it is still, but; however, if calcium hydroxide is also present then typically the pH of concrete will range from 13 to 14. If it is not present and if you have pozzolans then it will be in the range of 12 to 13. Now what is the dosage of silicon silica fume that is usually added.

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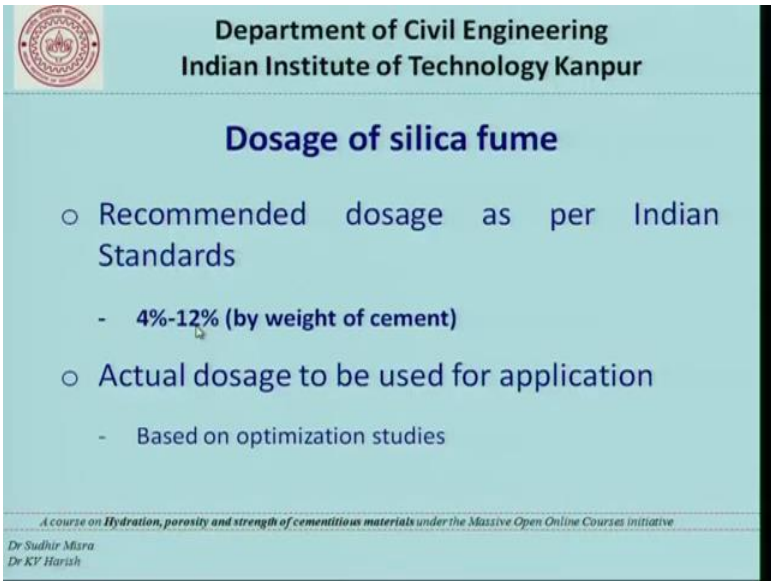

So, the recommended dosage typically varies from 4 to 12 percentage and remember that this is by weight of cement when you replace it by weight of cement and another information is that this is as per Indian standards.

So, the Indian standard typically says that you can try between 4 to 12 percentage, but usually when it exceeds 12 percentage either the mixture becomes too costly for the simple reason that silica fume even though it is a industrial waste material it is a very costly product unlike fly ash. Fly ash is completely 0 cost where as in case of silica fume the cost of silica fume is approximately 2 to 3 times that of cement. So, from the standpoint of economy which we have discussed some 4 or 5 lectures before silica fume is usually not used as a replacement for a cement unless you need special properties from silica fume.

So, largely we prefer to use fly ash or slag which are either less costly or completely no cost compared to silicon fume; however, the recommended dosages is between 4 percentage to 12 percentage, but the actual dosage to be used for application depends upon what is the special properties required for that application. For example, if it is going to be pumpable then again you may have to do some optimization studies within the recommended dosage to find out which can actually suite the application. And likewise if it is going to be for say ultra high performance concrete which is actually different grade of concrete which is getting popular during the last 5 to 10 years where silica fume is used at the dosage of about 15 to 25 percentage which is much higher than what is recommended what is the recommended by standards.

So, for such a special application we have to do optimization studies at different dosages and find out which actually suit is which dosage actually suit is that particular application. Now most important things what are the effects of silica fume on specific properties of Portland cement based paste system.

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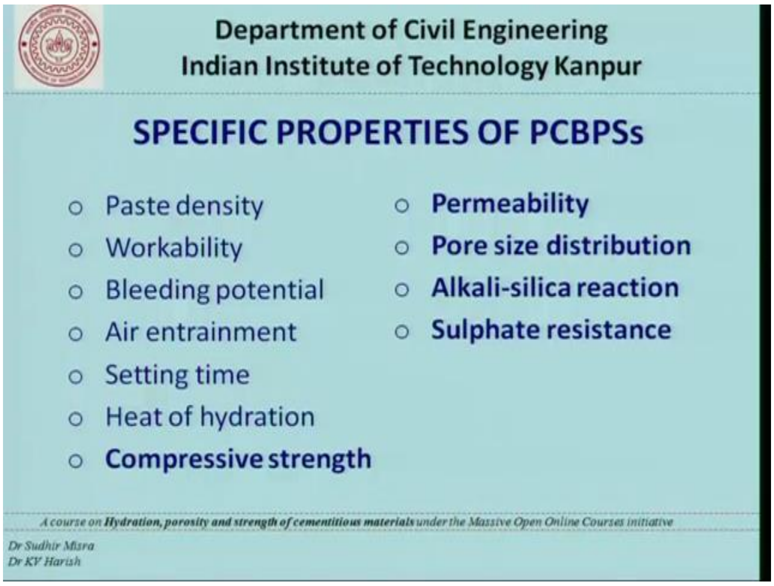

Some of the properties that we are going to see or page density workability breeding potential air entrainment, setting time heat of hydration compressive strength permeability, pore size distribution, alkali silica reaction and sulphate resistance remember that many of these properties have been already seen for fly ash. So, now, we are actually seeing similar properties for silica fume.

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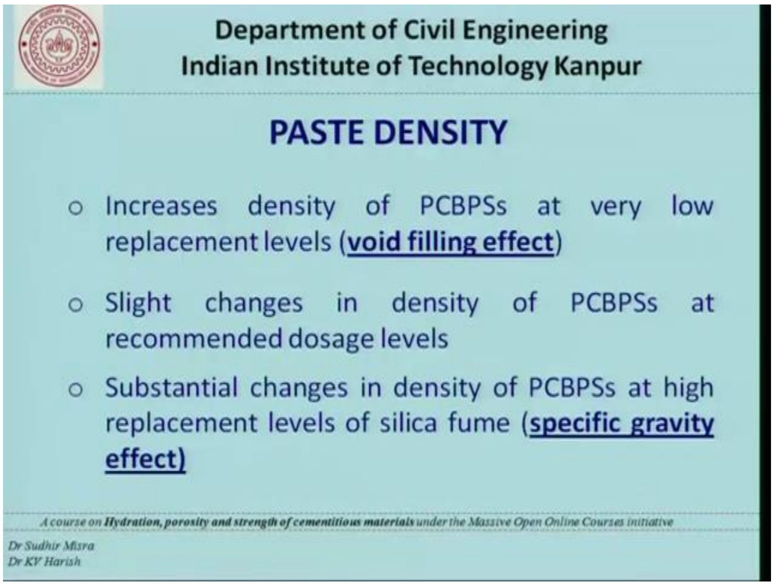

Now, with regard to page density the addition of silica fume increase the density of Portland cement based paste systems at very low replacement level. That very low replacement level is extremely important terminology for the simple reason that the silica fume particles have a lower specific gravity compared to cement articles. So, what happens is the usual tendency is that when you use silica fume as a replacement for cement or as a additional material for cement the density of the page density tends to reduce, but that is that usually happens only at higher dosage levels. At very low dosage levels what happens is the voids that are present in cement grains or cement particles they are being filled by silica fume particles as we have already seen in some few slides before.

So, that is a void filling effect and that is also a specific gravity effect slight changes in density of Portland cement based paste systems or observed when the silica fume dosage is at recommended dosage which is between 4 percentage to 12 percentage; however, there is substantial changes in density if the silica fume is used at a higher replacement levels. So, that at higher replacement levels the specific gravity affect dominate all others and you will find that the silica fume mixtures have lower density compared to the reference mixtures which do not contain silica fume.

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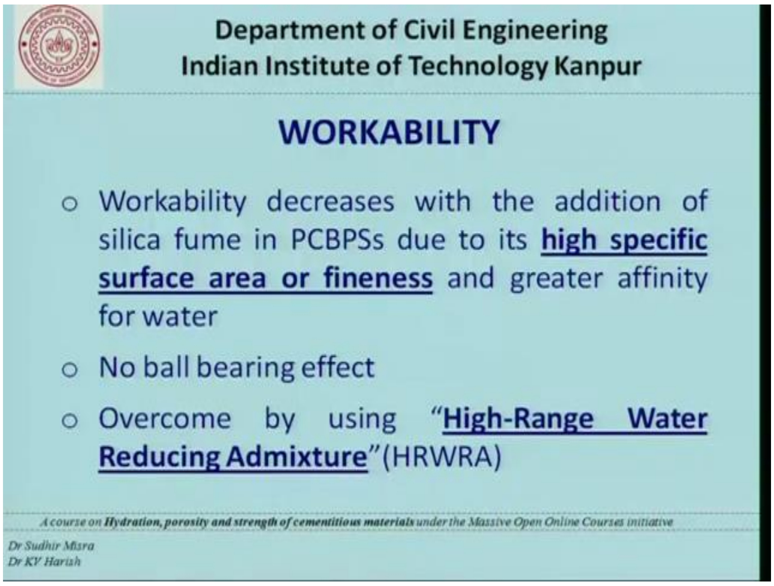

Now, coming onto the property which is workability; the workability decreases with the addition of silica fume in Portland cement based paste system, primarily because of the very highest surface area or fineness of silica fume particle. Remember that silica fume particles are spherical in shape, but remember having been spherical in shape it cannot increase the workability primarily because of the particle size, in the case of silica fume the very fine particle size dominates when it comes to workability compared to the shape the same is not true in the case of fly ash what we have seen with fly ash is that fly ash particles are also spherical in shape, but their size are much larger compared to the silica fume particle, and their particle sizes are also comparable with the cement particles and hence there the particle size does not dominate. For fly ash particle size does not dominate, but particle shape dominates and it actually helps in providing ball bearing effect and all others which we have already seen.

So, in the case of silica fume the specific surface area or fineness largely dominates and because of that the workability decreases. And the other thing that is very important is that there is no ball bearing effect which we can see with flash particles. And how do you overcome the effect of decrease workability. Very simple thing is that we use high range water reduces. So, remember that the use of chemical admixtures and silica fume both are actually costly. In the case of fly ash and slag it is a cheaper material. So, usually with regard to application silica fume material as a pozzolone is actually less preferred compared to fly ash or slag. Not only that when you use silica fume you also require high range water reduces which are also costlier.

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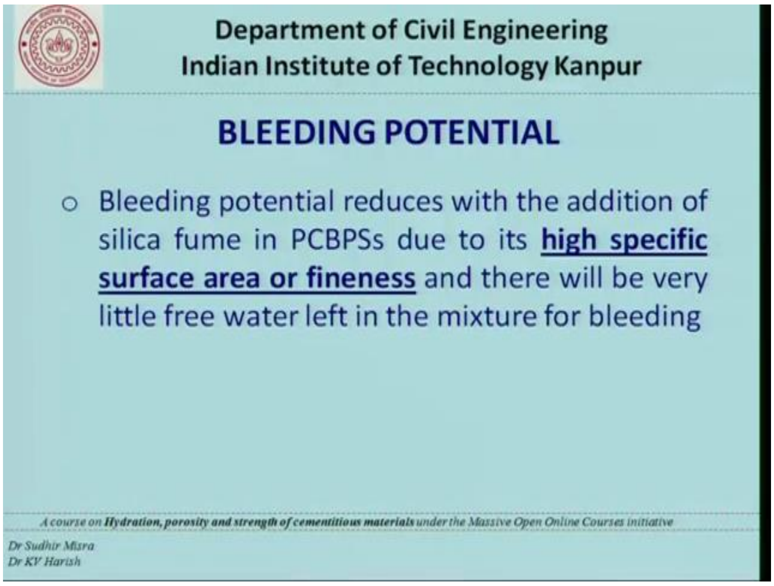

Now, the third property is bleeding potential, and what you can see is that bleeding potential reduces with the addition of silica fume, which is actually a positive thing. And this is again due to very high specific surface area. So, remember that higher fineness of silica fume or very low particle size of fly ash helps in reducing the bleeding, whereas with regard to workability that also reduces. So, in the case of bleeding potential we are able to see a positiveness in adding silica fume whereas when it comes to workability we find that it is getting drastically affected.

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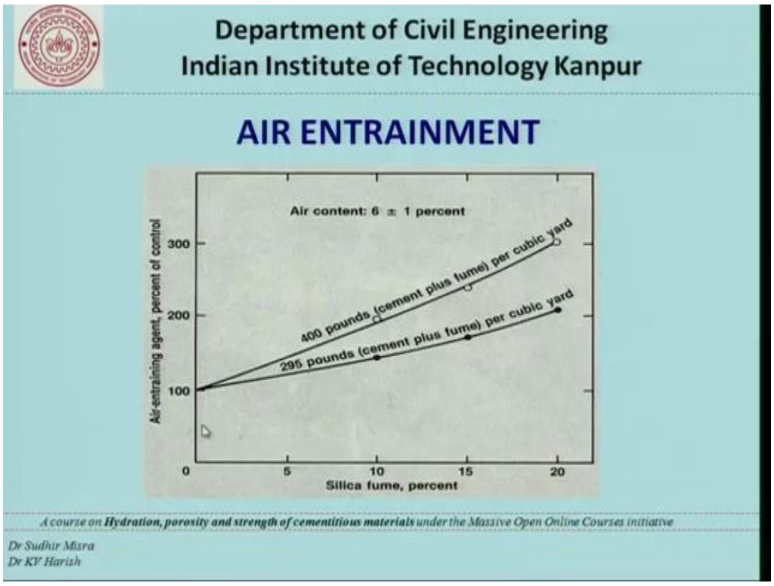

Now, coming onto air entrainment in this figure what is shown is the silica fume dosage is taken in the x axis ranging from 0 to 20 percentage. And the air entraining agent is taken in the y axis which is represented as percentage of control which means that has assumed that you need a x amount of air entraining agent in order to achieve air content of 6 plus or minus 1 percentage. And remember that this quantity of air content is required to effectively resist the free stock actions in concrete.

So, if you want to use a control concrete and if you need x amount of air entraining agent in order to get a air content of 6 plus or minus 1 percentage then that x amount is considered as hundred. And likewise you have 200 and 300 indicating that there is hundred percentage increase above the control and the 200 percentage increase above the control. So, what you find in the y axis is air entraining agent specified in percentage of control and in the x axis you have silica fume dosage.

And what we find is that with increase in the silica fume dosage the air entraining agent required increases substantially. So, to attain a 6 percentage or plus or minus 1 percentage air content the amount of air entraining agent that you have to put in the concrete to achieve 6 plus or minus 1 percentage is actually higher for silica fume mixtures compared to control mixture. So, in other words in terms of cost you may have to spend more if you are using silica fume mixtures, and hence you need additional air in the mixture to resist free stock and hence you need more air entraining agent.

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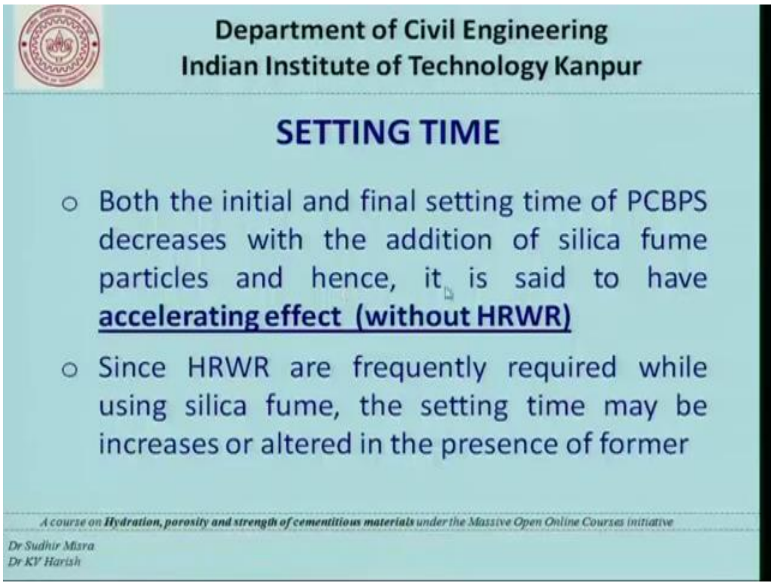

Now, coming to the next property which is setting time both the initial and final setting time of Portland cement based paste system decreases with the addition of silica fume particles. And hence it can be said that it has an accelerating effect when it comes to setting time, but remember carefully that this accelerating effect is applicable only if you do not have a high range water reducer. For mixtures which do not have a high range water reducing admixture. This is true for the silica fume mixture, but the moment you have a high range water reducing admixture that can also affect the setting time.

So, since high range water reducing admixtures are frequently required while using silica fume the setting time may increase or get altered in the presence of the former which is nothing, but high range water reducing admixture. So, if you consider without high range water reducing admixture then the effect of silica fume is to reduce the setting time there by creating accelerating effect on the hydration of a cement.

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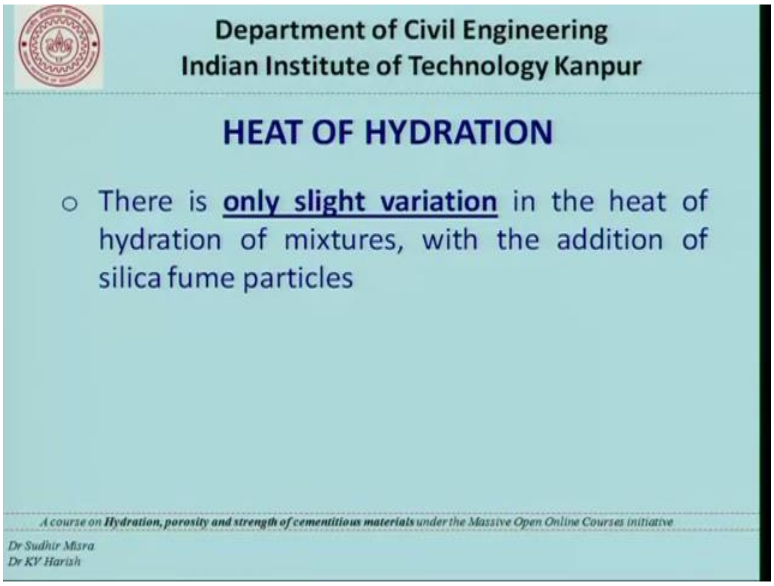

Now, the next property is heat of hydration and what is generally observed is that there is only slight variation in the heat of hydration of mixtures with the addition of silica fume particle and this as the primary 2 reasons one is that silica fume is used at usually at lower dosage compared to fly ash or slag. So, typically what we have seen is that the recommended dosage is between 4 to 12 percent and at such dosages the amount of cement that is taken out of the system is relatively less compared to fly ash.

So, and hence the heat of hydration is now substantially increased or decreased. So, there is a only slight variation in the heat of hydration and hence for applications where heat of hydration is a very important factor then the use of silica fume may not be a good option, but for applications where you need a higher early strength or others or you want the accelerating effect with regard to setting time then silica fume mixtures are preferred. When it comes to compressive strength which is a very important property especially when it comes to Portland cement based paste systems.

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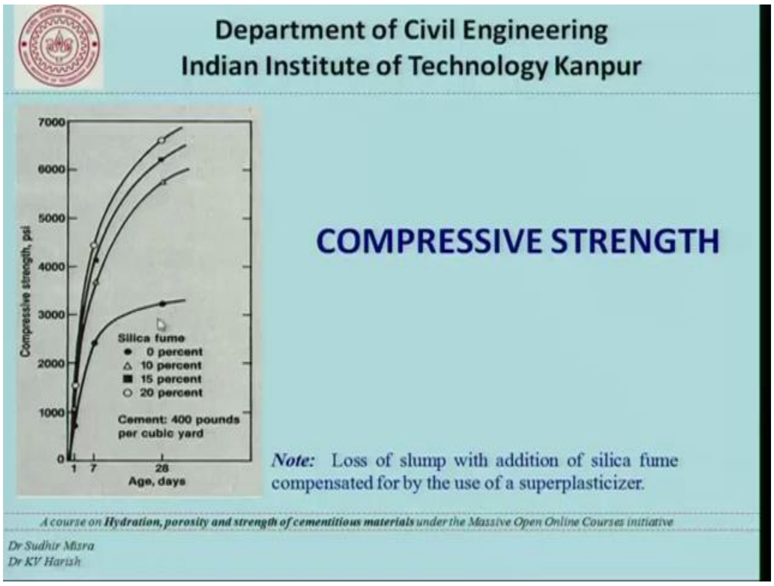

Ah some information is provided here typically you have 4 curves in x axis we are taking a curing age and in the y axis. So, you have compressive strength expressed in psi pounds per square inch. So, what you find is that you have to 4 curves one is 0 percentage or the reference curve the other one is 10 percentage silica fume the other one is 15 percentage and the third and the forth one is 20 percentage.

So, what you find is that the more and more you start adding silica fume the strength is getting increase, but remember that there is always a optimal percentage somewhere between 10 to 20 or 25 where the strength again decreases. Because in this one silica fume is used as a replacement material for cement. So, the more and more you replace cement and you add silica fume, because of the reduction in the cement content the strength also decreases. So, whatever is shown here as a increasing trend that holds good only up to a certain level of dosage. So, right now for this type of silica fume that they have investigated, what we find is that the strength keeps on increasing, but usually what happens is 10 to 20 percentage is a dosage at which you tend to see that you get a decrease in compressive strength somewhere between 10 to 20 percentage.

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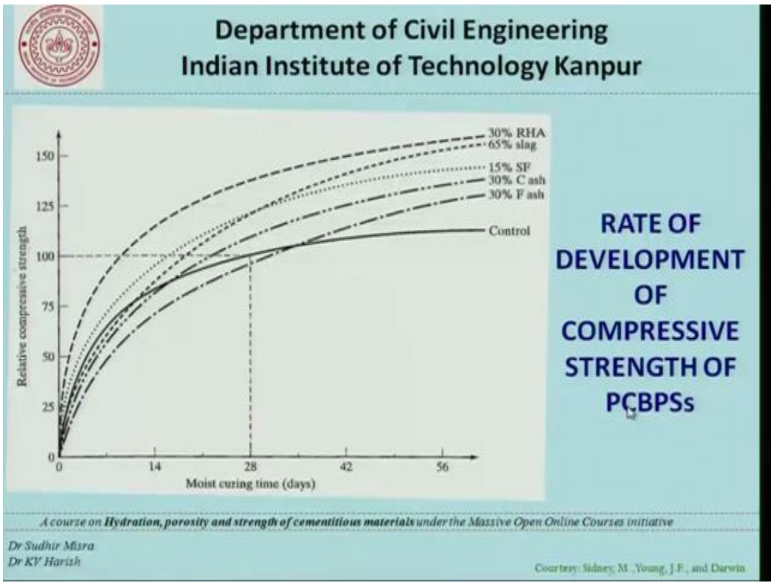

Now, coming to the rate of strength development graph, if we have to compare it with the other admixtures like fly ash and in specific class C or class of fly ash the figure is shown remember that this is a revisiting figure in the sense that we have already seen this in fly ash the same figure is shown just to compare how silica fume mixture performs compared to a fly ash mixture or control.

So, what we have seen is that in the case of control mixture there is a steep increase in compressive strength during the early stages say up to 28 days. And after which the increase in strength flattens in the case of silica fume mixtures if you carefully observe comparing it with the control mixture the strength increases much higher even at the early period say between 1 to 7 days or 1 to 14 days. And it is much higher in the sense it is much higher than even the control mixture. And right throughout the curing period from say 0 days to about 56 days the strength of silica fume mixture is much higher than control measures.

But remember that in this figure the percentage dosage is 15 percentage. So, if you take lower dosage probably you will find the sum curves which are above the control curve, but below the 15 percentage curve. And if you also compare the silica fume mixture with class C or class F fly ash you can notice that silica fume mixture generally give highest strength compared to fly ash mixture. And we also have 2 others slag and rice husk ash which we will come at a later stage.

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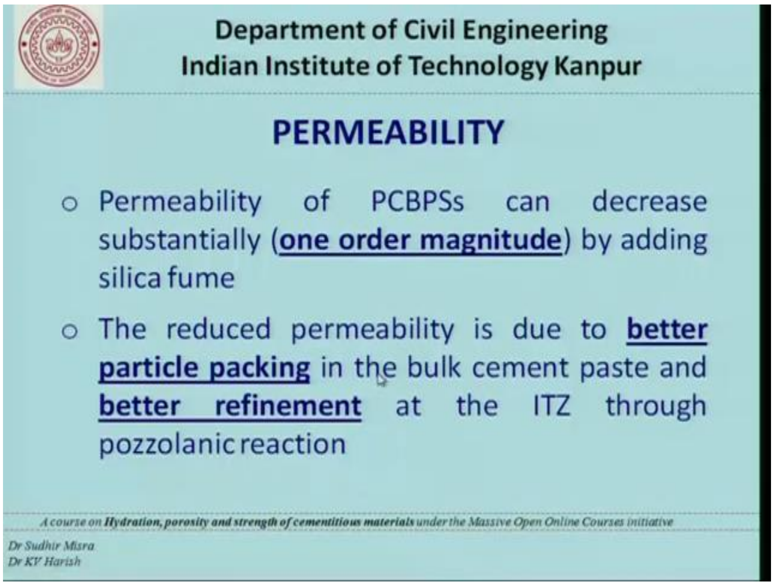

Now, next one is a permeability of Portland cement based paste system can be decreased substantially. And when we say decrease substantially it is about one order magnitude. The reduced permeability is due to better particle packing in the bulk cement paste and better refinement at the ITZ through pozzolanic reaction.

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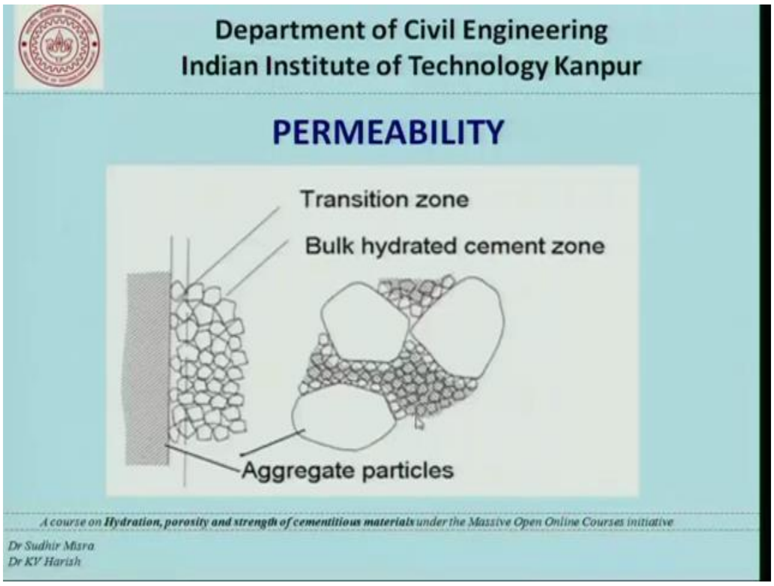

So, to explain this we will go to figure which actually shows the aggregate particle and also the cement paste which actually contains cement as well as silica fume particles.

So, what you find is that there are 2 different zones. One is the transition zone the other one is a bulk hydrated. Zone transition zone is actually the zone that is very close to the aggregates. So, this figure is a idealized figure compared to this aggregate compared to this figure in the sense that here it is considered as a wall the aggregate is considered as a wall and 2 zones are identified one is the zone that is very close to the aggregate called as a transition zone and the other one is the zone that is substantially away from the aggregate which is called as a bulk hydrated cement zone. So, in the figure what you find is that this transition zone basically is zone around this particle, and the bulk hydrated cement zone is actually the zone at the away from the aggregate particles or towards the center of the main cement paste. So, what we find is that the reduced permeability is due to better packing in the bulk cement paste. So, if you take the cement paste zone which is the shaded region that is very high packing density primarily because of the white filling effect that we have already seen.

In addition to that you also see better refinement at the ITZ. So, even if you take this zone and compare the zone that is around the aggregate particle and compare it with another mixture which do not contain silica fume, this zone is much more refined for mixtures which contain silica fume.

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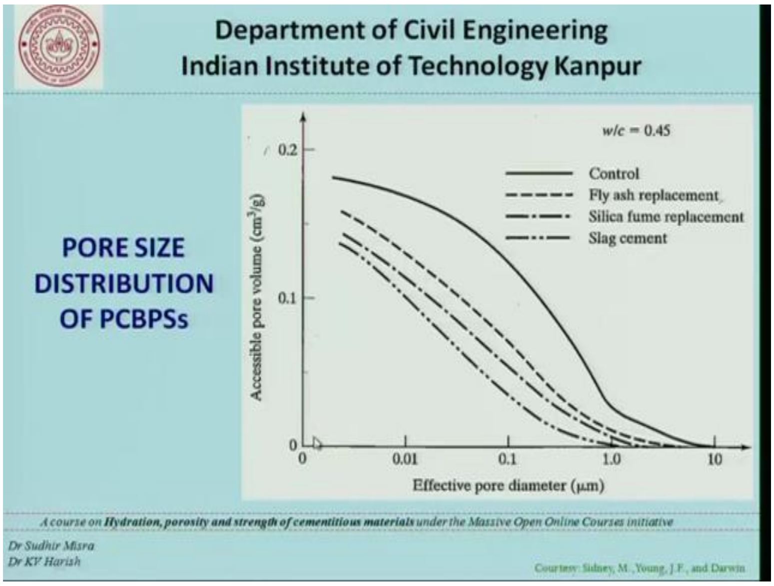

The next property is pore size distribution and what we find in this figure is that you have effective pore diameter in the x axis ranging from 0 micron meter to approximately

10 micron meter. And accessible pore volume expressed in centimeters centimeter cube per gram. Remember that does effect of pore diameter and accessible pore volume are primarily from mercury intrusion porosimetry curves. So, primarily you have to get back to those curves to understand the explanation for what is pore volume and pore diameter and all others.

So, here in this curve what we find is a control mixture, where the pore diameters you typically vary from 0.001 micron meter approximately to as high as 10 micron meter. And if you see the fly ash which we have already seen in the previous lectures on the pore size distributions are much slower as shown in the dotted a dotted line in the figure. And if you take a silica fume replacement we will see that the these are much lower. So, in that the third line that shows you find that the pore size distribution is much lower. And the remember that the pore size distribution is also connected to porosity and if the pore size distribution is smaller then the then the porosity is smaller and hence the permeability is also very low.

So, if you get back to the permeability property that we just discussed, now the permeability decrease a substantially one order magnitude compared to that of the control mixer. So, compared to the control mixture you find the pores sizes are much smaller that it is very difficult for any water or external agents to actually permeate through silica fume based mixtures.

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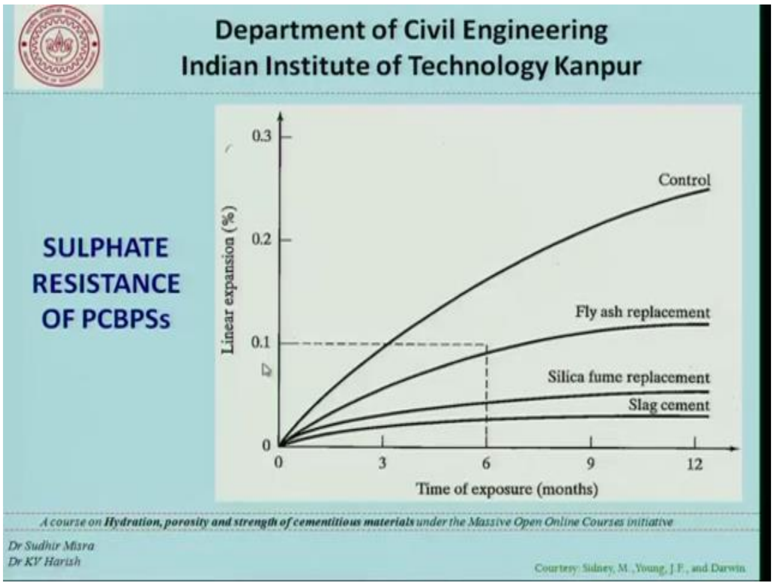

When it comes to sulphate resistance again remember that this figure is already discussed with regard to fly ash replacement. Now we are recovering silica fume replacement. So, compared to control mixture the silica fume mixture substantially reduces the expansion due to sulphate. So, as you can recall that this 0.1 is limited expansion specified in code at period of 6 months. And for silica fume mixture it is substantially lower and even with the more time the silica fume mixture it expansions with silica fume mixture does not go above 0.1 percentage, but the same thing is not true for a fly ash mixture at a later age of the fly ash mixtures can also show high expansions much higher than the limited expansion that has provided in standard codes.

But remember that here the replacement level of fly ash and silica fume are not specified. So, what we have to understand is that these are replacements which are the within the recommended replacement levels. So, if you take fly ash the replacement that it is specified code anywhere range between say 15 percentage to 35 percentage because that is what is the specified replacement level for fly ash in the case of silica fume whatever is specified here is between 4 percentage to 12 percentage. So, within the recommended level silica fume mixtures perform much better than fly ash mixtures.

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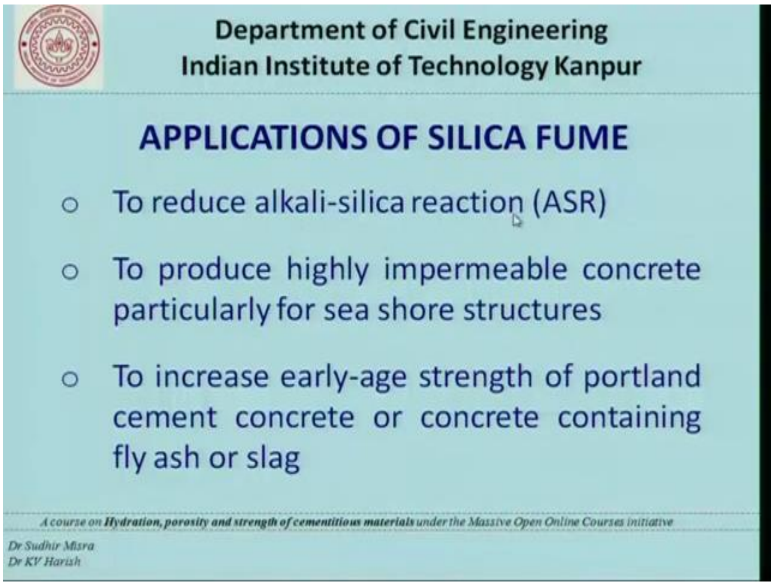

Applications of silica fume. Silica fume is primarily used to reduce alkali silica reaction. It is a very effective pozzolone and the alkali silica reaction problems are largely encountered by using silica fume at very low dosages. Even fly ash is capable of reducing expansions, but not to the level silica fume reduces.

The next application is to produce highly improbable impermeable concretes particularly for sea shore structures. So, if you want to use where we have different actions from solutions and others and the silica fume can be a good choice, but remember that the choice of a particular material depends also on the economy. So, since silica fume is not the economical material other pozzolanic materials which are cheaper are preferred. That case even fly ash and slag are used for such low permeable applications. The third one is to increase early age strength of Portland cement concrete or concrete containing fly ash or slag. So, in fly ash what we have seen is one of the problems or limitations that we found with fly ash is at a at the higher dosages or under a cold environments, you do not get the early strength or at least the minimum strength that is required for the particular d molding purpose or others.

So, in such cases in the mixture we can add a little bit of silica fume somewhere between 4 to 8 percentage. So, that the silica fume in the mixture provides the earliest strength properties and laterite strength properties are provided by the pozzolanic reaction from the fly ash. In such cases where silica fume is also used along with fly ash or slag those mixtures are referred as ternary blend mixtures.

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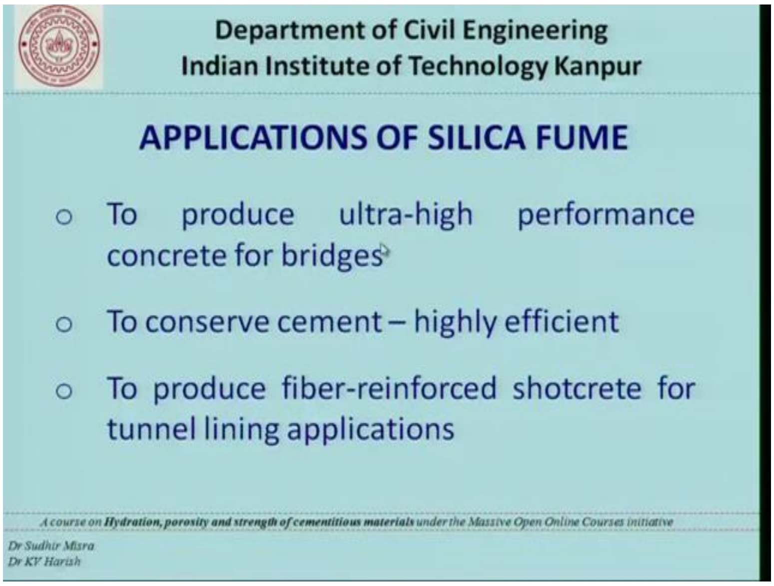

The other application is as already mentioned; silica fume can be used at a much higher dosage in ultra high performance concreted for bridges. And sometimes if it is specified that the quantity of cement is substantial and it creates higher reactivity in the in the in that particular application. Silica fume can also be used to conserve cement or to reduce the use of cement. The final one is a silica fume can also be used for fiber reinforced shotcrete applications primarily in tunnels.

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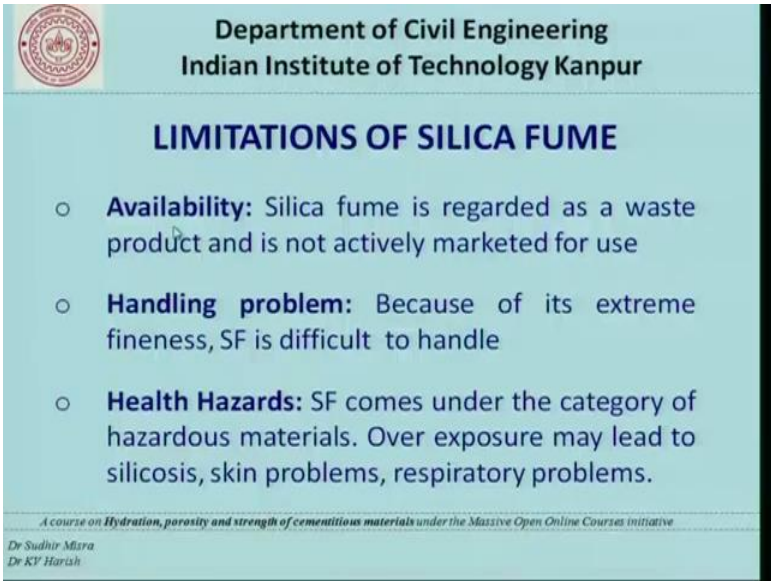

In addition to all this application we should also remember that we also have limitations of using silica fume. One is the availability either silica fume is considered as a waste product and it is not actively marketed for use. This is primarily for 2 reasons one is that the dosage is very much restricted and silica fume is a very costly material, the other one is silica fume also had applications in other industries not just in construction industry where as fly ash does not have application in other industries.

So, that is one reason why silica fume is also a very costly material compared to others. Silica fume has very good application in other industries. Handling problem because of it is extreme fineness silica fume is difficult to handle people who work silica fume have to be little more careful because it is a finer material and it can sort of a create some smoke or well making a mixture. And it can also eventually lead to health hazards and the constant exposure to silica fume may result health problems like silicosis skin problems and other respiratory problems. Some care should be taken while using silica fume in concrete.

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In addition to that the biggest limitation is a very high cost and usually we can assume that it varies from anywhere between half to 2 times the price of normal Portland cement. And this half to 2 times is actually in India. In united states it is typically 2 to 3 times costlier than normal Portland cement and also we find that you have huge a disadvantages when it comes to entraining air in the sense that you need higher amounts of air entraining dosage and that also adds to the high cost of the entire mixture.

So, with is we are completing the silica fume and now our next topic will be slag. So, the next topic is blast furnace slag. The word blast furnace primarily because slag is by product industrial by product in the manufacture of steel in the manufacture of iron or steel and usually blast furnace is actually used in the manufacture of iron ore or copper ores. So the term blast furnace basically comes along with slag because of the process that is used.

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Now, what is the definition of slag? The most the more appropriate definition of slag has provided here. The nonmetallic product consisting essentially of calcium silicates and other basis developed in a molten condition simultaneously with pig iron in a blast furnace is called as slag. And it is a byproduct obtained from the blast furnaces used to make iron. And many times nowadays even during the extraction of copper blast furnaces are used. And even in that process we also get a slag in that case it is called as copper slag. So, in all other cases generally. So, slag is called as a blast furnace slag.

So, the principle elements the principle raw materials used on iron or copper in the case of slag.

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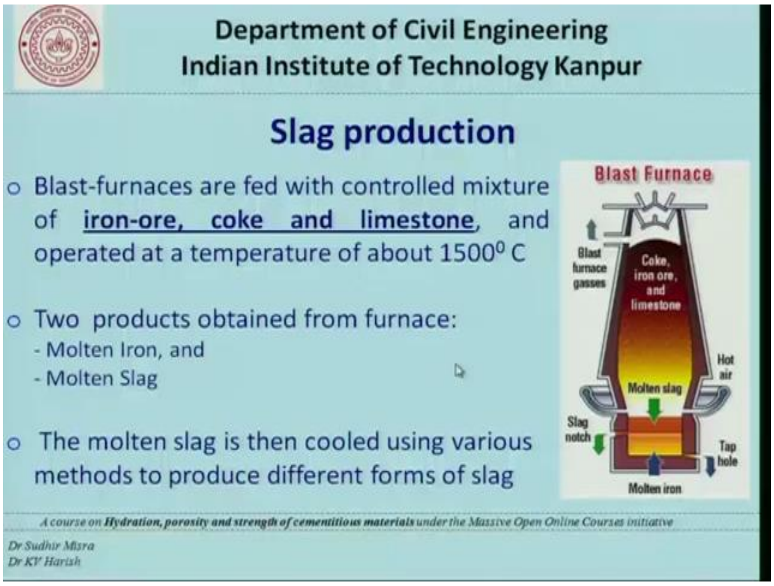

Now, the production process has already mentioned for silica fume. The production process is not very important for this course, but at least you should know what are the basic raw materials that are used what is the temperature levels and some other minor information about the production process. So, what you have is that you have a blast furnace in this figure. And you have the basic raw materials such as coke iron ore and limestone. Remember that coke and limestone or basically the basically other materials that are present in the ores. And they are basically heated to a temperature of 1500 degree Celsius and basically at the temperature the mixture melts and in at one end you get a slag and at the other end you have the molten iron which is used for the iron making process.

So, the slag is basically obtained as a byproduct. And above whatever gases that come out of the heating process that is kept out to the atmosphere. So, blast furnaces are fed with control mixture of iron ore coke and limestone. Remember that the raw materials are used in some appropriate proportion. And the operational temperature is approximately 1500 degree Celsius. 2 products are obtained from furnace one is a molten iron which is actually used by the iron companies for making steel or other products and other one is a molten slag which is later on cool down and the cooling is again a stage by stage process. The molten slag is then cooled using various methods to produce different forms of slag and this is again another schematic figure to represent the slag production where you can find.

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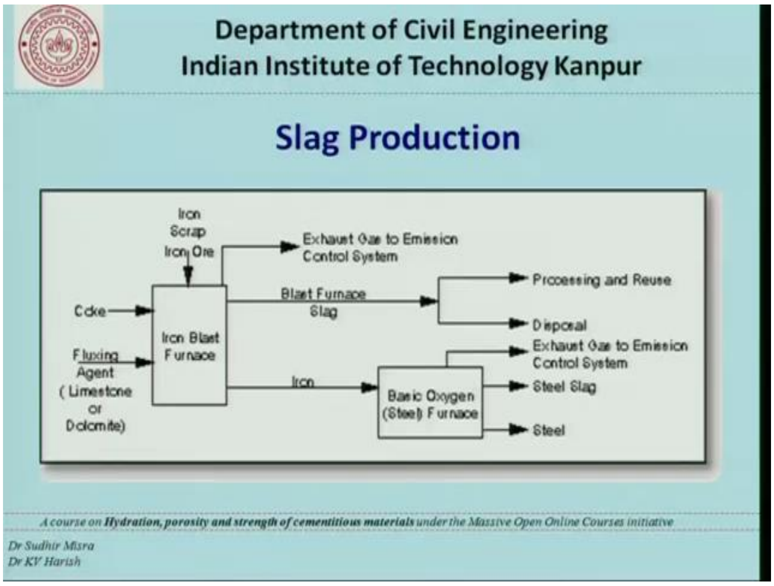

The coke or limestone or dolomite which are actually the raw materials for iron, and again you may have some iron source which are added as a scrap material into the furnace and you get the iron the pure iron and you also get slag and again this slag can be either disposed or this can be processed and reuse and again in this iron you have the basic oxygen furnace through which steel is produced.

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So, this again a schematic representation just to show what happens in the production of slag. Now the molten slag comprises approximately 20 percentage by mass of iron. The slag primarily consists of silicates and aluminosilicates of lime and magnesium. This is a very important point slag primarily contains silicates and aluminosilicates of lime and magnesia. Remember that lime is lime and magnesia are usually creates expansion and hence and we have seen these things in a cement and fly ash. So, the same thing also holds good here. So, whenever we use slag there are also limit is for lime and magnesia specified in the codes. Slag from different plants differ in chemical mineral and physical constituents and hence it is important to study the physical and chemical properties.

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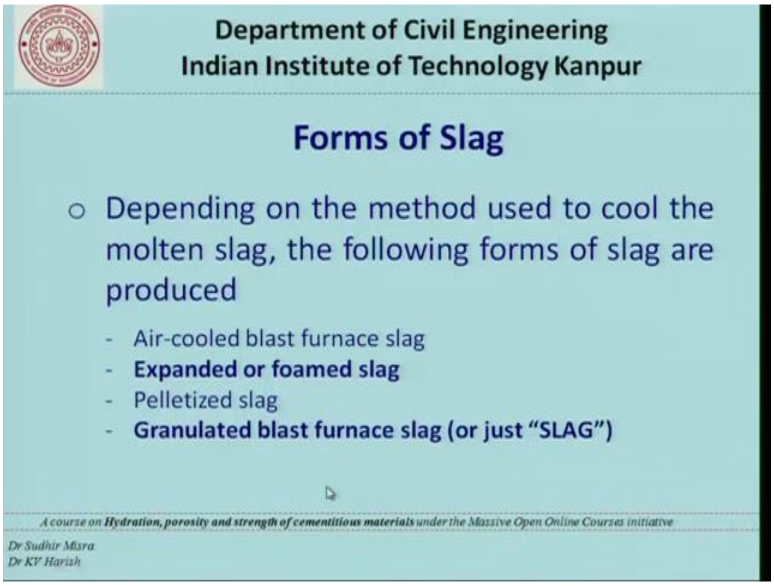

Now, the different forms of slags that are available are as follows. One is air cold blast furnace slag the second one is expanded or foamed slag third one is pelletized slag and the forth one is granulated blast furnace slag. So, this is the granulated blast furnace slag is actually more popular and many times it is just called as slag. And you get these 4 forms of slag because of the different methods that are used in the in the cooling stage of slag. And we will in this lecture largely see the ground granulated blast furnace slag or simply called as slag.

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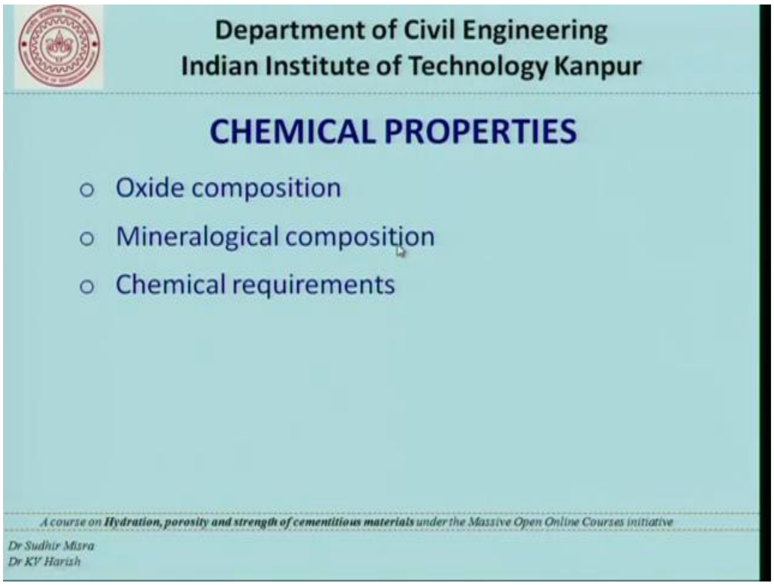

Now, the chemical properties of slag are as follows. One it is important to know the oxide composition. The other one it is important to know mineral composition or mineralogical composition. The third one it is important to know the chemical requirements mentioned in the course. So, what we will do right now is that we will go through this, but remember that the mineral or mineralogical composition is not yet fully understood by researcher event today.

So, there is a good scope for research in that area. So, mineralogical composition for this course is not really important although it is specified what types of material minerals are present in it.

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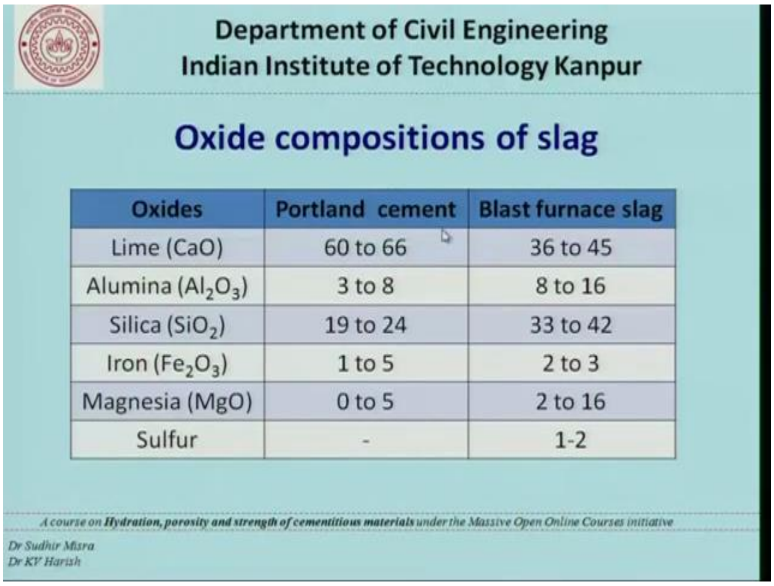

Now, the first one is oxide composition of slag. What is shown here or the oxide starting from calcium oxide to Sulphur trioxide. And here you have 2 columns one is for Portland cement other one is for blast furnace slag. So, if you carefully look the blast furnace slag has a substantial amount of calcium oxide, but the amount of calcium oxide present is much lower than what you find in Portland cement, but remember that the calcium oxide president in slag is much higher than the calcium oxide present in fly ash or silica fume. In fact, for silica fume are typically the calcium oxide is 0 are very little where as in the case of fly ash you still have some substantial amount of calcium oxide when it comes to even classify ash compared to even the classify ash the blast furnace slag has higher amounts of calcium oxide. And when it comes to alumina silica and iron the rangers are provided here 8 to 16 percentage 33 to 42 percent, and 2 to 3 percent and what is more important second most important after calcium oxide is silica.

So, the silica is typically 30 to 40 percentage which is much higher than what you have in Portland cement. The comparative oxide compositions of slag with other materials is also required and that is also important from the standpoint of assignments quizzes or exam.

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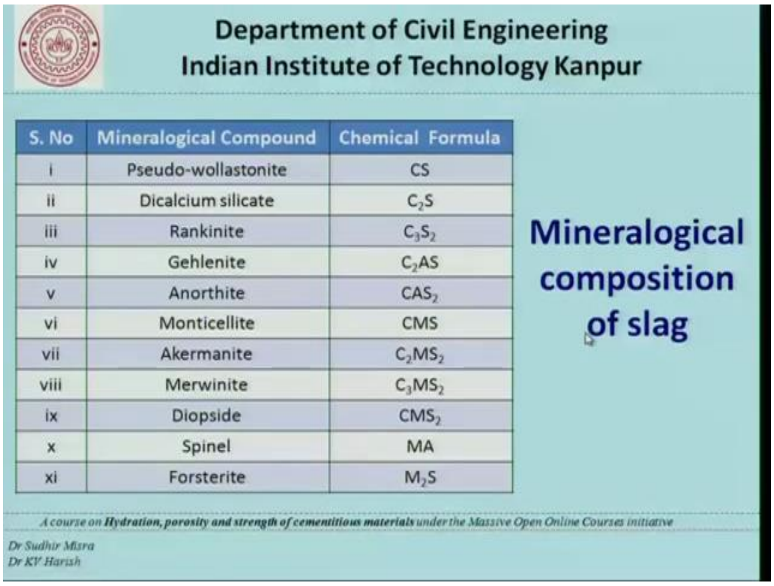

S. No	Mineralogical Compound	Chemical Formula
i	Pseudo-wollastonite	CS
ii	Dicalcium silicate	C_2S
iii	Rankinite	C_3S_2
iv	Gehlenite	C_2AS
v	Anorthite	CAS_2
vi	Monticellite	CMS
vii	Akermanite	C_2MS_2
viii	Merwinite	C_3MS_2
ix	Diopside	CMS_2
x	Spinel	MA
xi	Forsterite	M_2S

Now, when it comes to mineralogical composition what is identified is that there are several compounds that are formed in that are available in slag. So, about 11 compounds are definitely identified as a mineralogical compound in slag, and some chemical formulas are provided here. Remember that as I mentioned previously the mineralogical composition is still under research. And hence we do not have to discuss about the slide are very much in detail.

But you can understand that there are very many compounds that actually makes it very difficult to understand the slag.

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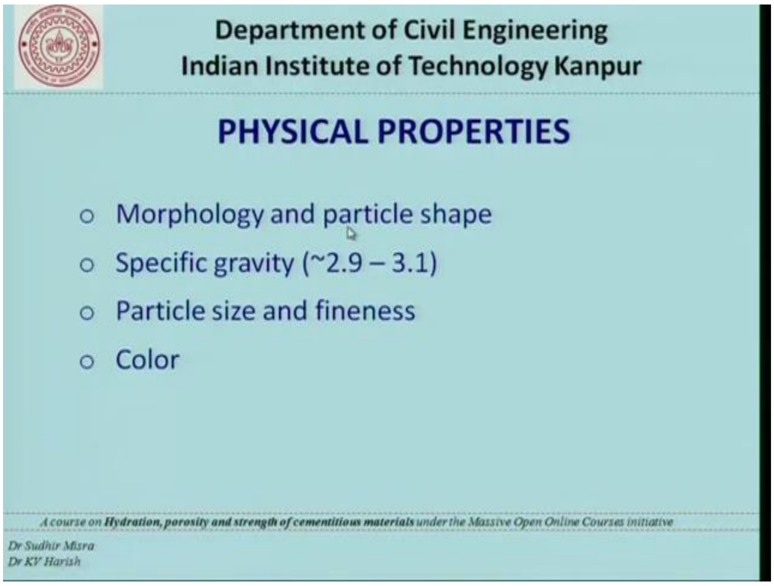

Now, coming to the physical properties; the important physical properties that are discussed on morphology and particle shape specific gravity and particle size and fineness and color.

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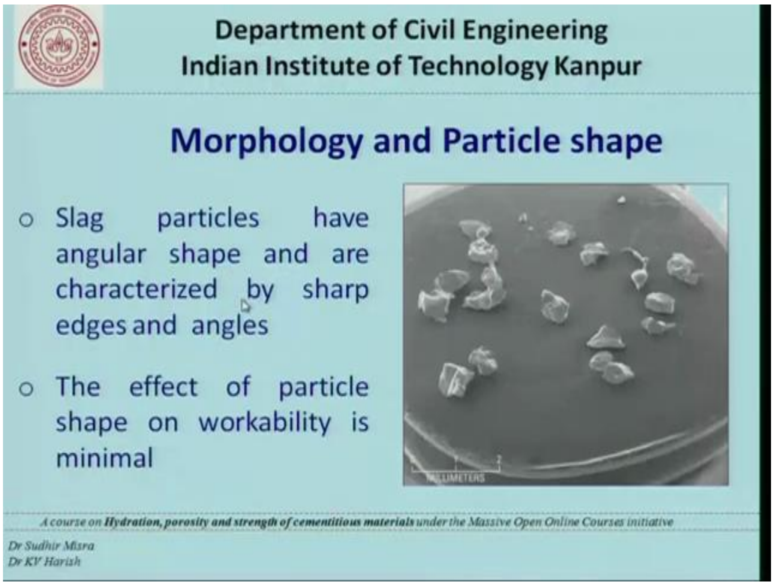

So, morphology and particle shape. Slag particles have angular shape and they are characterized by sharp edges and angles. So, this is pretty much similar to that of cement in the sense that the particle size is angular in shape. And this is typically what you see with slag particles. So, the particles will be completely angular in shape. The effect of particle shape on workability is minimum minimal. In the case of a cement what we have seen is the angular particle actually there is a problem for workability. In the case of fly ash what we have seen is the particles are spherical in shape that helps in providing workability.

In a case of silica fume what we have seen is the particles are spherical in shape, but the fineness of the silica fume is much more a dominating factor with regard to workability. In the case of a slag the particles are angular in shape, but he does not it is not a big factor when it comes to workability there are much other factors like particle size of fineness which are important factors for workability. So, shape is not really considered as important factor with regard to workability.

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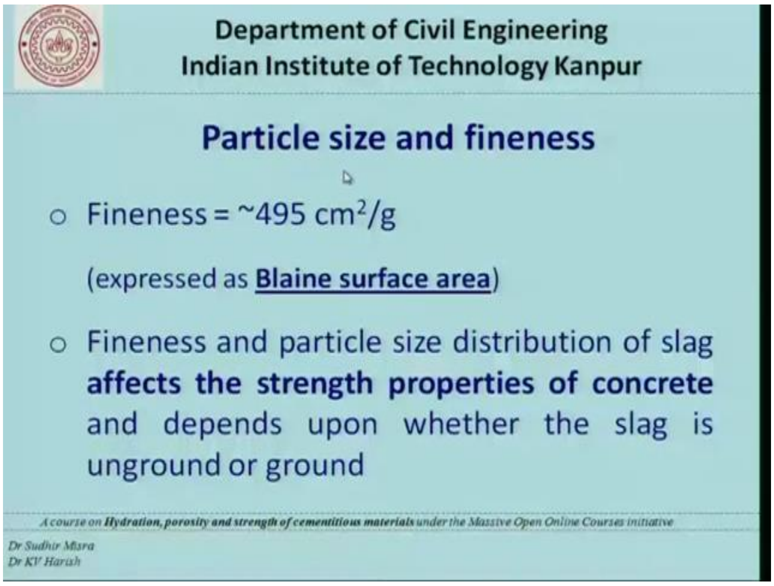

Now, coming to the next property which is particle size and fineness. The fineness of slag is approximately 495 centimeter square per gram and this is expressed in terms of blaine surface area. So, the surface area mentioned here is a determined based on blaine fineness. And the same procedure that is followed for the fineness of cement particle fly ash and others can be used for determining the fineness of slag particles also.

Fineness and particle size distribution of slag affects the strength properties of concrete and depends upon whether the slag is underground or ground. What you have to understand is that the material granulated blast furnace slag that we directly get from the plant is actually in the unground form. So, the question comes whether you want to grind it for finer or you want to have it without grinding. If you have it without grinding, then the properties of slag is not fully use for the application. So, in most of the cases the slag is actually ground to a very fine size and then it is used for applications.

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So, the next property is color in the case of slag is white in color. And a comparative color of cement slag silica fume and fly ash is provided again what you have to understand with respect to silica fume is that silica fume can also be in white in color, although it is usually dark grey or grey in color primarily because of the presence of carbon or iron, but remember that silica fume can also be white in color and likewise fly ash shown here is actually largely yellow in color, but remember that fly ash can also be grey or dark grey in color depending upon the quantity of silicon dioxide and calcium oxide present in fly ash.

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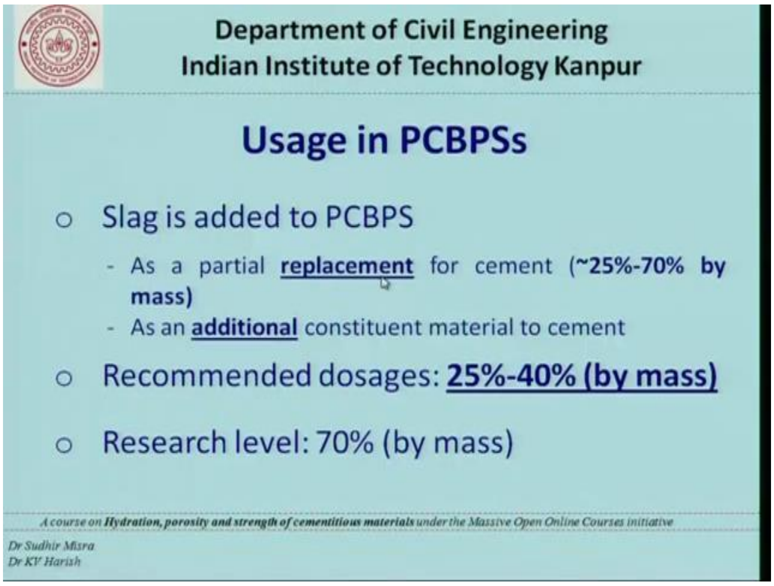

In the case of slag largely slag is white in color. Now when it comes to usage in Portland cement based paste systems slag is used as a partial can be used as a partial replacement material or it can be used as an additional constituent material to cement. In the case of partial replacement material, the typical dosages that can be generally used or between 25 percentage to as high as 70 percentage; however, the code the code provided recommended dosage levels is between 25 percentage to 40 percentage by mass of cement. And at the research level people have also gone up to 70 percentage by mass of cement.

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The 2 strategies that are used while using slag are as follows. Slag can be either added directly in the cement manufacturing unit. Or it can be used at the concrete making side it directly as a admixture in a concrete.

In the cement manufacturing plant again there are 2 things that are followed. One is the slag can be added to clinker and gypsum. And ground separately which means slag is separately ground clinker is separately ground and gypsum is separately ground and all these thing can be blended well and then used then doing that process. Many times the slag maybe ground or may not be ground depending upon the consistency that you obtained for the clinker and gypsum.

So, that is about separate grinding in the sense that the ingredients can be separately ground and then blended well. In a case of second one which is called as inter grinding slag clinker and gypsum are mixed together in desired proportion and then ground all together. So, many times what happens is in some cases the separate grinding is preferred because the energy required to grind separately maybe lower. In some other cases grinding all materials together requires higher energy. So, depending upon lower energy one of these is preferred in the manufacturing plant. And that the other way is that slag can be a slag of desired fineness can be added to concrete directly during the mixing process.

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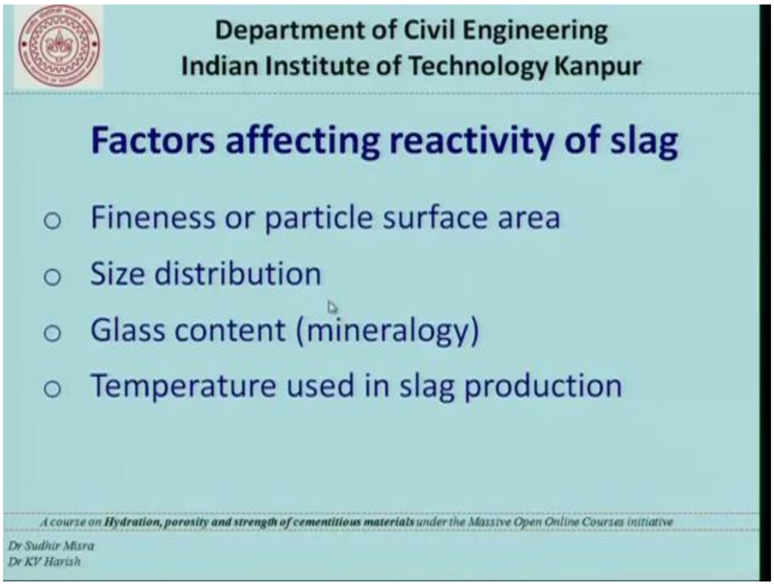

So, these are the 2 strategies while using slag in Portland cement based paste systems. Now is there any factors that affect the reactivity of slag yes we have several factors and largely some factors are physical properties and some factors are chemical properties. Fineness of particle surface area is a very important factor that provides the reactivity to slag and also the particle size distribution has immense effect on the reactivity of slag. In case of chemical factors, we have the glass content or mineralogy remember that again the mineralogy constituents of slag is not discussed elaborately in this lecture primarily because that subject is actually under research so, but we have to understand that the glass content in the minerals can actually affect substantially the reactivity of slag.

In addition to the physical and chemical properties you can also see that the temperature that is used in the production process can actually affect the reactivity of slag.

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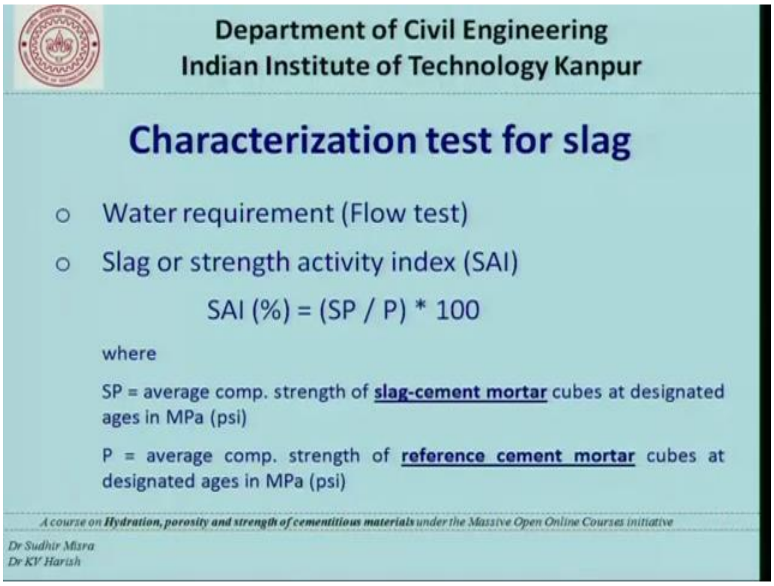

Now, when it comes to characterizing slag as a pozzolanic material in Portland cement based paste systems. 2 properties come in to picture one is water requirement the other one is slag or strength activity index. If you have again recall some of the characterization test methods that were performed for fly ash to serve as a pozzolanic admixture in cement based paste systems. What we found is that we had this type of taste like water requirement strength activity index or other test autoclave test or others that came into picture.

So, I am not getting into the details of water requirement and others because that that is already explained. Now we come to the strength activity index. Here in this lecture it is denoted as SAI and it is expressed as a SAI equal to SP divided by p into hundred and SP is nothing, but the strength of the mortar cube that is prepared using slag. And it is average compressive strength divided by the average compressive strength of the reference mixture which does not contain slag. So, if you find this as a percentage that is what is called as slag activity index or strength activity index. This factor is important and this is many times used to classify slag into different categories.

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So, now coming to the classification of slag, we do not have a proper is classification for slag, but we do have some ASTM standards ASTMC 989 provides the classification for slag based on slag activity index. And based on that you have 3 different grades. Grade 80 grade 100 and grade120 and all these things are based on the strength activity index.

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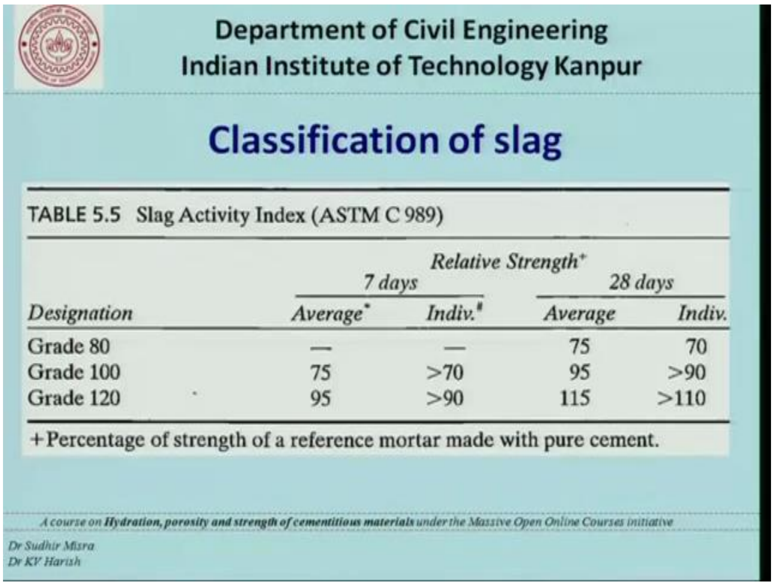

TABLE 5.5 Slag Activity Index (ASTM C 989)

	Relative Strength+			
	7 days		28 days	
Designation	*Average**	*Indiv.#*	*Average*	*Indiv.*
Grade 80	—	—	75	70
Grade 100	75	>70	95	>90
Grade 120	95	>90	115	>110

+Percentage of strength of a reference mortar made with pure cement.

So, to understand what is grade 80 grade 100 and grade 120 table is provided. And what you find is that in this table here you find the 3 grades and you find the relative strength compared to that of the control. So, if you consider a control strength to be hundred these are the values that these are the limit is that are specified for 7 days and 28 days. Right now for getting the 7 days let us go to the 28 days because primary the 28 days provides the design strength. So, what you find is that you have the average values that are provided and also you have the individual values.

So, for a grade 80 what is important is that the average 28 days' compressive strength that you find should be at least 75 percentage that of the control mixture. So, this is expressed as relative strength with respect to control mixture or reference moltar. So whatever slag that you are using if a 75 percentage average compressive strength or 28 days and remember that 75 and 80 are very close. So, then that slag is classified as grade 80 slag likewise if the relative strength is approximately 95 percentage which is slightly below hundred percentage, then that slag is classified as grade hundreds likewise 115 if the slag that you use has given 115 percentage of the strength that you get from control motor then it is termed as grade 120.

So, these things are very important and the information from the 7 days for this course is not required, and hence you can eliminate this. So, when you study this classifications study only from the standpoint of 28 days. Coming on to the next important topic which is effects of slag on specific properties of Portland cement based paste systems. As you already know that we have already covered fly ash and silica fume and how it affects different properties. Now here we will quickly go into the individual properties because we most of the slides shown are the repetitive slides for from fly ash or silica fume mixtures.

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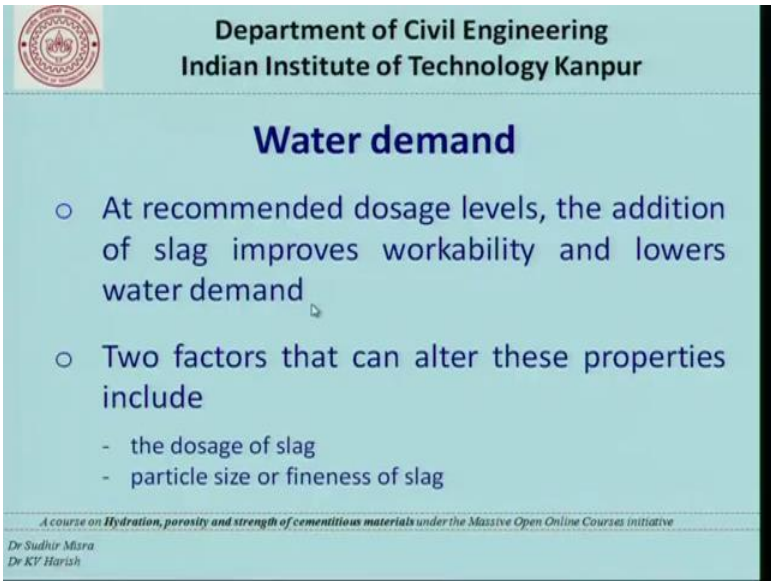

Now, with regard to water demand at recommended dosage levels the addition of slag improves workability and lowers water demand and this is primarily due to 2 effects one is that what is the dosage of slag that you use. So, like already mentioned in the previous point a, the recommended dosage which is between 25 to 40 percent. Typically, the workability increases, but remember that the moment you actually increase the dosage beyond 40 percentage then then the workability will be lower.

So, you have to be very careful with the dosage of slag that is used the second important thing is fineness of slag. So, if you use flag of very high fineness then that will that can also for reduce the workability and increase the water demand opposite of what we saw at the recommended dosage. So, the point here is that even at recommended dosage level you can also see that slag can actually reduce workability. And increase the water demand, but if it does that then we can be little sure that the particle size of slag is very small or in other words the fineness is very high.

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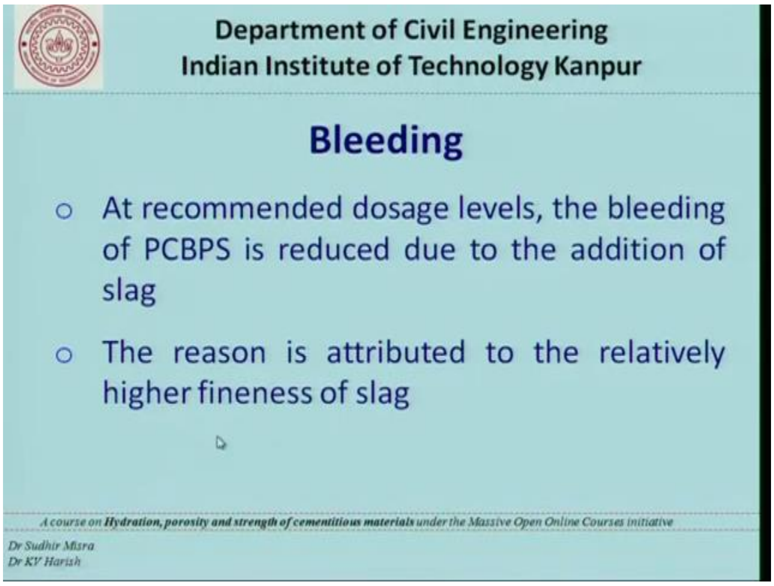

The second the important points bleeding and we find that the bleeding is reduced because of the addition of slag. And primary the reason is due to the higher fineness of slag particles. The same effect we have also seen with silica fume. So, the same thing holds good for slag also.

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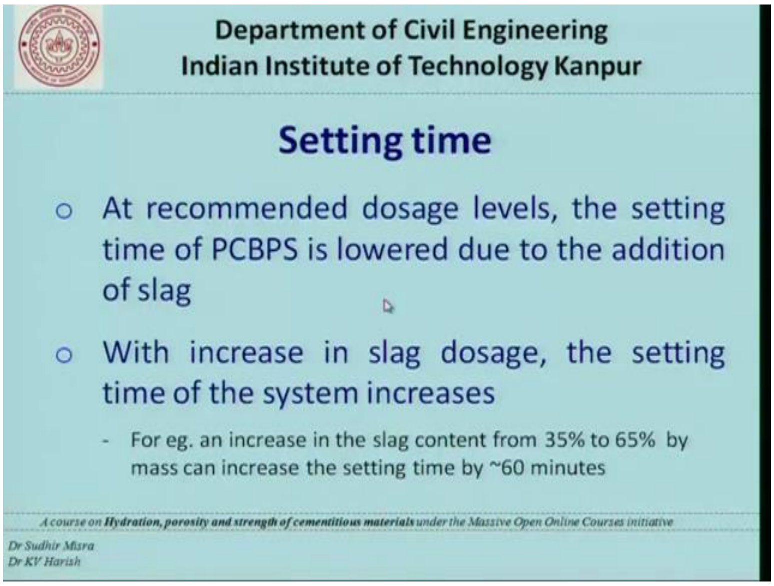

Now, coming to the setting time at recommended dosage levels the setting time of Portland cement based paste system is increased because of the addition of slag. And with increase in slag dosage beyond the recommended dosage the setting time of the system increases. So, for example, an increase in the slag content from 35 percentage to as high as 65 percentage can actually increase the setting time by 60 minutes that is very important point. When we go to setting time becomes a very important.

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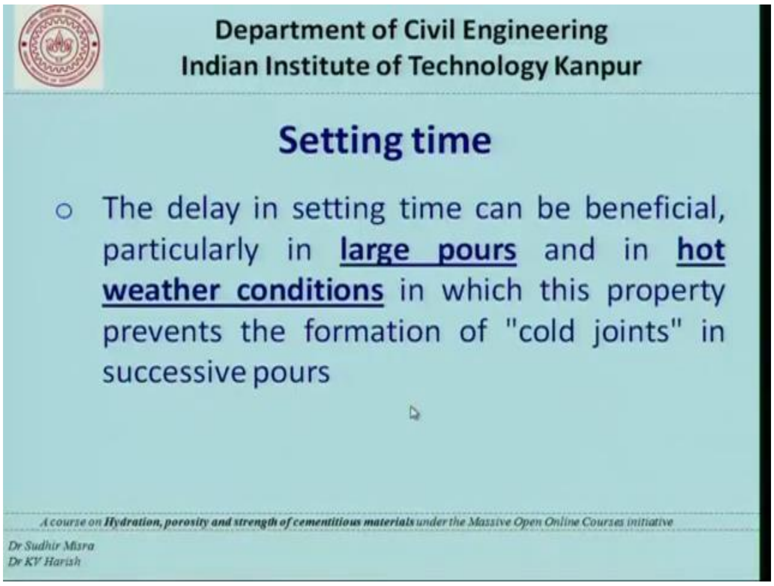

Ah factor when it comes to large volume of concrete. So if you take an example of dam or other structure where huge amount of concrete is used this, this point is very much valid the delay in setting time can be beneficial particularly in large pores and in hot weather conditions in which this property prevents the formation of cold joints in successive pores.

So, even though we have a negative thing with respect to slag addition. In cases where you have large pores remember that when you have a large pores huge amount of cement is present and when you replace huge amount of cement with slag the heat of hydration completely reduces. So, in places where the strength is less important the early age strength is less important and the heat of hydration is a very important factor then slag is a very preferred pozzolone compared to others. And likewise even in hot weather conditions where we want setting time to be a little longer slag is actually prefer primarily from the standpoint of cold joints and others.

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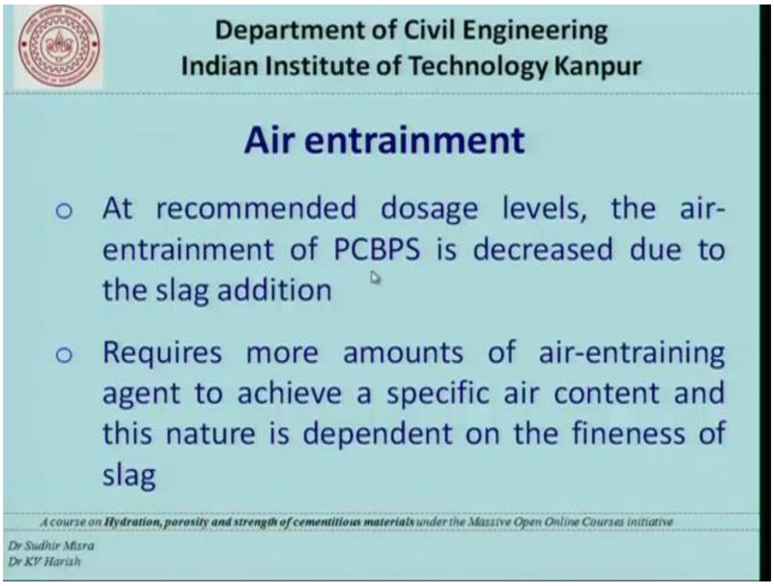

The next properties is air entrainment at recommended dosage levels the air entrainment of Portland cement based paste system decreases with addition of slag. And the this is similar to that of silica fume. And more air entraining admixtures are required to achieve the specific air content that is required.

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And this again depends on the fineness of slag. So, fineness of slag has a substantial effect on many properties of Portland cement based paste systems containing slag. Now if slag finer than cement greater amounts of much higher amounts of air entraining admixtures are required.

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Now, the next important property is compressive strength. What we can find is that with the addition of slag the early age compressive strength drastically decreases. This is one drawback of slag with respect to application is curve with respect to application; however, slag provides highest later extend which again can be converted into the advantage.

So, for applications where early age strength is required slag, is usually not preferred and silica fume is preferred. And for applications which require a later age compressive strength slag is largely preferred. The compressive strength of slag concrete approaches that of control concrete somewhere between 7 days to 28 days and beyond 28 days, we what we usually find is that the slag strength of slag concretes are much higher than the control concrete. So, the graph that we see for the fly ash and the silica fume the same figure is shown. So, where you find that the slag mixtures initially do not give much strength. So, when you compare it with the control mixture they are much lower.

However, with the time the slag mixtures gains strength and you can find that say above say 40 to or 56 days the strength of slag mixtures are much higher than even silica fume mixture or fly ash mixtures. So, slag has a very different property and because of that the applications for the usage of slag also varies. The dosage that is provided for rice husk ash is currently not required and hence it can be omitted for this lecture.

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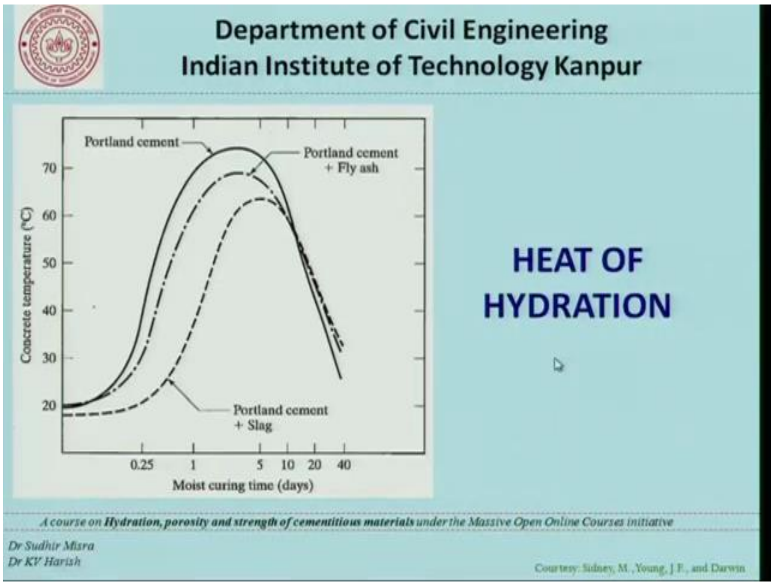

Likewise, you see the already seen heat of hydration graph where you can see that the use of slag substantial substantially lowers the heat of hydration in the Portland cement based paste system expressed in terms of concrete temperature um.

So, compared to Portland cement system the system containing slag provides much lower concrete temperatures. Likewise, the same we can observe with pore size distribution also in terms of pore size distribution slag based mixtures have much more smaller pores and the pores volumes are also much lower. Likewise, if you take the sulphate resistance slag cements are much more capable of providing much lower expansions compared to even silica fume fly ash or control mixtures.

But remember one thing very carefully that here the dosage is not mentioned and whatever dosage that we have seen is only recommended dosage. So, it is not at a fixed dosage levels so; that means, here fly ash is used at a typical dosage recommended dosage level of 15 percentage to 35 percentage. Here silica fume is used at the typical dosage level of 4 percentage to 12 percentage and slag is used as typical dosage level of 25 percentage to 40 percentage. If you do text where if you fix the dosage level of pozzolans in each of this in that case the behavior could be different. Some other mixtures could give better performance compared to the slag mixtures.

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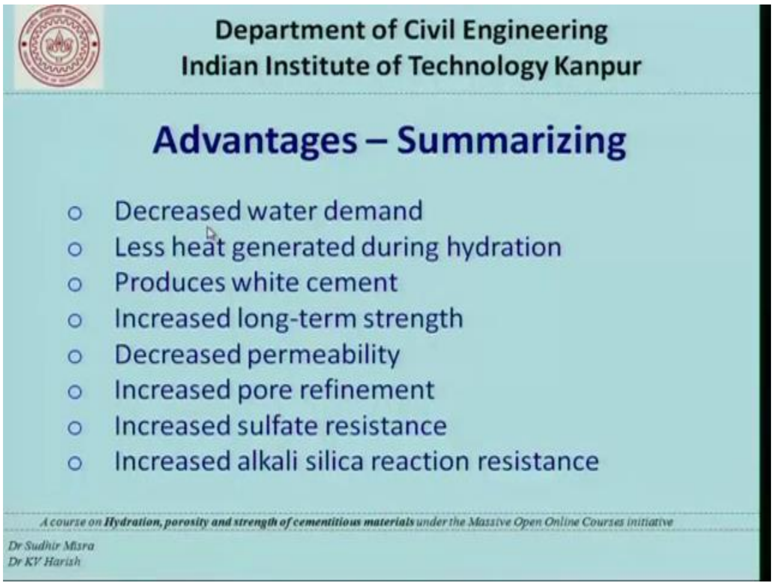

So, these replacement levels are at recommended replacement levels. Now summarizing some of the advantages of slag. Slag decreases the water demand. Less heat is generated during hydration. It also produces more whitish cement in addition to that it also has increased a long term strength, decreased permeability, increased pore refinement which means a smaller pore size, increased sulfate resistance and increased alkali silica reaction resistance.

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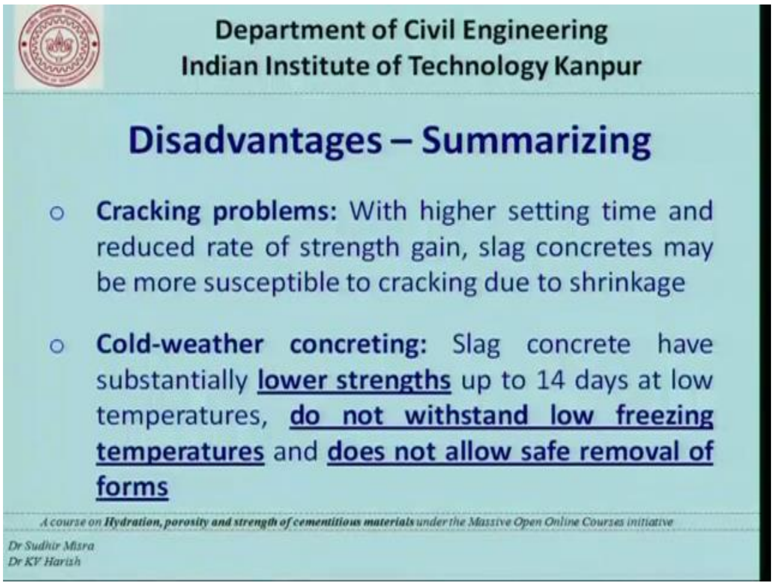

So, this is about advantages that does not mean that you do not have disadvantages. You also have disadvantages such as cracking problem especially because of the lower because of higher setting time and reduced rate of strength gain and others.

In addition to that, in the case of cold weather concreting the strength attained by slag based mixtures are very low and again when it comes to freezing and thawing environments the strength of the mixtures are very poor. And again when it comes to situations where we have to remove the form work as early as possible, even in such situations slag concretes have disadvantages.

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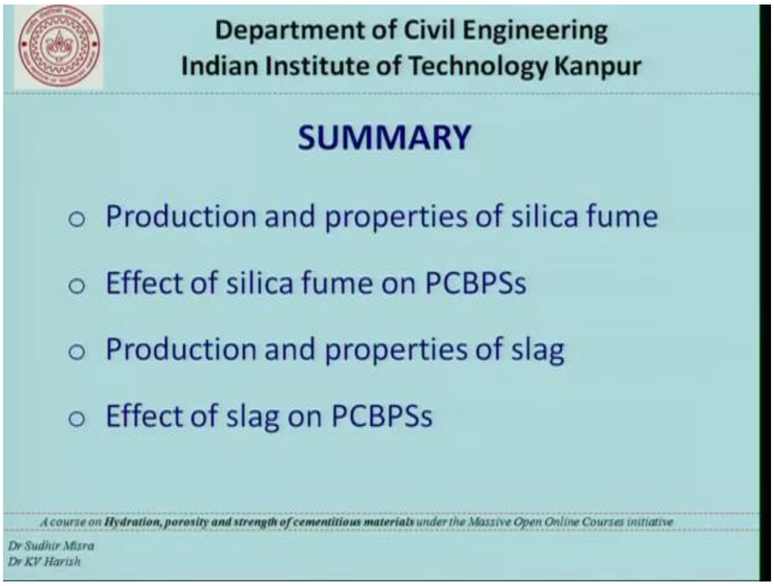

And in summary what we have seen in these lectures from 28 to 30 is that we have seen the production process of silica fume, we have seen the physical and chemical properties of silica fume, we have seen some of the important effects of silica fume on Portland on properties of Portland cement based paste systems. And similar things we have also seen for slag. At the bottom line what you have to understand is that even though mineral admixtures generally include very many things like slag fly ash silica fume and many times all these pozzolans are commonly called as mineral admixtures and or supplementary cementing materials.

The property the physical and chemical properties of each of these materials can immensely affect each of the properties of concrete when it is used as a mineral admixture in Portland cement based paste systems. And understanding the physical and chemical properties of each of these will actually help in understanding what property is it can what improved properties you can obtained with Portland cement based paste systems. So, with this the set of lectures from a l set of lectures from 20 one to 30 is coming to an end.

Thank you.