Admixtures and Special Concretes

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Lecture -37

Mineral Admixtures: Silica fume - Part 1: Introduction

So we will begin on slightly different material today. We talked about fly ash in the last lecture. So today we will talk about slag, then we will go on to silica fume, metakaolin and in general about calcined clays before finishing up this segment with limestone calcined clay cement which is one of the new technologies that people are looking at all around the world. So we talked about different types of fly ashes, type C versus type F, looking at the composition properties and the kind of performance you can expect in concrete which is made with these fly ashes, right? Let us start talking about silica fumes which are also known as micro silica depending upon the location you are in or sometimes the products are sometimes written differently, sometimes called silica fume, sometimes micro silica and so on.

Silica fume - Source:

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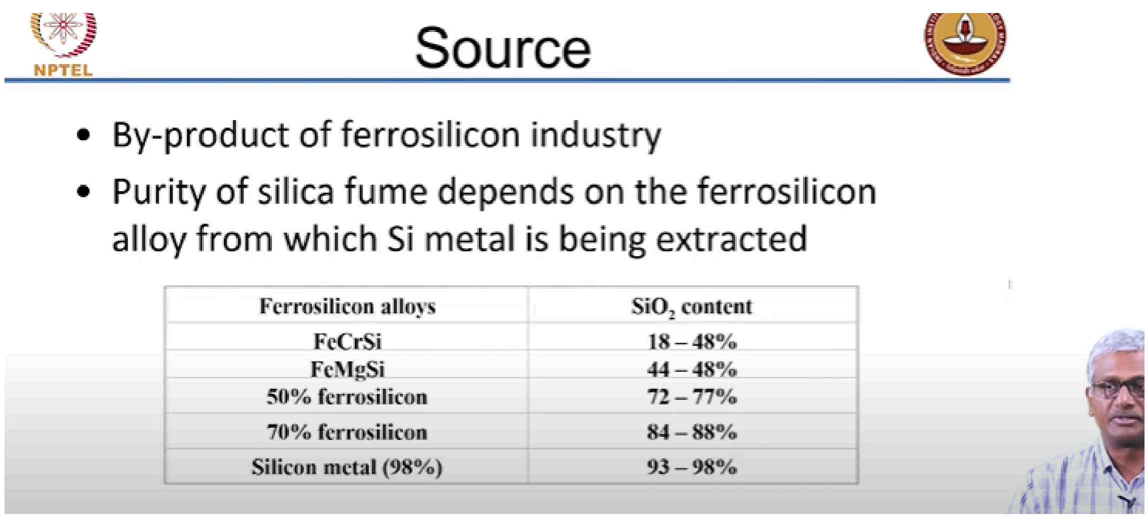

Ferrosilicon alloys	SiO_2 content
FeCrSi	18 – 48%
FeMgSi	44 – 48%
50% ferrosilicon	72 – 77%
70% ferrosilicon	84 – 88%
Silicon metal (98%)	93 – 98%

It is a byproduct of the ferrosilicon industry. So you are obtaining silica fume as a waste from the processing of ferrosilicon alloys. The kind of alloys have different types of silica content. Of course you are trying to get silicon metal, you are trying to extract silicon metal for the semiconductor industry and in this process there is a lot of fine silica that is getting released. The silica content will depend on the type of alloy that you are processing. So if you are looking at the impure alloys like iron, chromium, silicon combination, you will have only about 18 to 48% silica but if you go to the other end when you have pure silicon metal which is getting processed to extract silica from it, you get very high purity silica but mostly you deal with ferrosilicon alloys that will give close to about 85 to 90% silica content. So silica fume is high purity silica, you need high reactivity from this material and that is why we are going with the processes that involve ferrosilicon type alloys which have high content of silicon.

Silica fume – Production:

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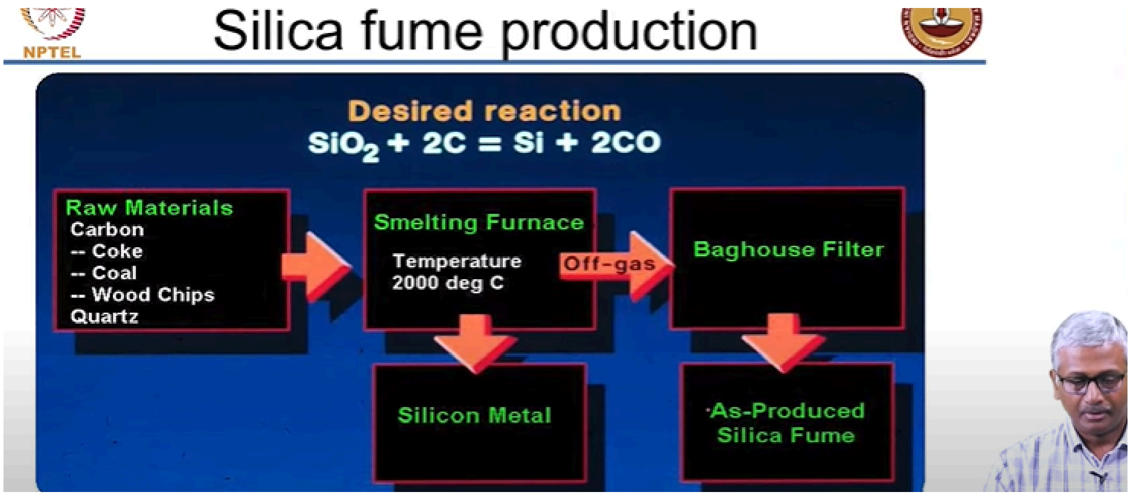

So silica fume is produced in the production process of silicon metal. So again similar to your steel production process of course which we will take a look at later on. Here also we use various different ingredients as raw materials, your quartz is a raw material obviously, and carbon source is your coke or coal or wood chips which leads to the burning. Quartz of course is just given as an example, it could be any of these ferrosilicon alloys which have different contents of silica. Silicon metal is extracted from pure quartz but all the other ferrosilicon alloys have some level of silica content in them. So these are the raw materials in the smelting furnace, you have temperatures up to about 2000°C which are used and the process essentially leads to a reduction of the silicon to silicon metal, from silicon dioxide to silicon metal and of course it is also releasing carbon monoxide as a gaseous impurity. At the same time a lot of the silica which is very fine is not getting converted, it is basically flying off and that off gas basically which carries the very fine particles of silica along is collected in a bag house filter and as collected not produced probably as collected silica fume is directly tapped from the bag house filter.

The process obviously leads to the production of silicon metal, so you can imagine that this is a highly specialized industry and because of the highly specialized nature of the industry the costs associated with silica fumes are quite high. The material itself is a waste but then it is sold for a very high cost in the cement and concrete industry because of the specialized nature of the industry from which it comes.

Silica fume – Collection:

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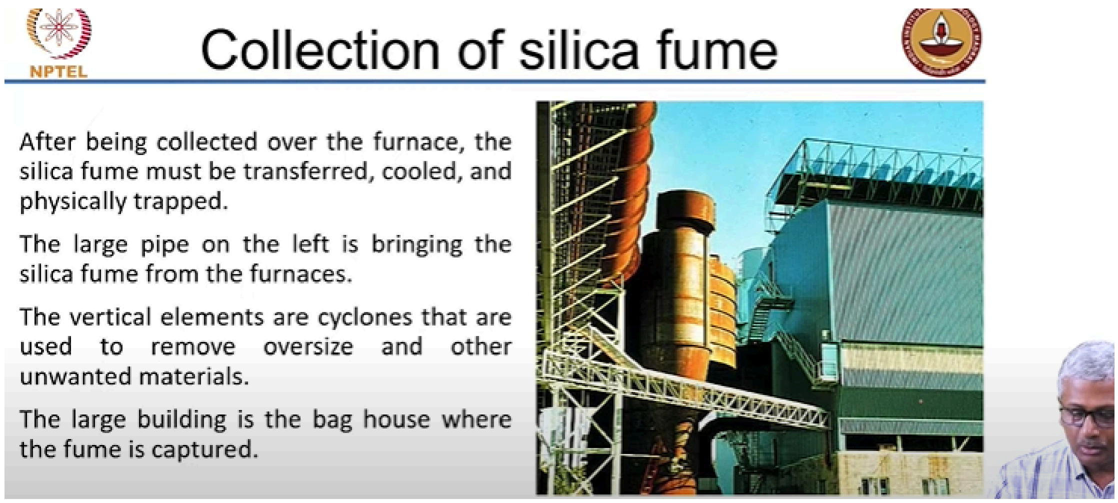

So again this is just a layout from a plant like this. I presume that the collection efficiency of particulate matter of the size of fly ash, the bag houses are probably not that efficient in collecting particulate matter of that size but here we are talking about very fine sizes and the bag house appears to be much more efficient but that is my guess I am not really 100% sure. So you can see the large building here houses the bag houses into which the off gas goes with the particles of silica fume and then it is getting collected on the bag.

Bag house precipitator:

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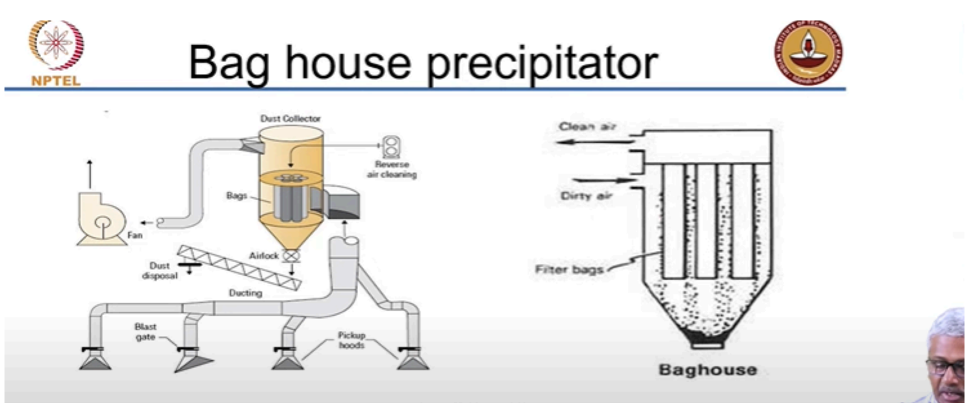

As the name implies the bag house filter is where you have the dirty air which is carrying the particles and these are the filter bags like these three are the filter bags and the powder basically is simply stuck on the top of the bag and slowly it falls and is collected at the bottom of the bag house filter. So this is the overall layout that you can find in Wikipedia also of this dust collector system bag house filters are used in several processes for dust collection and in this case of course we are collecting the dust and using it useful later on as silica fume.

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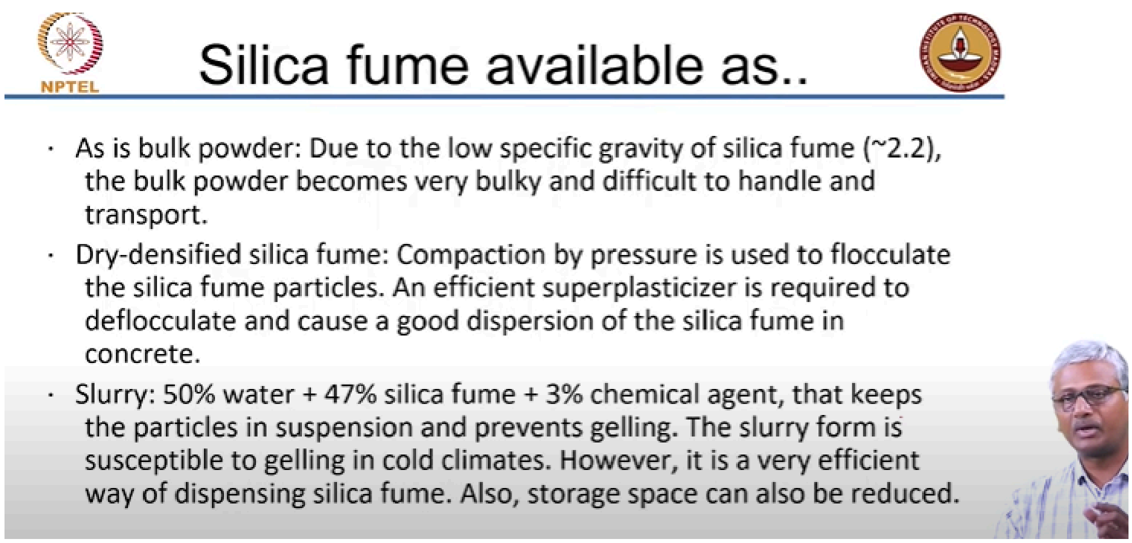

Now when you collect the powder itself it has got a very low specific gravity and it flies around everywhere because it is extremely light. The particle specific gravity is 2.2 but the particles are so fine we are talking about sub-µm size particles so these are flying everywhere. So when you try to pack such particles in a bag like for instance if you have a 50 kg bag of cement the particles are packing with some level of density there. The typical density of a cement bag is about 1500 kg/m^3 the density of the bag. I am saying the density of cement packed in a bag. But the same bag if you pack silica fume which is as collected you may end up getting only about 5 to 10 kg in a 50 kg size bag of cement and that is because of the fact that being extremely fine you cannot pack this material well together. So the collected dry powder is very difficult to handle and it just starts flying off.

I remember I did my bachelors project when I was doing my bachelor's degree here at IITM. My bachelor's degree project was on the use of silica fumes and high strength concrete. I had no idea where to collect silica fumes from. I found a source in Andhra Pradesh where I asked one of my friends to actually ship it to me. So he said that okay it is located at this godon go and collect it from there then I went to this go down expecting that okay I had asked only 10 kg. I thought it would be a nice small bag. I can just carry it back by bus in those days of course personal transport was very expensive. So then I found this bag. It was a huge, really big bag and the bag was so dirty because the powder was coming out of the pores of the bag itself. And finally I had to carry it back in an auto by the time I came I was covered in silica fume.

So it was that bad to handle and the powder is extremely fine because of which if you are working with the dry powder and if it gets into your respiratory system you can actually have problems of silicosis which is a problem which a lot of dust, basically fine dust can actually bring to people. So we need to handle it with care when it comes to the bulk powder because of which it is hardly available as a bulk powder because transportation and handling of large quantities is tough that is why we go for dry densification of silica fumes.

Dry densification means as the name implies in the dry state we are pelletizing or compacting the particles to make larger agglomerated particles out of these. Now while this is good for handling and transport because now you are shipping lesser quantities but when it comes into the concrete you have to remember that the mixing efficiency has to be good enough to break down these particles into the individual small particles of silica only then you get the high reactivity. So I have multiple particles which are flocculated together so the mixing should shear off these particles so they start separating and it is not just the mixing which will help also the presence of super plasticizer that will help in actually separating out these particles well enough so that they individually able to react with your lime and produce calcium silicate hydrate.

So reactivity of silica fumes can be enhanced when you have the particles liberated in a concrete so this happens because of super plasticizer and also because of efficient mixing essentially in the presence of aggregate. Here I should tell you that there are some studies where people have looked at the efficiency of mixing and its impact on the performance of silica fume concrete. In some instances if the mixing has not been good what people have seen is that these agglomerated balls of silica fume the pellets of silica fume just lie as pellets inside the microstructure of concrete and they may also act as reactive aggregate.

Now I told you earlier that reactive aggregate is also reactive silica pozzolanic material is also reactive silica so what is the difference? Pozzolanic material is extremely fine so the alkali binding or reaction that takes place happens very early in the life and it does not lead to any volumetric changes in the But when the aggregates are of a certain size the volumetric changes occur over a longer time period for the concrete and that leads to expansive stresses that cause cracking. So here some of these agglomerated silica fume particles could end up being sources of alkali silica reactivity that has been some research that shows that. So again I think we briefly talked about this earlier when we talked about compatibility with super plasticizers that when we start putting materials like silica fume inside we have to change the mixing sequence we also have to ensure that the mixing produces sufficient shearing to break down these particles. So that is why often when we add silica fume it is beneficial to add it along with the aggregate the coarse aggregate particles as they are moving past each other can shear the grains of silica fume and release the individual silica fume particles and only then you will get the full efficiency of using silica fume.

Again when you read research papers in silica fume you will see that in some instances people have used silica fume without any super plasticizer again that is a totally senseless thing to do when you are using silica fume you have to have a super plasticizer otherwise the flocculation in these particles will render silica fume totally ineffective. That is also another reason, I am connecting several things here but that is also the other reason why research studies that have worked with cement paste do not have the same impact of silica fume as research studies that have used cement mortar or concrete. In fact there are papers written about it as to why silica fume usage in paste is not as effective as in mortar or concrete but one of the primary reasons for that happening is you do not get this breakage of the particles which is needed. So to avoid this people also sometimes make silica fume available in a slurry form. So here you take the as collected powder and you make a slurry with mixing a lot of water in it about 50% water is mixed in the system and there is some dispersing agent which ensures that the particles are always in suspension but obviously like any other slurry or any other suspension of particles like this there will be gelling problems that can happen especially in winter. You have particles settling, you may have some coagulation that happens within the slurry and so on. So again when you are selling it as slurry first of all you are handling double the material. If you need 100 kg you need 200 kg of slurry and then you need to compensate for the water and the mix because otherwise you have excess water present in your system.

So slurry is difficult to handle but in some instances it works out well if you have problems mixing condensed or compacted silica fumes in your concrete. So dry densified is also called condensed silica fume or compacted silica fume but it is the most common form of silica fume available in the industry.

So a typical bag of silica fume dry densified silica fume will be 25 kg because the size will be approximately similar to that of a 50 kg cement bag. Even after dry densification the density is not high enough to pack into a 50 kg or mass of 50 kg cannot be packed into a regular cement bag. So that is again see we may think it is all a matter of identifying what is what but on the site the handling is being done by the people at the forefront who are not necessarily having the training and identifying what is cement, what is silica fume. So imagine instead of cement they use silica fume in your concrete. First of all they will be going on adding water because absolutely it is going to soak up every water that you put in. Secondly the concrete will not set at all because silica fumes cannot react on their own with water. So if the size of the bag is the same then the guy is totally confused. So you have to have some markings which make it look quite different. So all of this has to be done very carefully.

So it helps in better dispersion if you have water already suspending the particles of silica fume. It helps in better dispersion because the concrete when you mix the concrete the silica fume particles are available for reaction. So generally this is better for reactivity. Having a slurry is better for reactivity. The only thing is you need to compensate for the water that you have added extra. Silica does not react on its own with water. You need lime, you need calcium hydroxide that is generated because of cement hydration. So silica on its own cannot react with water.

Forms of Silica fume:

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So these are the forms as you can see here the bulk powder you can see how fine it is it is flying off everywhere of course there are some agglomerated particles there also but you can see the compacted particles it looks much coarser and seems to be not flying everywhere it is easier to handle and that is the slurry. This is a super plasticizer not the slurry that is the powder as collected. That is a densified powder and this is a slurry.

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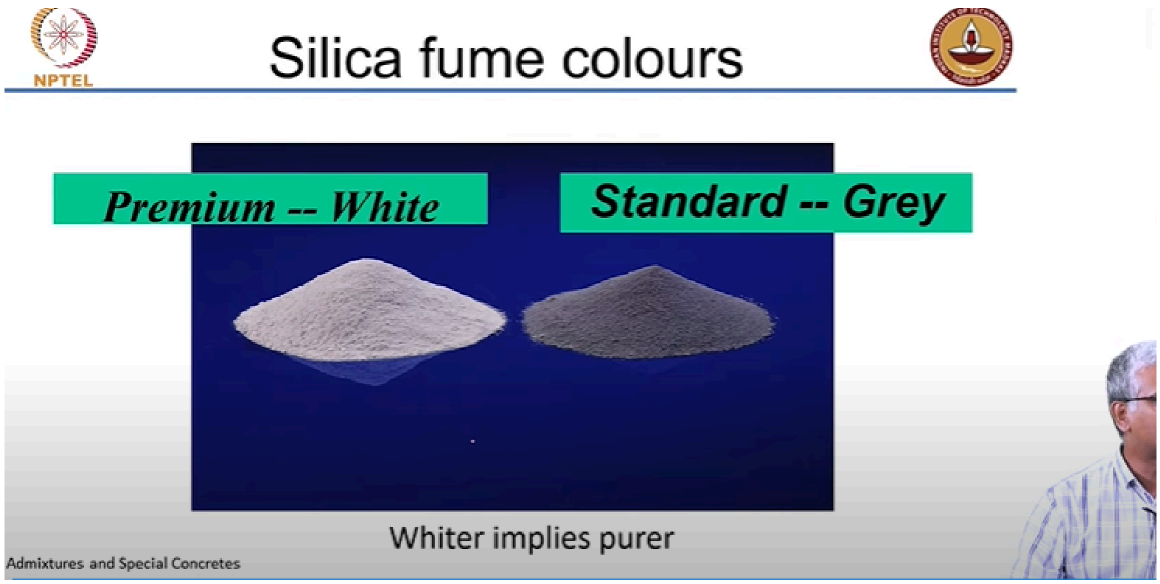

So the color will depend obviously on the other oxides that are present in the system. If you have a lot of iron present it will be a darker color which is impure. So this is with sorry which has more iron oxide present it will be darker in color but if it is a more purer form of silica it will be lighter color. So premium silica fumes are typically available as a white color.

There is also another product in the market which we call a silica flower. Now silica flower is not the same as silica fume. Silica flower could also be fine crystalline silica. Usually it is the fine crystalline silica which is obviously not going to be reactive at all. Silica flower is used in paints and things like that. In paints we use fillers. The right lot of fillers are used in painting limestone silica flowers; these are used in paints to thicken the paint and provide a good texture. So silica flower cannot be used for silica fume because it is not reactive. It is essentially crystalline; it is finely ground quartz essentially very finely ground quartz. Of course in this picture you have a bluish color. Maybe there are some other oxides which lend it to the blue color.

Silica fume physical properties:

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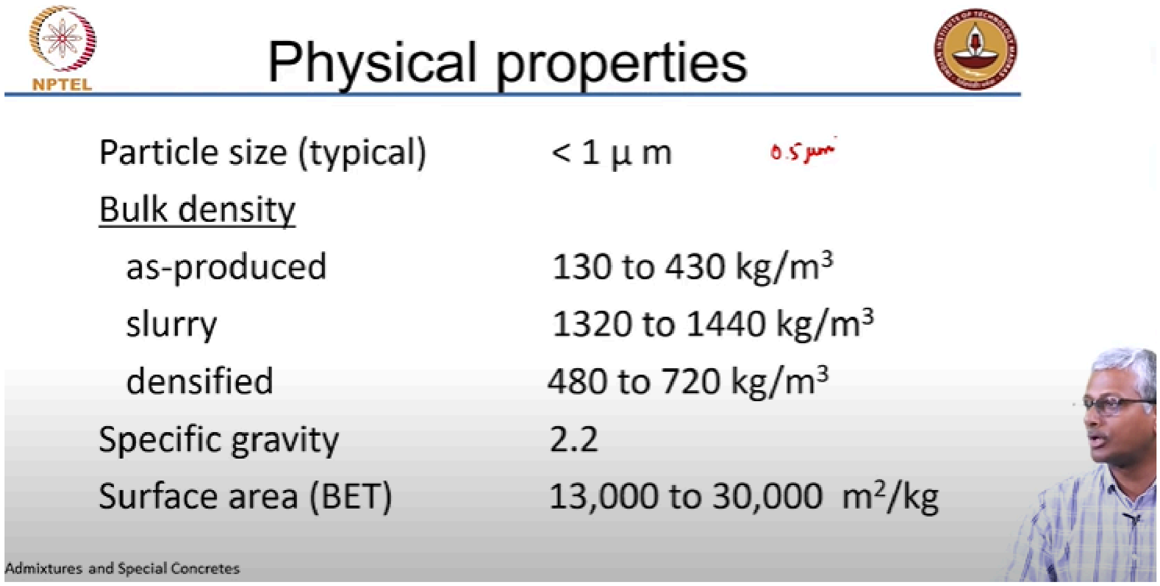

So these are the physical properties as I said we are talking about sub-micron size particles. More often the silica fume particles are close to about 0.5 µm average size if you take individual particles of silica fume. Cement was how much? 15 µm average particle size of cement is 15 µm. So here you are talking about a material that is 30 times smaller 15µm if we divide by 30 it comes to 0.5 µm so 30 times finer material is being used. So as produced silica fume or as collected silica fume has a bulk density which is very small but when you densify it the bulk density increases by at least 3 times because of which you are able to pack it in bags but still 25 kg bag of silica fume is looking similar in volume to a 50 kg bag of cement.

As a slurry of course you can pack in much more material so you can actually increase the density of the slurry. So this is gravity about 2.2 if you consider individual particles of silica fume and surface area if you do it as per this method called Brunor Emmett and Teller (BET) method which is based on nitrogen sorption of course the technique is not important here. Why I wanted to specify that here is that this is not the Blain's method. We are not using Blain's air permeability when we go for very fine materials. We cannot use Blain because it is not going to give us a result because air has to flow through this packed bed of material. With silica fumes if you take the as collected particles air will not flow through the bed of silica fumes because of which you have to adopt other strategies for determining surface area. This BET method which is nitrogen sorption is one more technique which states that the surface area of these particles is of the order of 13,000 to 30,000 m^2/kg.

Cement was how much? It was about 300 m^2/kg. So in terms of actual surface area we are talking about nearly 100 times finer 50 to 100 times finer. So you can imagine that this fineness lends itself to the high reactivity that is exhibited by silica fume.

Cost and Benefits:

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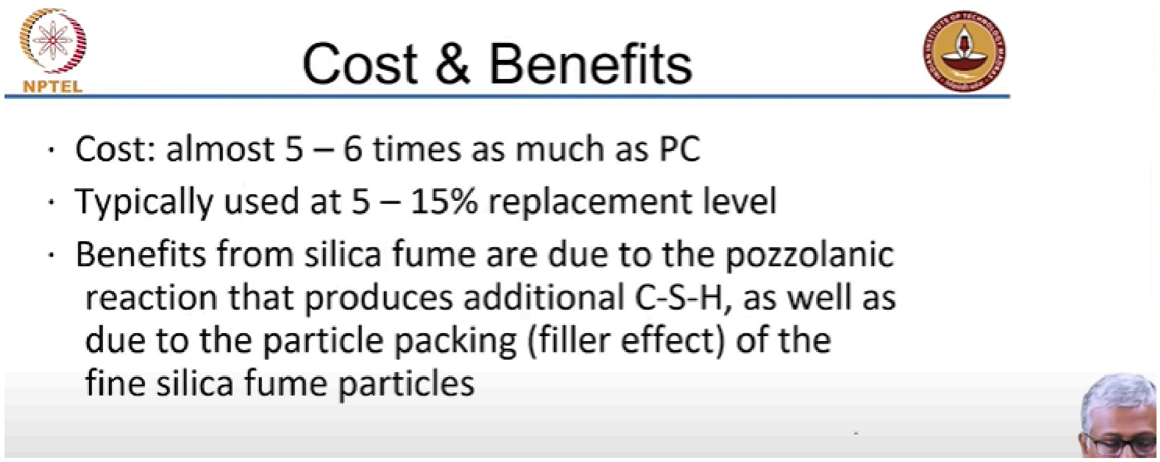

Now the cost is very high. Why is the cost high? It is a waste no. Why is the cost high? Some processing is involved. You need to collect it first of all and then you need to dry, densify or compact it. You are collecting it from an industry which is highly specialized. Instead of a thermal power plant where you are producing fly ash and you call it a waste, here you are producing a value added product from a ferrosilicon processing plant because silicon metal is used for semiconductors, nature of the industry is slightly more sophisticated and because of which the product that comes out is also being sold for much higher cost. So 5 to 6 times as much as Portland cement.

So what is the cost of cement? Per kilogram? 6 to 7 rupees in bulk, probably around 6 rupees or less. So when you talk about bulk silica fumes the cost will be at least 30 rupees per kg. There are cheaper versions of silica fume available also which are for a lesser price but around 30 rupees per kg for good quality silica fume. So you can imagine that using silica fume you need to be really justified in your choice for using silica fume otherwise the cost is going to go significantly higher. Typically we use it at 5 to 15% replacement level. Now when you talk about fly ash we look at 25-30%.

Why are we restricting ourselves to only 5 to 15% with silica fume? So silica fumes if you put in excess of it, it is going to react with lime rapidly.

There is not going to be enough lime present in your system anyway to compensate for so much additional silica that you add. So most of it will just sit there as filler but too much of it will also not be a good thing even if it is a good filler. Why? Cost is high, too expensive. Second, it increases the water demand tremendously. So concrete will not be able to be workable if you have too much silica fume inside the system. It increases water demand and if you are trying to compensate for the water demand by adding super plasticizer again your cost is going up. And the fine particles of silica fumes can also tend to make a mixture very sticky. So you need to be very careful in using the right dosage of silica fume. So while 5 to 15% is okay but more or less you will see any construction project where silica fume is used, it is usually always less than 10%. One would not be using much more than 10% silica fume as a replacement or an addition to the cement that is already present in the system.

Now of course benefits are obviously arising from the fine sizes as well as the extremely high reactivity with calcium hydroxide. So all of this lends to a much denser microstructure. Mind you again I have to distinguish between dense microstructure and density. Concrete density is not getting changed but the microstructure is getting more and denser. It is getting better packed. In other words you are reducing the porosity present in the system or rather you are making the pores finer and finer. Please remember that reduction in porosity may not always happen but the pore sizes are going to get reduced significantly when you use mineral additives like silica fume.

Effects on fresh concrete:

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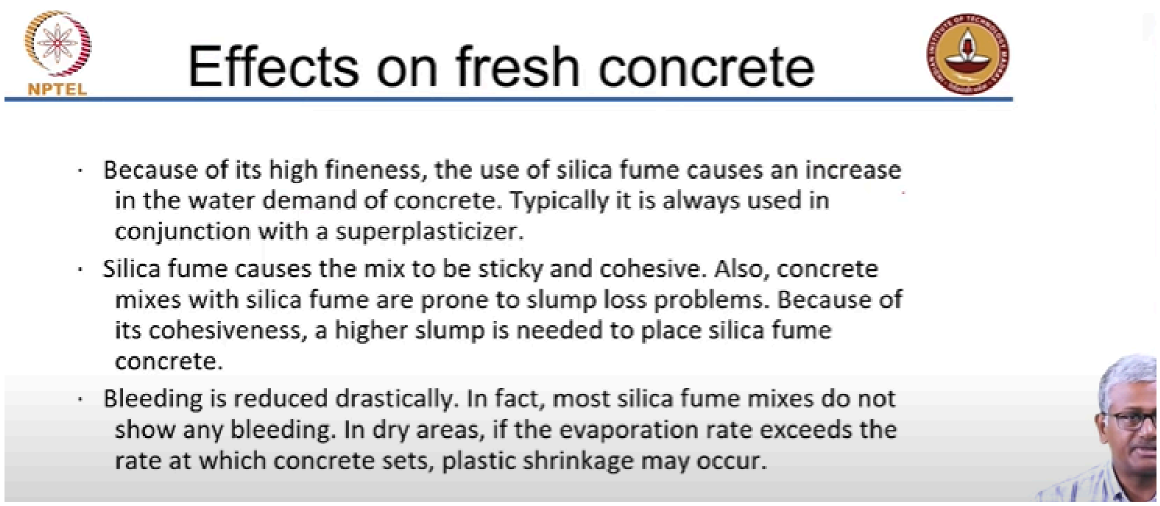

Now water demand is increasing so you need to compensate with a super plasticizer. If you see a research article or a published paper where silica fume has been used without a super plasticizer, it is not really worth reading the paper because it is something which cannot be worked out in practical situations.

Stickiness is often reported with silica fume mixtures. So if you are trying to pump such mixtures, it is going to be a lot of effort because it is going to start sticking to the pipe and pushing this concrete will become more and more difficult. If you put silica fume concrete on a slab and try to use a trowel to finish the surface, the material will stick to the trowel. Because of the fine particles it becomes really sticky. So all these are practical issues when silica fumes are used. So slump loss is again very large because water is not freely available to move around and then you need more slump to place silica fume concrete because it is cohesive.

After all, workability associates itself with many different things, not just placement or compaction but also finishing is an important aspect of workability. So if you have to provide the same level of finishing as conventional cement concrete, you may need a higher slump with silica fume concrete.

There is practically no bleeding. You cannot imagine that any water will be able to escape and come out to the surface and in such instances your tendency for plastic shrinkage goes up significantly. Again what is plastic shrinkage? So you have water evaporating from the top surface and the top surface the concrete is trying to contract but the bulk of the concrete does not allow it to contract and in places the top surface under tension and when that happens there is cracking that appears on the surface. Most of the cracking is restricted to the surface but with time these cracks can start growing and go all the way to the bottom of your slab and then allow for moisture penetration easily.

Plastic shrinkage cracking is not a structural problem to begin with but then it can start causing durability problems in the long run. So you need to be aware of reducing plastic shrinkage cracking. How do you do that? You need to start curing early. You can start sprinkling water or putting a wet cloth over the concrete right after the finishing operation has been done.

One of the common strategies that many people adopt for restricting plastic shrinkage is to use a wooden float and simply float and rub the cracks as soon as they appear. So when the cracks start appearing on the surface you take a wet wooden float and simply rub on top of the cracks you will get them to go away. But all this means that when you are actually attending to a surface like a slab which has a very large exposed surface area which can be susceptible to temperature, wind and other actions right. So plastic shrinkage is very high in a slab. In a beam it is not really a problem because most of your area is covered but in slab a lot of exposed surface is available.

So you need to have a lot more workmen on site to do this kind of operation and those workmen have to be very vigilant in the first few hours after concrete. That is when these cracks appear. So if you go away after finishing and come back after one day it is already too late.

One of the decks of the Chennai metro rail that was being constructed, I was called to inspect one such deck where water was actually leaking from the bottom. So water was actually gushing out from below the slab. So we went to the top of the slab and took a look. It was all cracked completely. The entire slab was completely cracked and it turns out that they used M60 grade concrete with silica fume self-compacting concrete. This was done sometime in August of course Chennai temperature is always above 30, August they are well above 30. These temperatures to avoid problems in such temperatures concreting is usually undertaken at night. They started around 2 or 3 am late in the night and the concreting continued up till about 9 or 10 am in the morning because there is so much volume to be done. So after finishing the top surface they only came back after 24 hours to do the curing. Interestingly none of them noticed any cracking at that point of time. They cured and somehow it also passed through the check of the PMC, maybe PMC was sleeping, but it passed through the check of the PMC and after about 2-3 weeks or so or no maybe even more they started seeing water gushing from the bottom.

Now what is going on here then you take a look at the structure from the bottom you could actually see some white deposits around the locations where the water is gushing out. What is the white deposit? Which is essentially your calcium hydroxide which is leached out by the water gushing out and gets converted to calcium carbonate upon atmospheric exposure. So you start seeing these leaching signs so you go up to the top of the slab and then everything is cracked.

So now the question is if they had taken action in the beginning none of this cracking would have led to the propagation all the way to the bottom and water gushing could not have been seen at all. At least the gushing was good from the point of view of them going and checking the top of the slab otherwise they would have continued the same process throughout.

Nevertheless very clearly this is the case of plastic shrinkage cracking wherever humidity becomes low or when wind is high you increase the chances of plastic shrinkage cracking and this is exactly what happened here. So what could be done to avoid curing is one thing, floating is the other what else can we do? You can use curing compounds early in the life cycle as soon as the surface finishing is done and some dryness because curing compounds cannot be applied on a wet surface. By that time sometimes it could be too late. Another thing is to simply cover the surface and prevent evaporation. In a lot of places they simply cover it with a plastic sheet and prevent evaporation that could also work to some extent. You have to be extremely careful when silica fume is used and that is why a lot of industrial flooring also is done with silica fume because they need good strength and abrasion resistance which silica fume provides but again if they are not careful with plastic shrinkage cracking because industrial flooring the exposed area is very large. In such instances if you are not careful with early age cracking you need to avoid plastic shrinkage at all costs.