

Particle Characterization
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Module No # 08

Lecture No # 21

Particle Cohesion: Flowability Implications

Welcome to the twenty-first lecture in our particle characterization course. In the previous lecture, we discussed cohesion which is the particle-to-particle adhesion force, when particles are suspended in a fluid. We defined various types of forces that become effective when you have cohesive phenomena happening.

We talked about capillary forces, which can be classified into surface tension forces and pressure forces. We talked about viscous forces, which can again be classified as normal forces and tangential forces. We also discussed the spring like forces, which again can be classified as compressive and tangential or shearing.

Now, these are forces that operate in addition to the normal forces, that we have previously discussed for particle to surface interaction, such as the Van Der Waals forces, and electrical forces, and so on. So, the combination of all these forces is obviously to provide a strong mechanism of adhesion or cohesion between particles that are adjacent to each other in a solution.

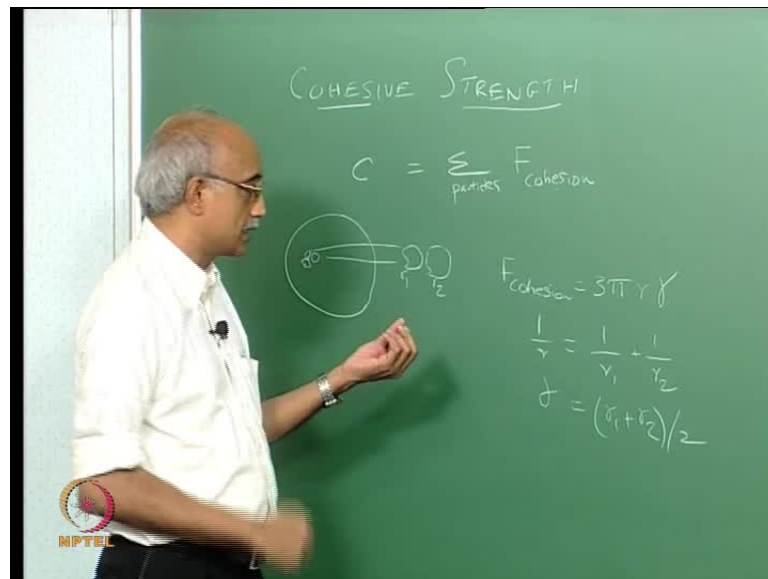
Now, is that a good thing or a bad thing? That depends on the application. For example, if you are trying to get a slurry to flow through a pipe line, and you want to maintain good flow of the slurry, then you probably do not want too much cohesion to happen, because that can interfere with a flow ability of the medium.

On the other hand, let us say that you are actually trying to formulate a product which requires that the particles be bonded together in a cohesive fashion. Classical example would be in the pharma industry. When you make a tablet, you want the tablet to remain intact; you do not want the tablet to fragment and become a powder.

But at the same time, you want to minimize tablet-to-tablet adhesion. So, for every individual tablet, you want very high cohesivity of the fine particles that make up a tablet. You know tablet is basically a collection of fine particles, right? So, you want the tablet to stay together as long as possible and really only dissolve when you actually put it in your mouth or whatever; but on the other hand, when you get tablets in a bottle, you do not want them sticking to each other.

So, these are interesting and conflicting requirements that the industry constantly deals with, but it is certainly important to characterize the cohesive strength of a tablet, which really depends on the cohesion between individual particles.

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So, when we are talking about the cohesive strength of any object, let us say that we define it as a c . This is really a summation over all particles that comprise that object and what you are summarizing or the individual forces of cohesion between pair wise particles. So, you take all the individual cohesive forces and sum them up, that will give you an idea about the total cohesive strength of the tablet.

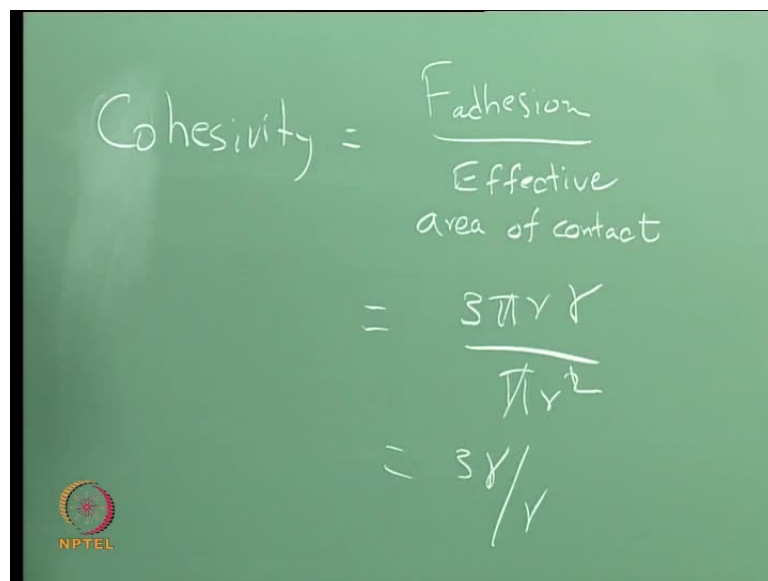
So, if we you have a large tablet like this, and you have many particles that comprise this tablet, what we are talking about? When we talk about F cohesion is these individual pairs.

How do the, how do a couple of particles that are close to each other interact? Whereas, when we talk about the strength - cohesive strength - of the entire tablet, you are talking about this entire array of particles and how intact the tablet is again under various stresses that you may apply to this tablet.

Now, this F cohesion is what we have been calculating earlier with a various components are contribute to cohesive behavior. In a simplistic way, the cohesive force can be modeled as 3ϕ or times γ , where, if this is r_1 and r_2 , this r is the reduced radius. So, $1/r$ equals $1/r_1$ plus $1/r_2$ and γ is taken as the mean of the surface energies of two adjacent particles.

So, essentially, in a very simplistic way, the cohesion force is simply taken as the multiple of an effective radius and an effective surface energy. So, this would essentially say that if you want to improve cohesive behavior, the maximum leverage is in surface energy.

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$$\begin{aligned}\text{Cohesivity} &= \frac{F_{\text{adhesion}}}{\text{Effective area of contact}} \\ &= \frac{3\pi r \gamma}{\pi r^2} \\ &= 3\gamma/r\end{aligned}$$

The image shows a green chalkboard with handwritten mathematical equations. The first equation defines Cohesivity as the ratio of F_{adhesion} to the Effective area of contact. The second equation shows this as 3πrγ divided by πr². The third equation simplifies this to 3γ/r. In the bottom left corner of the chalkboard, there is a small circular logo with a star and the text 'NPTEL' below it.

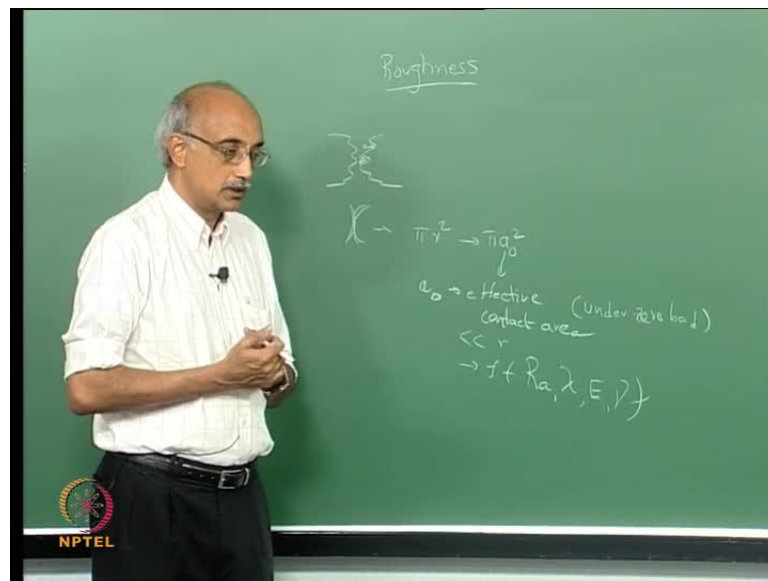
If you make particles that have high surface energy, they are likely to bond to each other fairly, strongly. There is a parameter called adhesivity which is equal to the force of adhesion divided by the Effective area of contact. If you look at this equation, something that you might find puzzling is we have always said that cohesion, the cohesive force increases as particles become smaller. Where, if you look at this equation, r is actually in the numerator, right?

So, that again is an apparent contradiction. This would say that as particles get larger, they are more cohesive. The reason is that when we say that particle size has an inverse effect on cohesion. What we are really talking about is this cohesivity or adhesivity parameter. Actually, in, in this context, it is known as cohesivity, because here, if you look at this expression, this is $3\phi r \gamma$ divided by ϕr^2 as an approximation. So, you can see that cohesivity itself has a dependence of 3γ over r .

So, this is more in line with what we have been discussing in this course so far that cohesion or adhesion, the tendency to adhere between adjacent particles scales with surface energy and scales inversely with size. However, the larger the particle, the most surface area there is, right?

So, even though the cohesivity or cohesion force per unit area may be less for larger particles. They kind of compensate simply by the size, because they have much larger sizes; they are able to achieve much greater adhesion forces or cohesion forces. Now, this discussion is obviously valid only when you have very smooth surfaces so that you can establish the area of contact or by simply modeling two smooth spheres that are near each other; but in reality, roughness plays a significant role.

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Now, the kind of role that it plays is depends on again the roughness asperities, and essentially, how well they match up against each other? Now, in general, roughness has an effect of reducing your area of contact, because instead of contact being between two fairly large contiguous surfaces. Now, you only you have intermit and contact between the peaks in your surface asperity. So, this has a tendency of essentially reducing your area from πr^2 to a πa_0^2 - where this a_0 is an effective contact area and the this a_0 can be significantly less than what we had earlier estimated as r . This effective contact area by the ways calculated under 0 load conditions.

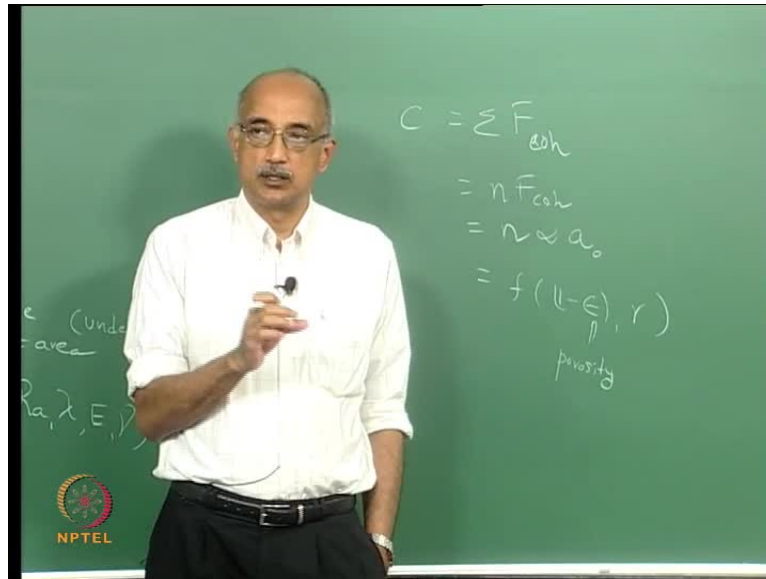
So, there is nothing pressing the particles against each other. They are basically in loose contact with the surface roughness providing the effective area of contact between the adjacent particles, and so, because the effective contact area is significantly reduced in the case of a rough particle, the adhesive force between two adjacent particles is also significantly reduced.

What is this a_0 depend on? The effective contact area is certainly a function of the roughness asperities both the height of the asperity as well as the distance between asperity peaks. So, it depends on an r/a value, a roughness height value as well as a frequency or wave length of roughness on the surface.

It also depends on the properties of the particles; particularly, again the elastic modulus and the poisson's ratio because they have a significant bearing on whether contact between two adjacent particles occurs in an elastic manner or a plastic manner, because adhesion or cohesion is again very very different in the elastic limit versus a plastic limit. In a plastic, in the plastic limit, the surface as tend to deform a lot more and there is much more accommodation of adjacent surfaces.

So, in general, cohesiveness will be much greater in the plastic limit compare to the elastic limit, and another way of looking at it is if you have two particles that are in elastic contact, again the contact area is going to be very small compare to two surfaces that are in plastic contact, where the contact area is can be significantly high, and so, for the same roughness, depending on the values of e and ν , that is the young's modulus and poisson's ratio. You can get very different kinds of behavior in terms of whether the adhesion is effectively greater for a rough particle or lower for a rough particle. The other consideration here is in terms of the total tablets strength as I mention.

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Now, let us say that you have going back to that formula c equal's summation over f adhesion or F cohesion. Another way to look at it is to say that this is equal to some n times F cohesion or n times the cohesivity, let us call that some α n times α times effective area a_0 .

Now, it turns out that this the strength of the tablet in addition to depending on these parameters which dictate the cohesive force between adjacent particles. In addition, it is also a function of 1 minus the porosity of the tablet. In other words, the more porous the tablet, the greater will be the or less will be the cohesion between adjacent particles.

So, high porosity, you know, if you if you formulate a tablet with high porosity, it is more likely to turn into a powder compare to one that has less porosity. So, in terms of manufacturing a tablet, one of the key considerations is always not to leave any open pores inside the tablet formulation to minimize any possibility of breakup, and of course, the, the size plays a big role also, because when you have a larger tablet, you have more effective interfacial area of contact between adjacent particles. The overall strength of the tablet tends to increase. Finer tablets actually tend to breakup more easily.

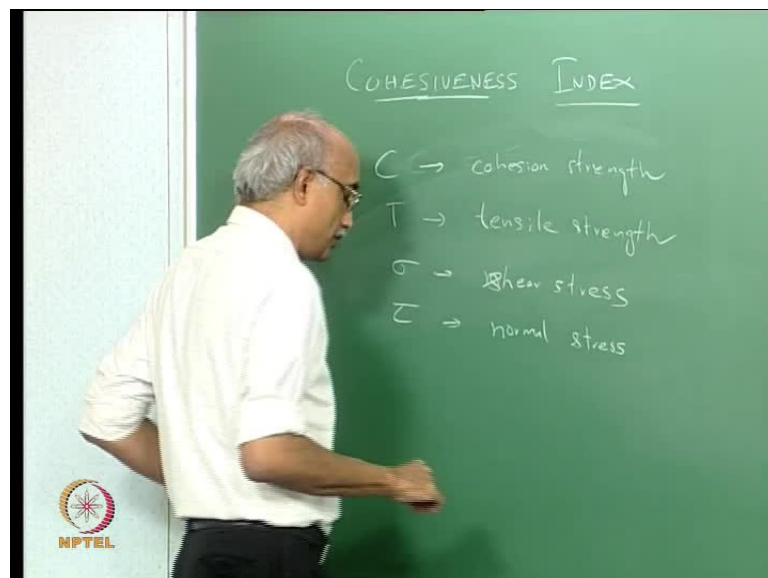
But that the difficulty with that is when you are trying to swallow the tablet, I am sure you have experienced is, a larger tablet is much more difficult to swallow than a smaller tablet. The reason for that is not only the physical size of the tablet, it is also the fact that the larger tablet does not dissolve as readily as a smaller tablet.

That's why everybody likes prefers to takes small tablets, because a - they are smaller and b - they dissolve faster in your saliva and in your gastric juices or in your blood. So, there are some interesting implications here for inter particle cohesion and its effect on the overall strength of a tablet that contains these individual particles.

Now, similar considerations of course apply in many different industries where you are trying to make a formulated solid product. For example, in the food industry, again, when you make condensed powders for various purposes, they consist of small particles, and in the case where you are using a solid formulation, again it is very important to be able to take this particles and produce a substance. That is very strongly adhere or cohesive as you ship it to the customer, but as soon as they use, it quickly breaks up in to fragments so that the ease of cooking is much higher.

Fertilizer industry again the formulation is very important. You typically want to supply in terms of, for example, pellets to a farmer. The pellets as soon as they are introduce in to the soil quickly break up in to their fragment. So, the pelletisation is another area where inter particle cohesiveness plays a huge role in terms of dictating the integrity of the pellet as a hole.

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Now, one of the considerations here is what we call the degree of cohesiveness? How do you define or how do you evaluate how cohesive a substance is? Say compare to another. So, people are try to come up with some definitions of this cohesiveness Index.

So, when we calculate this cohesiveness Index, obviously, this cohesion strength is involve that plays a role. As does what we call the tensile strength of the tablet? And other parameters that are involved in this definition are essentially the stresses that are applied. So, sigma, let us say is the shear stress that is applied for testing the tablet and let say there is a tau which is a normal stress that is applied to the tablet.

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$$\left(\frac{\tau}{c}\right)^n = \frac{\sigma + T}{T}$$

$n \rightarrow CI$
 $n \rightarrow 1 \Rightarrow \text{free-flowing } (c, T \rightarrow 0)$
 $n \rightarrow 2 \Rightarrow \text{highly cohesive}$

If you take tau over c to the power n and you equate this to sigma plus t over T, this is the equation that is used to define the cohesiveness index of the material; n is called the cohesiveness index. When n tends to 1, this is a free flowing material. When n tends to 2, it is a highly cohesive flow and values of n between one and two represent various degrees of cohesiveness.

Now, what do we mean by this? What does n tending to one mean? When that happens, c and T also tend to 0, because in the case of a free flowing mixture, essentially the cohesive strength is very very low tends to 0 and so does the tensile strength of the product.

So, c and t tend to 0 and tau then is equal to, in this particular case, sigma, that is, the normal stress on the shear stress that are applied essentially are balancing each other when you apply it to the mixture. In the case where n tends to two, the compressive or the cohesive strength of the material is significantly greater than the forces that are being applied to break the tablet apart.

So, this is an interesting equation, because essentially, what it says is by plotting the strength of the tablet versus the stress that you apply and looking at the slope, so, essentially you take a logarithm of this and plot this against a logarithm of this. The slope of the curve will yield the cohesiveness index for the tablet and you can decide whether it is a cohesive mixture or a non-cohesive mixture by looking at the magnitude of this index n .

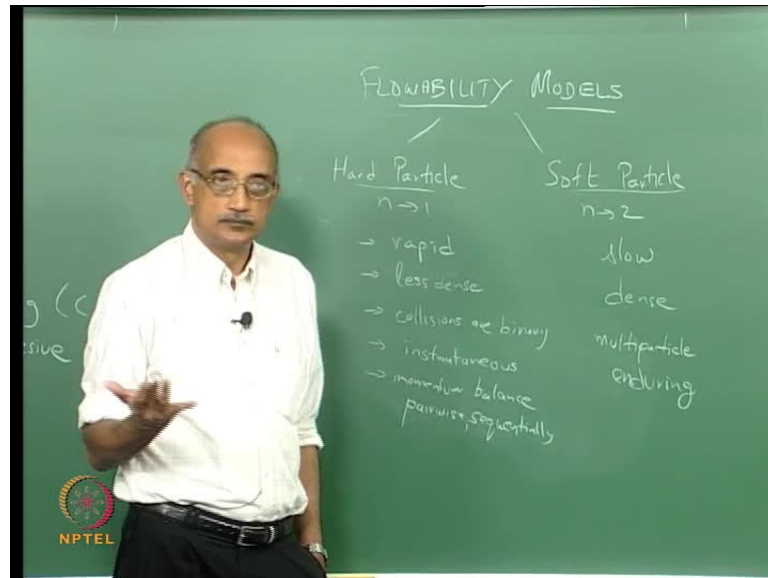
This type of cohesiveness testing or flowability testing is very important in many industries, because it affects wavy process these materials. Even simple things like grains that are being stored in huge silos, you know, classical problem that you deal with when you are talking about mechanical operations. For example, when you discharge the grains from the silo, the way that they discharge very much depends on their cohesiveness characteristics. So, if you have a grain storage where you are in the free flowing regime, then the material tends to discharge in a fashion. That is very very different compare to this, because the cohesiveness affects things like the repose angle of the material that stored. I am sure you recall repose angle is one of the parameters that really dictates how material is stored in a silo based on the angles that the material makes with the floor of the silo as well as the walls of the silo.

The cohesiveness has a bearing on essentially the correlation of motion between adjacent grains. So, the more cohesive the material that stored, the more correlation there will be between the motion of adjacent layers. So, as soon as you start the flow from a silo, as soon as one layer moves the other layer will also start moving in the same fashion, because it is correlated. Cohesiveness also affects the friction between layers. The more cohesive the material the less friction that is between the layers and the smoother will be the flow that is induced.

So, in this particular case, when you are discharging grains from a silo, is it advantageous to have a cohesive material or is it advantageous to have a less cohesive material? Less cohesive, true in general, but the advantage of cohesive flow is, in this particular case, it is more predictable, right? I mean you because it acts like one huge mass essentially. In the extreme case, when you have highly cohesive material, the whole thing behaves like a solid mass, right? So, it is, it is fairly easy to predict how that is gonna behave as oppose to a less cohesive mixture where the prediction becomes much harder, and the reason is every particle now will behave like an individual particle

and you have to predict the behavior of every particle in order to predict to behavior of the entire fluid.

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In fact, there are two models that are applied depending on whether you have a highly cohesive material or not. So, these are flowability models hence they are known, and the two models are - the hard particle model and the soft particle model. So, the hard particle model corresponds to the case - where n tends to 1 and a soft particle model tends refers to the case - where n tends to 2. What are the differences? One main difference is the in the case of the hard particle, you have a rapid flows, whereas, in the case of the soft particle model where you have a more cohesive flow, the flow will be slower. The hard particle model refers to cases where the materials are less densely packed, whereas the soft particle model applies to a case where the materials are more densely pack leading to more cohesion between adjacent particles or adjacent layers of particles.

Collisions are binary in the case of the hard particle model, whereas in the case of the soft particle model, you have multi particle collisions. As you can imagine, when you have a material which is completely non-cohesive, essentially there will be no correlated motion between the particles. So, one particle will essentially bounced against another and it will go in a different direction. So, the collisions become sequential. In fact, they are also instantaneous, whereas here the contacts are enduring. So, in the case of the hard particle model, you can assume that because of the lack of cohesion when one particles

strikes another, it is an instantaneous contact. As soon as the contact is over, the particles will move away from each other. The first particle will go in its own direction and the second particle will go in its own direction.

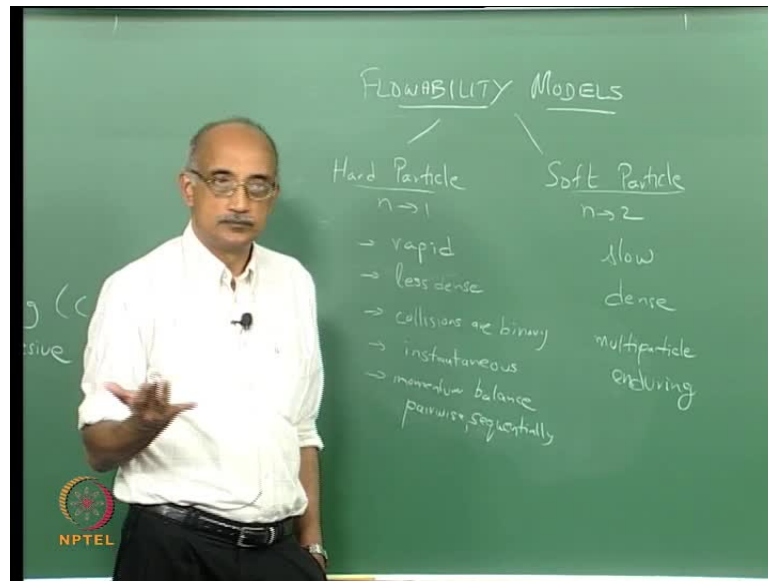
Whereas in the case of the soft particle model which applies for highly cohesive flows, when a particle touches another it tends to stick, and then, that will, then other particles will come and stick to this cluster. So, essentially you start to model clusters of particles and how they move and the contacts between these particles are enduring because there is nothing to break them apart. In a highly cohesive flow, any particles that come into contact tend to stay in contact, right? So, because of all these reasons, the cohesive flow which is represented by the soft particle model will be completely different from the non-cohesive flow which is represented by the hard particle model.

So, essentially here, if you want to develop a model, you will have to use, you will have to apply your momentum balances pair wise and sequentially. So, essentially, you will have to track each particle and look at what happens to it as a result of its collision with a nearest particle, whereas, in the case of a soft particle, you resort to essentially a two phase model.

When particles are highly cohesive, they essentially form a second continuous phase in the fluid in which they are entering. So, you go back to modeling of two phase flows and essentially you have to consider two separate continuum flows.

You have the fluid flowing as one phase and you have the particle flowing as one phase. So, you have to apply your mass balance, energy balance, momentum balance, etcetera for a classical two phase flow problem. So, clearly the mathematical approach to modeling will be very different, and as I said this is a more predictable model compared to this, because there is an element of uncertainty in this. It is more of a stochastic flow. When two particles collide, what happens to them afterwards depends on so many factors, especially, when you have non-spherical particles, because it can depend on the angle of impact whether, you know, flat surface impacts to the one on an angular surface or to angular phases impact on each other.

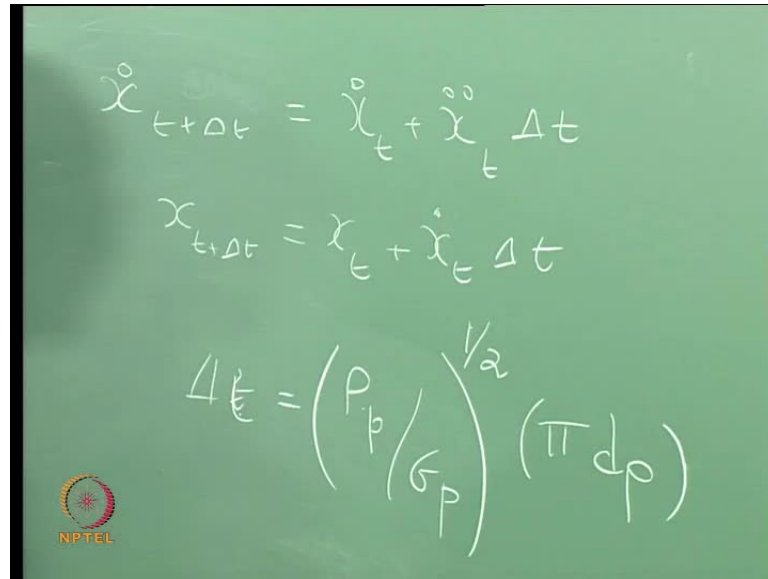
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What happens to the particles afterwards will completely depend on the direction of impact and also the surface area that that is in contact and so on.

So, it is become almost impossible to predict with any degree of confidence how particles are going to behave in this hard particle model. It is more like an Monte coreless simulation. You assume a high degree of uncertainty and you try to estimate the probability of how these particles will flow, whereas predictions in the soft particle limit can be done in a very deterministic fashion. You have a pretty good knowledge of how this phase is going to flow and behave as a function of function of time.

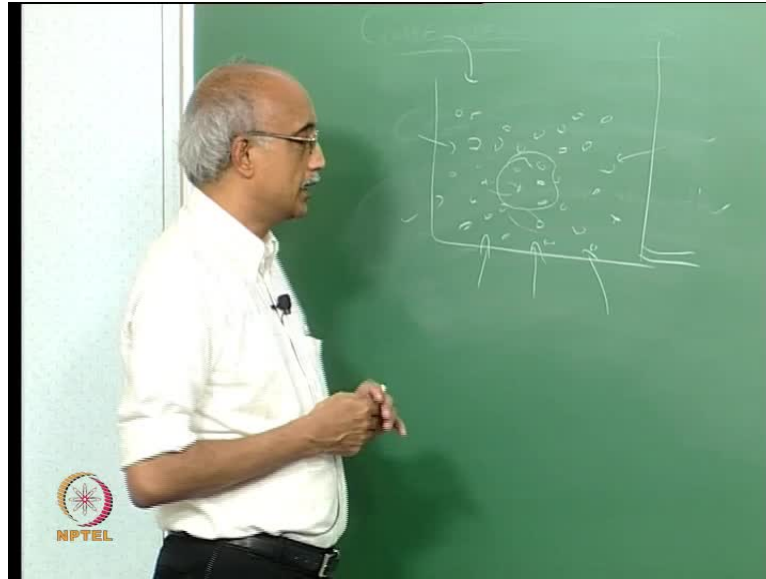
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$$\ddot{x}_{t+\Delta t} = \ddot{x}_t + \ddot{\dot{x}}_t \Delta t$$
$$x_{t+\Delta t} = x_t + \dot{x}_t \Delta t$$
$$\Delta t = \left(\frac{\rho_p}{G_p} \right)^{1/2} (\pi d_p)$$

One of the key parameters here in terms of modeling is a time step. When you are doing discrete element modeling or some kind of a finite difference type of an approach, you have to be able to define an appropriate time step to capture the characteristics of the flow.

Now, essentially the modeling will look like, now let us say that you have velocity at some time t plus Δt , this will be equal to x dot at t plus x double dot at t times Δt , you know, in simplest numerical approximation, and from that, you can calculate some x at t plus Δt equals x at t plus x dot at t times Δt , because this is forward differencing; you can also do central differencing or you know various types of approximations. This Δt itself turns out is very much related to two parameters, that is, the density of the particle and its shear modulus. In fact Δt is set as ρ_p over G_p to the power half times πd_p - where d_p is the diameter of the particle. It is suggested that the time step that you take be suitably customized based on the particle density, the shear modulus as well as the diameter of the particle. Basically what it is saying is as your particle size become smaller, you have to take time steps. As the density of the particle become smaller, you have to take smaller time step, and as the shear modulus becomes larger, you have to take smaller time step. So, essentially that time step has to be designed to be sufficiently sensitive to the flow characteristics of the suspension.

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The other thing when you are doing this type of modeling is, you know, any model is only useful when it is validated using experimental data. Now, the problem with experimenting on this, you know, as you can imagine, if you have a, let us take the case of a silo, in which, you have grains being stored, and let us say that liquid bridging starts developing because of, let us say simple humidity during storage, right?

And you want to feed in to the top and let us say you wanna discharge through the bottom here. So, what you would like to know is how flow able this material is; what is the flowability of this material?

Now, that can be modeled, you know, using those types of equations but you need experimental validation. The situation here those a little complex because when you have a highly densely packed material here, your experimentation the probes can only be stationed towards the boundaries. Otherwise, they become an inclusive effect themselves. So, experimentation is actually very difficult in the bulk of the particulate media that are traveling through the system. It is very difficult to do experiments on the interior of this fluid, but that is really the only way you can characterize the flow ability in an experimental fashion.

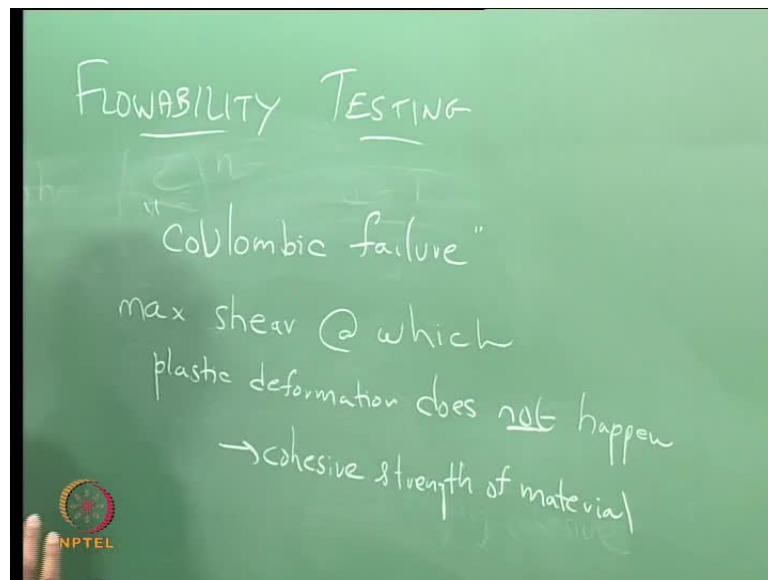
So, typically the approach that is used is to do your experiments around the perimeters and you do your predictions for the entire stored material, and then, you compare your predictions for the boundaries versus the actual measure data at the boundaries.

And as long there is good convergence between those two, you assume that because the model seems to be reasonably accurate around the perimeters, it is also going to be accurate in the bulk of the material.

Now, is that a reasonable assumption? It is not to say because when you talk about the boundaries of storage, the bounding surfaces play a significant role in determining flow. So, you know, if you look at particles here versus here, what is the difference? Particles in the bulk have many more adjacent neighbors, right? So, cohesive effects are much stronger in the bulk, whereas towards the boundaries, you essentially have only half the number of neighboring particles as you have in the bulk.

So, the particle to surface interaction becomes the first order effect and particle to particle interaction becomes second order effect. So, the fact that your theoretical model can match itself taken at the boundaries, does not conclusively say that your model is capturing cohesive phenomena equally well, and the other question, that, that we always face is how do you define flowability in general.

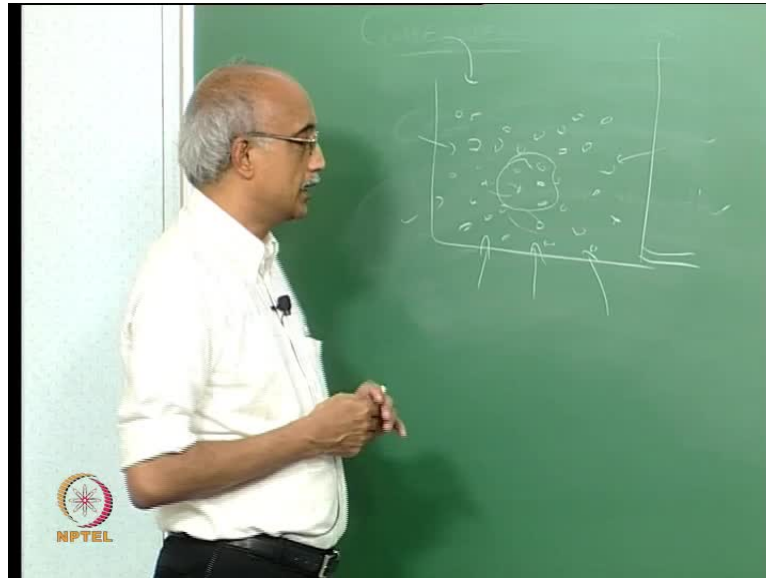
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You have to apply a certain stress and look at how this mass behaves under the given stress. Now, what stress do you apply? Well typically flowability is tested using a procedure known as the columbic failure mode which essentially says that you apply a certain shear stress to this pack of material and you find the maximum shear stress under which the material still does not undergo plastic transformation.

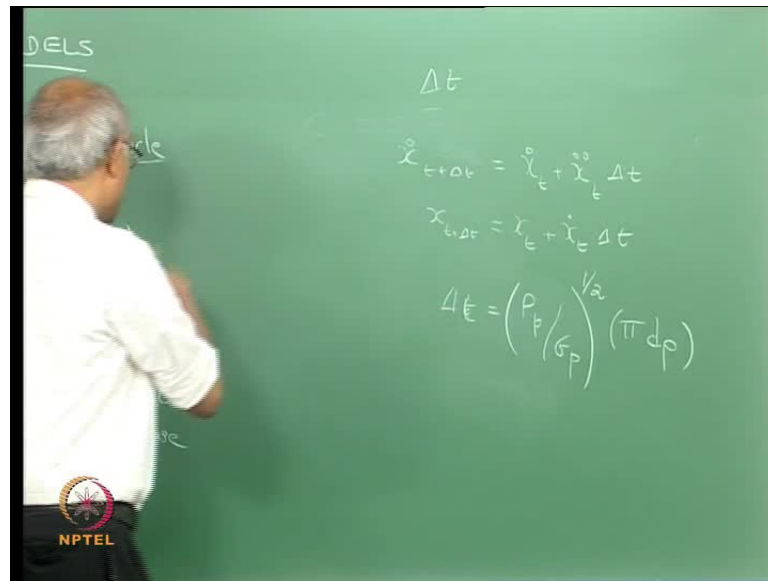
So, the maximum shear at which plastic deformation does not happen is considered a measure of the cohesive strength of the material. As the material becomes more and more cohesive, it is going to take a larger and larger force to make it flow, in, in a plastic mode rather in an elastic mode.

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And so, what this require is the use of shear testers. You have to apply shear stress and look for deformation characteristics, and again, that is why the problem comes in. It is fairly convenient to apply the shear stresses on the outsides and look at the induced flow, but it is very difficult to apply these shear forces in the interior or center or bulk of the material and note the induced flow characteristics.

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So, what that has made happen is that there is increasing dependence on coming up with accurate models that can predict how a mass of material will behave, when it is, when it is packed together tightly. So, that again, I mean this model itself you know depends very much on the cohesion model that you have built. So, unless you have a good theoretical prediction of the cohesive forces that are in effect, you really cannot, you know, predict this, because this is just a simple numerical scheme that tells how you particle positions are changing and so on. Whereas, you can imagine the velocity and the acceleration terms are very much going to depend on the forces that are being apply to the particles which are the sum of all those cohesive forces that I had mentioned earlier.

So, there is lot of premium on being able to predict cohesive forces accurately, because of the fact that experimentation is very very difficult in this area. Now, normally you see other way down, you know, for many parameters, it is easy to design experiments to empirically get data and then develop a model based on the empirical data, but particularly in the case of flow ability of granular materials, modeling is actually done more frequently and more effectively compare to experimentation.

With, with experimenting on the flow of **granular**- granular materials, there are two issues. You can try to be very very precise and that adds to the cost and complexity of the testing or you can do reasonably crude testing which will, which you do at low cost, but then, data that you get is of you know questionable value. Whereas modeling in this

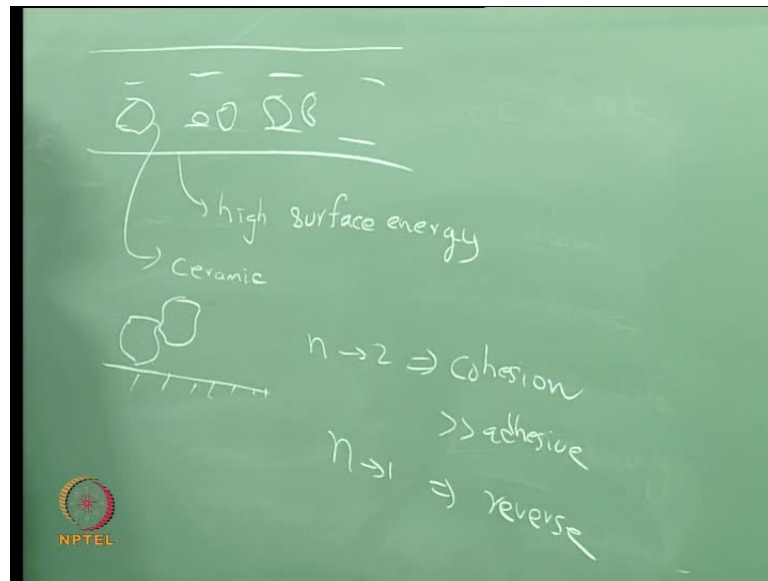
particular case it is fairly well established, and there are commercial c F d coarse that are available which can actually predict how granular material will flow under various conditions of charging and discharging and so on.

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The problem here, for example, is one that combines cohesion plus adhesion. Since it involves both sticking of particles to each other as well as sticking of particles to the nearest contiguous surface that they come in contact with, and this is fairly common in most problems where we are dealing with cohesion, you also simultaneously deal with adhesion.

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For example, flow of a material in a pipe. So, when we have pipe flow of a liquid with suspended particles in it, again the both cohesion and adhesion mechanisms come in to play depending on whether the particles are in the bulk of the fluid or whether they are adjacent to the surface that contains a flow. As the particles get closer and closer, they have to really choose between adhering to the surface or staying in cohesive contact with the neighbors, and here, the relative surface energies of the surface and the particle comes into play. For example, if your pipe is, let us say has a higher material, high surface energy material which is very common, because especially when you are using metallic pipes, the pipe surface has fairly high energy and the particles that are flowing, let us say that they are some kind of a slurry of a, let us say ceramic materials.

So, one particle - one ceramic particle - that is adjacent to another and also adjacent to a surface will essentially be making a choice whether it wants to adhere to the surface or remain coherent in the flow. Now, here is where cohesive flow I mean the cohesiveness index plays a huge role. When the cohesiveness index is high, then as n tends to 2 basically cohesive forces will dominate over adhesive forces.

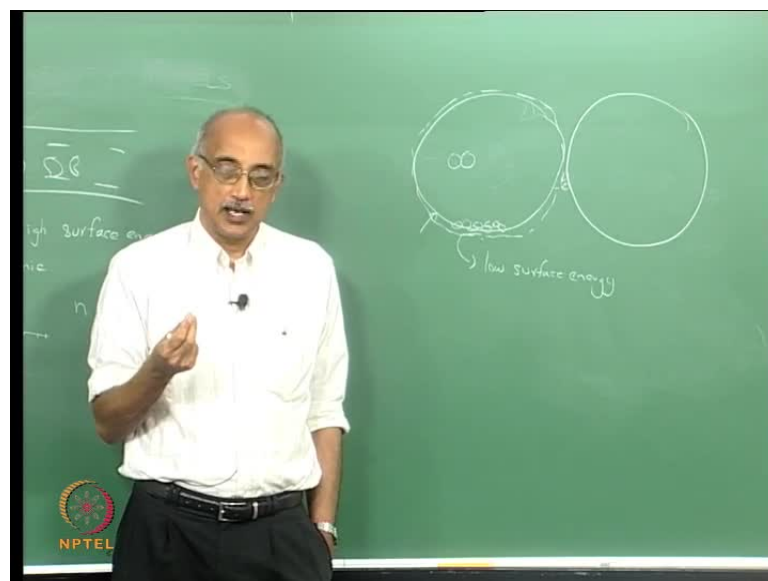
So, the particle cluster will essentially stay intact. Whereas n tends to 1, the reverse will happen and there will be a greater tendency for particles to attach themselves to the surface, and that is why, you know, when I asked earlier whether flow is preferably cohesive or non-cohesive, the answer was non-cohesive does not always apply, because

in a non-cohesive flow, it is also very easy to lose material because they can accidentally attach themselves to surfaces that they are flowing past; they can be substantial loss of material. Whereas in cohesive flow, the probability of that happening is very low.

So, it is actually a trade of there is usually an optimum cohesiveness index at which you get good flowability, but at the same time, minimum loss of material to contacting surfaces. In fact, it can be stated as an optimization problem and people have done that, you know, they can you can basically predict for various materials, for various applications, what is an optimum cohesiveness index to achieve what you are looking for, you know, high throughput, but at the same time, good quality.

Now, the other problem when you are flowing particulate suspensions is that the pressure drop becomes another issue. The more cohesive the flow, essentially the higher will be the pressure drop. That will be associated with the same flow rate. So, you will have to essentially pump order if you have more cohesive flow compare to a less cohesive flow.

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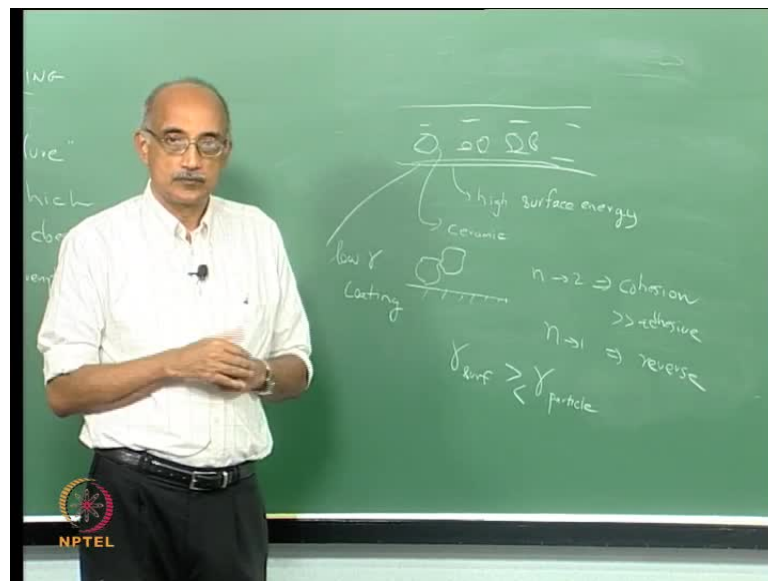


So, that again adds to the cost of the process and the affects the economics of production. Now, the issue that I mention earlier about when you have, for example, product, that needs to have different characteristics of inter particle adhesion. For example, if you have a tablet and you have particles in the tablet, you want these two to stick but you do not want this surface to be sticky. So that when you have an adjacent tablet, you want to minimize sticking between them.

Now is that possible to do, because you know the outside of these, if you look at it under microscope, is also going to be loose particle that are stacked against each other, right? So, how do you maximize adhesion between this layer of particles and next inner layer of particles, but at the same time, minimize their adhesion to the next tablet. Well, basically this is done by providing very thin coating around the outer circumference of the tablet and this is usually a low surface energy material.

You know if touch and feels a tablet or a capsule, it will feel very smooth and silky, and the reason is they actually have an additive that essentially coats the outer surface of this tablet or capsule or whatever it is, and it prevents it essentially from sticking to its nearest neighbor, but since its only applied on the outside, you are still not, you know, adversely affecting the integrity of the tablet itself, and similarly, in the case of material, that is flowing through a pipe or a tube.

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If you want to take advantage of a low cohesion flow, but at the same time, you do not want to lose material to the contacting surfaces. You do something similar where you apply a coating, a low gamma coating or plating or other surface treatment which will lower the surface energy of the surfaces that these particles are flowing apart, flowing past, because what really matters is the differential. Gamma surface is it greater than or less than gamma of the particle.

You want to design the system in such a way that the surface on which you do not want material to accumulate always has lower surface energy compare the surface energy of the material that is flowing past. As long as you can assure that, you know that the tendency to attach to the surfaces is going to be minimized and the particles are going to want to stay in the flow of the slurry or suspension.

These are some interesting aspects of particle flowability and the effect of cohesion and adhesion on the flow ability of such particles. It is also important to understand how particles move in general. You know what are the transport properties of particles? Because that again is of important in many many different processing industries, and of course, the transport mechanism of a particle - single particle - very much depends on its size and shape. So, the two morphological properties that we looked at early on this course turn out to be the two most important properties in terms of affecting the transport phenomena, that, that are prevailing.

So, we will conclude our discussion of particle adhesion and cohesion with this lecture, and from the next lecture onwards, we will move on to consideration of particle transport properties. We will start with simple concepts of particle dynamics however particle will behave dynamically in a in a flow, and then, we will look more closely at how various mechanisms of particle mass transfer influence the rates at which they move and at which they also deposit on surfaces that they come in contact.

Ok. Any questions on what we have talked about in this lecture or previous lectures related to cohesion or adhesion? Ok. So, I will see you at the next lecture then.