Rock Engineering

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Lecture-13
Failure Mechanism and Post-Failure Behaviour in Compression, Indirect Method for UCS

Hello everyone. In the previous class, we had the discussion on unconfined compressive strength test. We saw that what all are the various factors that influence the results of UCS test, then we saw that what can be the failure modes. So, I discussed with you that there can be 3 modes of failure and out of which I explained you that why all these 3 modes of the failure they are occurring.

And we saw that the first mode is the most common mode of the failure. So, today we will extend our discussion from that point onwards and we will see more details about the failure mechanism. Then, we will see some aspects related to post peak behavior of the rocks under UCS test. Then this will be followed by the discussion on some of the indirect methods that are used to determine the compressive strength of the rocks.

Because in case of the poor rocks, it may not be possible to get the regular specimen with L/d= 2 or between 2 to 3. So, therefore, we need to have some kind of an indirect method in such cases, so that we can find out the UCS of rock. So, let us start with the discussion related to failure mechanism of specimens in compression. I mentioned to you that be there are 3 modes of failure.

The first mode was comprising of that at the end that is at the failure you will get 2 end conical fractions along with the highly fractured zone. So, all other part except for the conical regions to end conical regions you will get heavily microcrack area. So, why that is happening? Let us try to get the answer of this why today.

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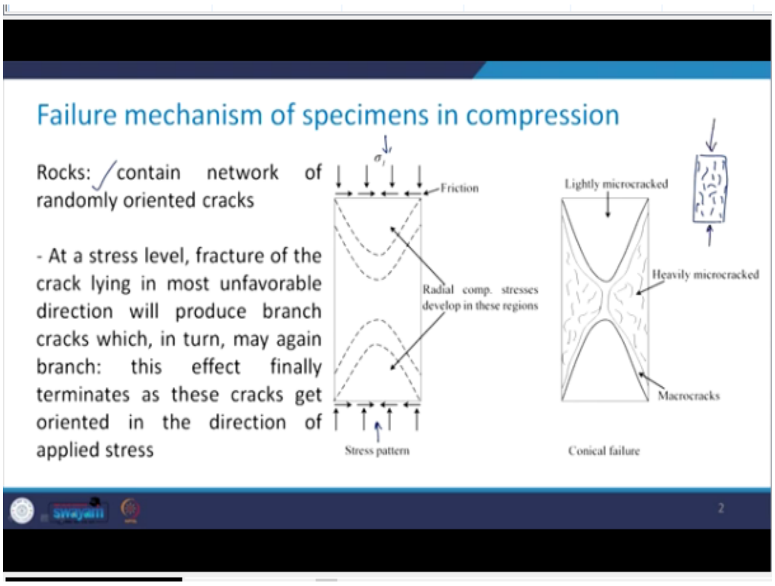

We all know that rocks have network of randomly oriented cracks, we call them as micro cracks or micro fractures. We do not count these under the category of discontinuity or joints. So, any intact rock will have these micro cracks. Now, when we conduct the test, we do not apply the whole load in one go, we apply the loads in increments. So, let us say from the 0, I incremented it to let us say, some value of σ.

And then we keep on increasing till the failure of the specimen occurs. So, what happens when we apply the first increment or the initial increments? The cracks are oriented randomly. So, their orientation is in all the direction. Now, the loading is applied in this direction, that is, in the axial direction which is vertical here. So, what will happen in the initial phases of the loading, whichever crack is lying in the most unfavourable direction, that crack will start propagating.

And it will produce the branch of the crack and with the increase in this load, what will happen is, this branch will again branch. So, you have initial crack upon the application of the load. This branching will take place and these branches will again develop further branches. This is called as branching effect and this effect will finally terminate as these cracks get oriented in the direction of applied distress.

So, you see that earlier, if this is the specimen earlier the cracks are oriented in any kind of fashion. Most randomly they are oriented. The moment you apply the load the crack which is lying in the most unfavourable condition with respect to the application of this load, it will start propagating. It will develop its branches and these branches will further branch and what will happen that slowly this branching effect will be in such a manner that all these cracks will slowly orient themselves in the direction of the applied distress that is this one.

Now, what happens to the next most unfavourably oriented crap? Because the one which was most unfavourably oriented that has aligned itself in the direction of the loading. So, but still we have not reached up to the failure.

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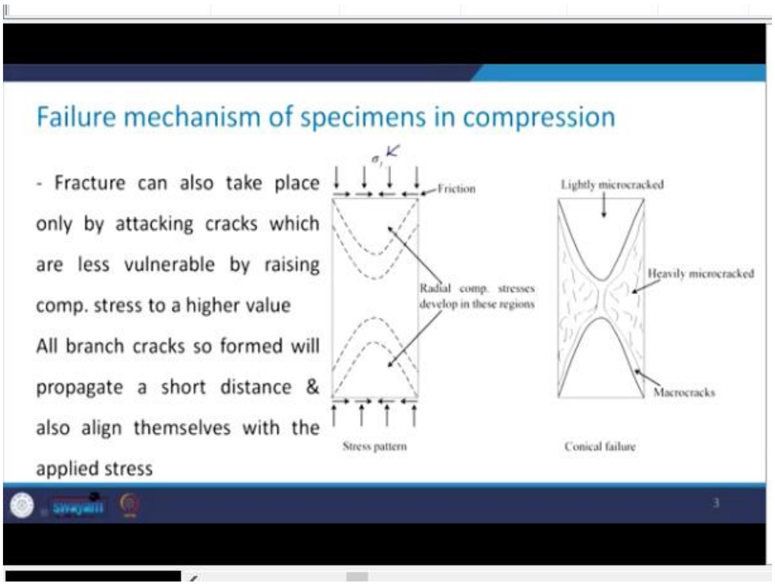

So, we are still increasing this axial stress which is, say, σ' here. Now, these fractures can also take place only by attacking the cracks which are less vulnerable when you increase the compressive stress to the higher value. Now, what happens when you increase this value of this applied stress? All the branch cracks which are found they will propagate to short distance and again they will align themselves in the direction of the loading, that is again in this vertical direction.

So, this process will continue till all these cracks they orient themselves in the direction of the loading. Slowly the first which is the most unfavourable one, first it will orient and then next one next one like that, you will have a series of these events. So, almost all the cracks which were earlier randomly oriented throughout the specimen with the increment in the applied load, they all will branch and align themselves in the direction of the applied load.

So, what will happen ultimately? There is going to be sufficiently intermeshed network of crack that would be formed and that would lead to macroscopic failure to result.

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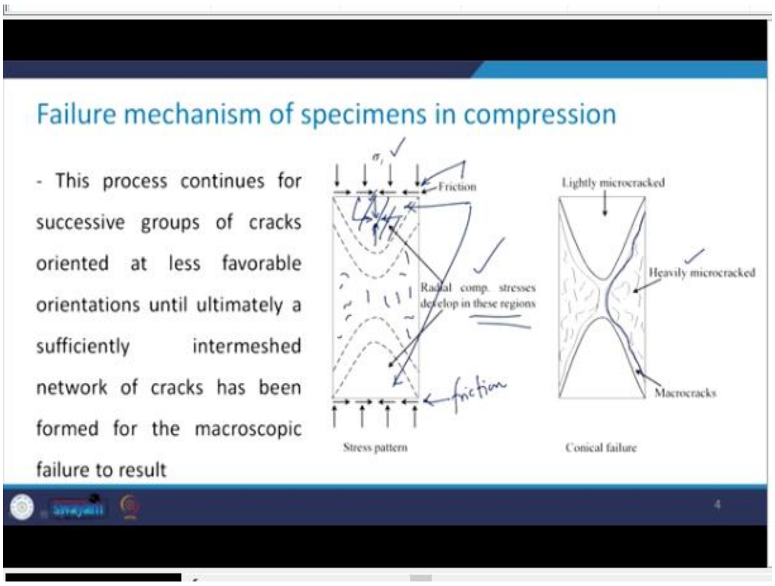

So, you see that here in this figure, this portion is heavily micro cracked. So, all these cracks, which were earlier very randomly oriented in all the direction. Now, you see here more or less they are oriented in the direction of the load application, that is in this direction. Now, we have discussed about this, that there is going to be the friction between the loading platen and ends of the surfaces.

Like you see here, I have shown, this is what is your friction, here as well as here, there is friction. So, what will happen because of this? That there is going to be biaxial state of stress which is compressive in nature. So, it will look like this, you see. So, this is biaxial compressional stress in these 2 zones. So, what will happen? I have already explained it to you that such type of biaxial state of compressive stress, it will have the strengthening effect.

So, what will happen is that when the cracks are propagating and aligning themselves in the direction of the applied distress, because of this effect here in these 2 zones, which are the radial compressive stresses developed in these regions. So, what will happen? These cracks will not be able to propagate up to this zone. So, they will only be restricted to this kind of situation which has been shown here with this zone, which is marked as heavily micro cracked on either side.

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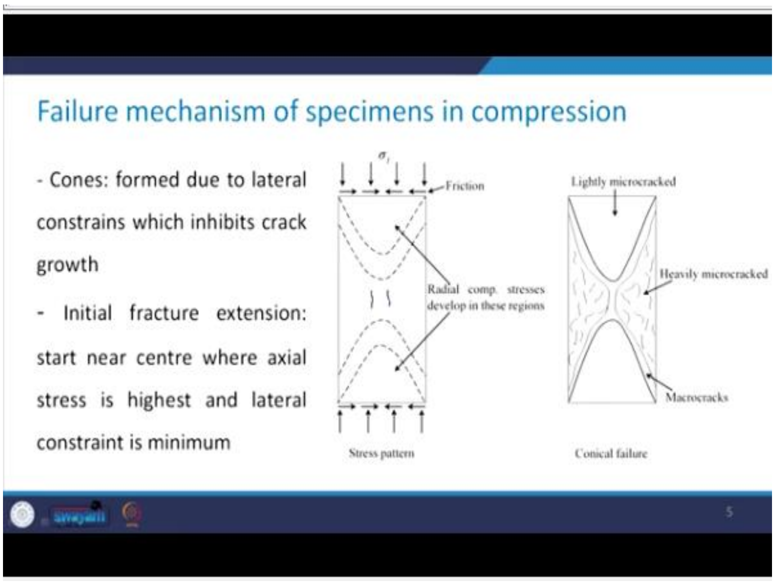

So, these cones, once again, because of the lateral constraint. So, this will inhibit the crack growth in these conical zones. So, therefore these cracks, they will not enter into this. So, what will happen is that initial fracture extension, it will start near the center that means here near the center here it will start, because the actual stress is highest here and the lateral constraint is minimum.

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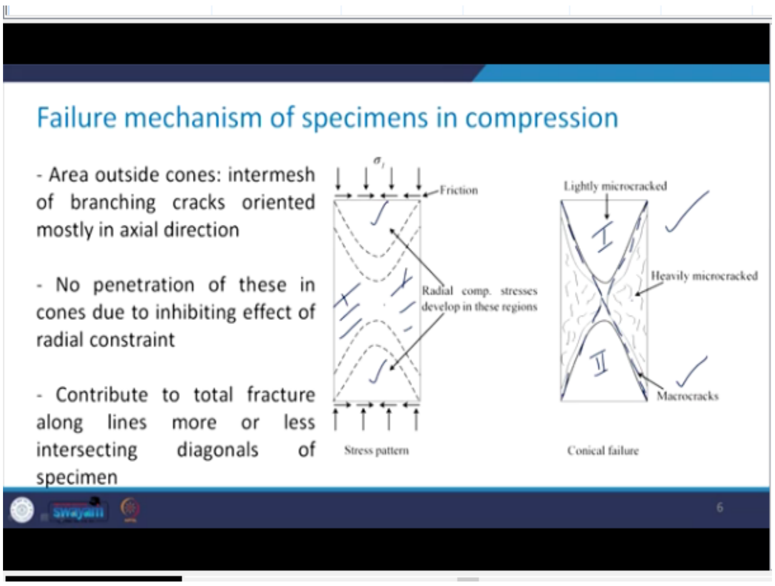

So, slowly what will happen? When you will have the area, which is outside the cone, that is, this total area. So, in this area intermeshing of the branching cracks will be there and all these will be oriented mostly in the axial direction, that is, the direction of the applied distress level. Because of this inhibiting effect of the radial constraints, this crack will not enter into these 2 conical zones.

And they will contribute to the total fracture along the lines more or less intersecting the diagonals of the specimen like you see, here we have shown more or less these are like if I just try to draw the diagonal of this specimen. So, it will be like this. Similarly, here also you will have the other diagonal, mostly along the diagonal direction, they will have macro cracks and finally add the failure what will happen is you will have this kind of situation where along the diagonal, you will have the micro cracks.

Then you will have these 2 conical sections, which will be free from these micro cracks and then the remaining portion will be heavily micro cracked. So, this is what is the reason behind the first type of failure mechanism, which is the most common mechanism of failure of rocks in compression.

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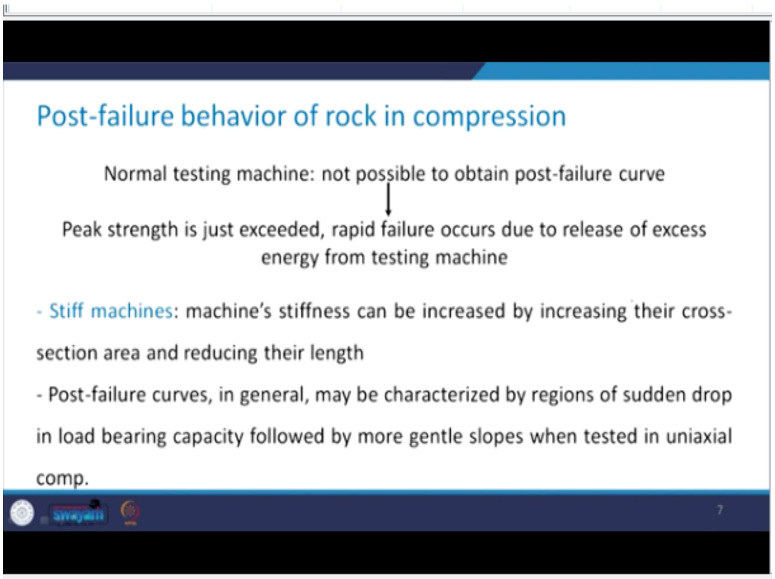

Now, I mentioned to you in one of the earlier classes, that post failure behavior of the rock in compression is important in order to see how this is going to behave in the field or what is going to be the strength after it has achieved the peak strength. So, as far as the normal testing machine is concerned, it is really not possible to obtain the post failure curve using such machines. I have already given you the range of the stiffness of these normal testing machines.

So, when you test the specimen in the normal testing machines, what happens is that peak strength is just exceeded and then suddenly the rapid failure occurs because of the release of that excessive energy from the testing machine. And that process is so rapid that it becomes almost impossible for the normal testing machine to capture that. That is how the stress strain response is going to be post peak.

So, in order to capture that post failure behavior, one needs to go for the use of stiff machines that is, test the specimen using stiff machines. When I say stiff machines, it means stiffness of the machines are more as compared to the normal testing machine. Again, this is not in our hand, manufacturer will take care of this. But then we should know philosophically that what is the difference between normal testing machine and stiff machines and how are machines stiffness is increased.

See, any machine is comprised of various elements there can be beams, columns, anything. You will have the loading pattern and then you will have a jack through which it will move in the vertical direction. The increase of the cross section of these elements take place and reduction in their length is there as compared to the one which normal testing machine has.

So, that machine we call us a stiff machine. What I mean to say is that for making a normal testing machine to stiff machines, we need to increase the stiffness of the machine by increasing the cross-sectional area and reducing the length of various elements of that machine. So, that is how we get the stiff machines. Again, it is not in our hand, there are ready made machines which are available.

So, depending upon the requirement that we want to have in our lab, we purchase the machine with predetermined stiffness. These post failure curves in general, they are characterized by sudden drop in the load carrying capacity, load bearing capacity, followed by more gentle slopes, when they are tested in uniaxial compression. So, let us see that how this post peak and pre peak stress strain response, it looks like.

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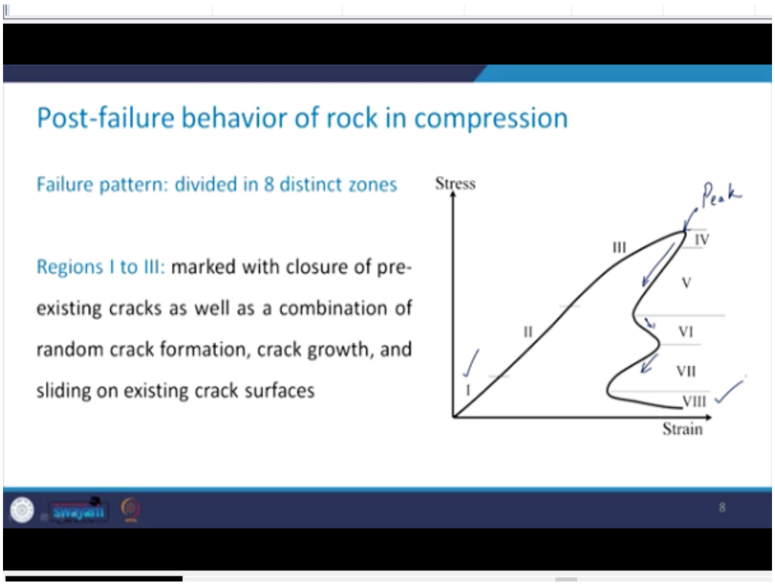

So, as I just now mentioned that, say this is here the peak is reached. So, immediately after the peak, there is sudden reduction and that is followed by gentle slopes along this and here. So, these failure pattern can be divided into 8 distinct zones, as I have shown here. You can see that it is varying from zone 1 to zone 8. Now, the question is, what each of this zone signifies? Regions 1, 2, 3 what happens when you apply the load in the very beginning.

When these loads are applied, some of the existing cracks they close, that is, they were already there in the specimen. So, upon the application of the load. First there is some closure, then there is going to be some random crack formation and you keep on increasing the load and those cracks will propagate. So, there is going to be growth of the cracks and then they will start sliding on the existing crack surfaces.

So, all these phenomena happen during these regions 1, 2, 3. That is, these things are being signified in these regions 1, 2 and 3. Please remember these, that regions 1, 2, 3 they are marked with closure of pre-existing cracks plus the crack growth random crack formation and sliding on the existing surface.

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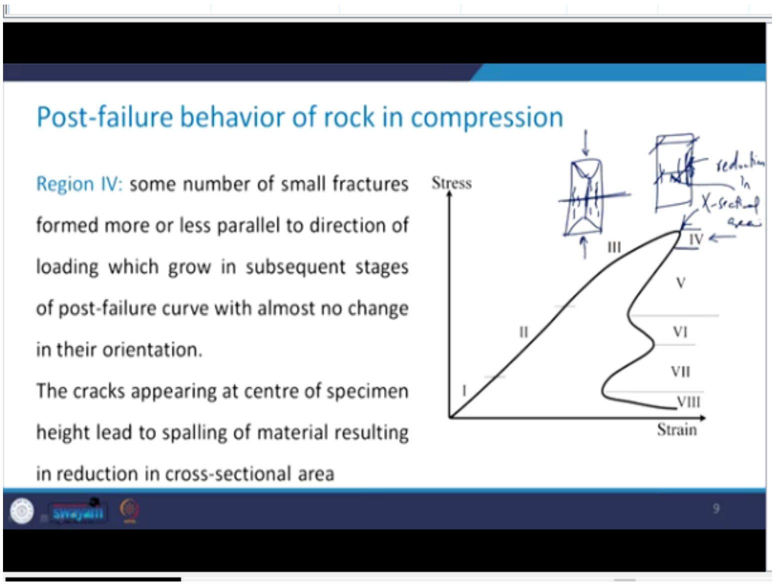

Now, what happens you have reached up to the peak at the end of the zone 3. So, wherever there is a transition between zone 3 and 4 somewhere you have got the peak. Now, what happens in region 4, that is, this region from here to here. Some number of small fractures, which are formed more or less parallel to the direction of the loading. What happens is that they grow in subsequent stages of the post failure curve with almost no change in their orientation.

So, let us say, this is your specimen and the cracks have already been oriented like this. Of course, you will have here the 2 conical zones and almost all these cracks they are oriented approximately in the direction of the applied loading. Now, what happens, post failure immediately after the peak occurs here, what happens is, they increase their length or they just propagate, they grow in this direction only without changing their orientation.

So, that is what happens in zone 4 or region 4. So, the cracks appearing at the center of the specimen height that is in this zone here. It leads to spalling of the material. So, I have already explained you that, this spalling of the material, what exactly it is. So, you see that it is there and the cracks are being formed and what will happen that this much portion it may chip off from here.

So, what will happen when the spalling takes place, the area which was originally this it gets reduced to say maybe this. So, there is a reduction in the cross-sectional area.

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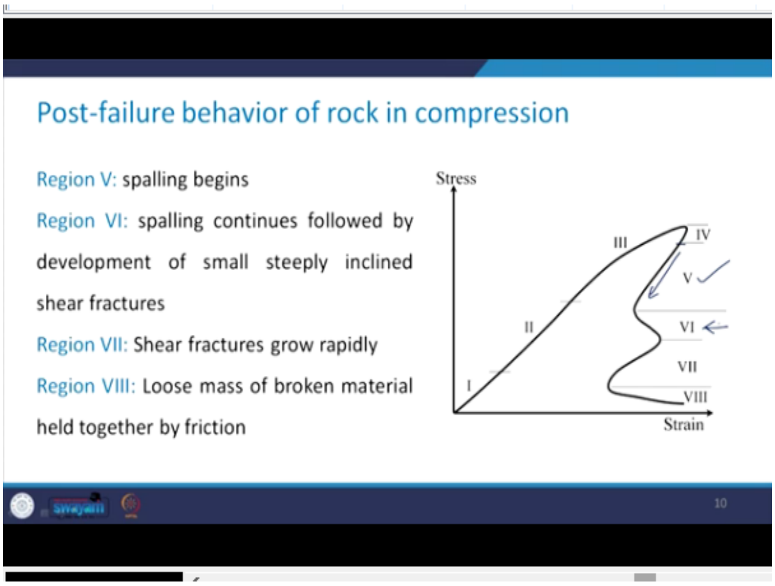

And what will happen because of that? That spalling will keep continuing in the region 5 and you can see that there is going to be the drastic reduction in this stress. Why this is so? Because of the spalling there is going to be the reduction in the cross-sectional area. So, that spalling continues in region 6 also, but it is followed by small steeply inclined shear fractures like you see here it is.

So, it will be like this, development of the shear fractures. And in region 7 that is in this region from here to here, the shear fractures they grow rapidly and ultimately in region 8, what you have is a loose mass of broken material. But then they are held together with the help of the friction. So, this is how these 8 regions in a typical stress strain behaviour response of the rock in compression. They have their physical significance. This is how that they can be interpreted.

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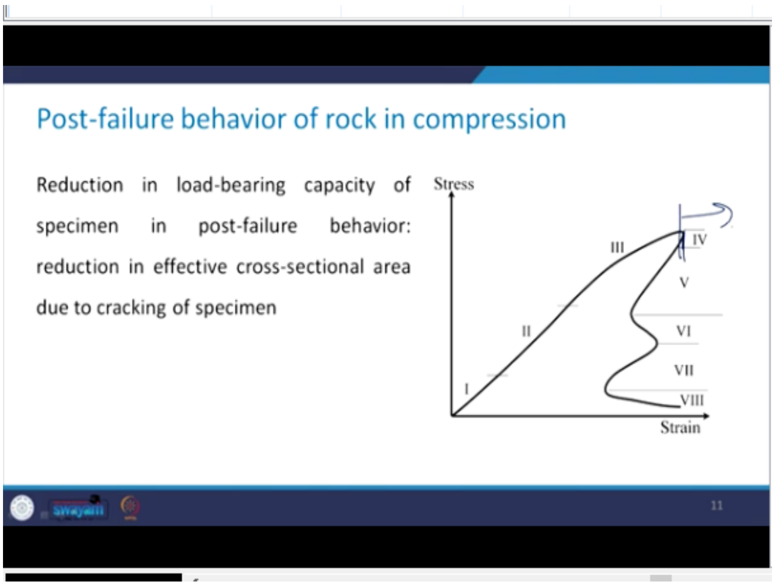

Now, the reduction in the load bearing capacity of the specimen in this post failure behaviour that is, beyond this is because of the reduction in the effective cross-sectional area due to cracking of the specimen. Then the reduction in the cross-sectional area of the specimen is going to be there, then you will have that specimen with lesser strength characteristic. So, it is all because of the reduction in effective cross-sectional area.

Now, we will have some different types of rocks. In case if we have reasonably good quality rock and the core recovery or from the field that whatever we have got, if we have got some good length of the specimen or if we are able to make the specimen of *L/d* more than 2, then it is easy for us to carry out the UCS test on that cylindrical specimen in the lab following the standard procedure as we have already discussed.

But what happens, you know that different type of rocks exists. Now, what happens when rock contains cross cracks or flaws? Or say, when they break down in the presence of water or during the preparation of the specimen. For example, these 2 types of rocks mud stones and shells, they have this tendency to break down by the water or they are pretty weak when you go for the preparation of the specimen.

Then testing of regular shaped specimen becomes extremely difficult. So, in that case, there are few methods that the testing of the irregular specimen can be carried out in that case, it is useful especially in case of the weaker rocks, where it is really not possible to have the regular specimen with *L/d* ratio more than 2. But at the same time, it is also useful for very strong rocks.

Because sometimes these very strong rocks, again, the extraction of the specimen from the sample becomes very difficult and you may require special machines to extract the specimen from the sample. So, in that case also the testing on the regular specimen is helpful.

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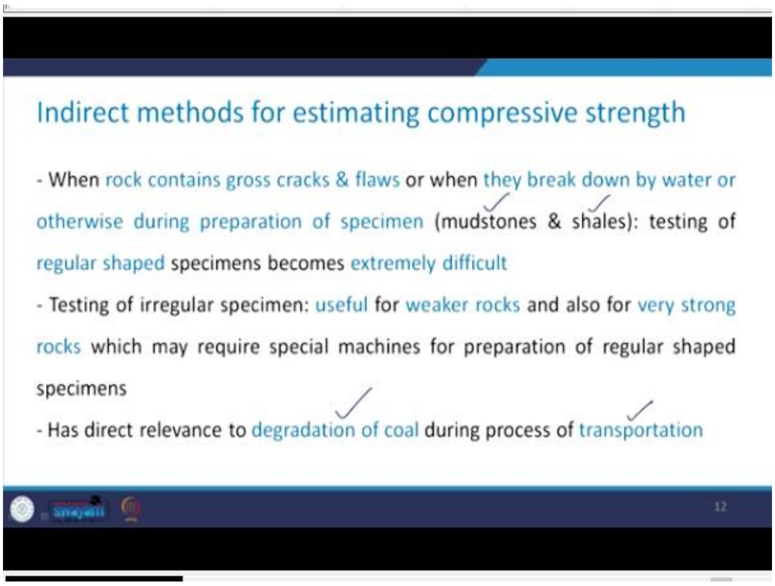

Now this testing on the irregular specimen it has a direct relevance to the degradation of coal, which can happen during the process of the transportation. You remember I mentioned to you that during transportation, one needs to be extremely careful. So, that new cracks are not propagated in the specimen that have been retrieved from the field. So, there are a few methods. So, we are going to discuss two methods here.

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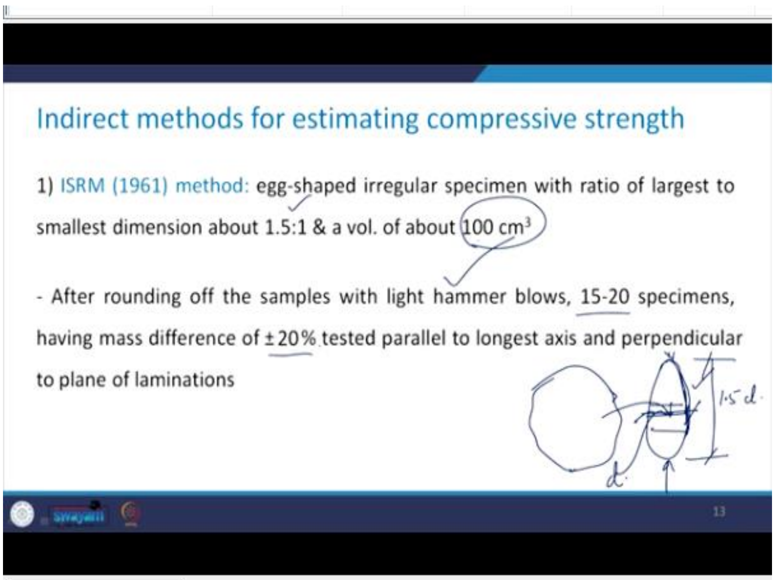

The first one is named as ISRM method. Once again, this ISRM is International Society of Rock Mechanics. So, they proposed method in 1961. So, what is done in this case is that egg shaped irregular specimen is taken. Now, on one side we say that it is the egg-shaped irregular specimen and other side we are saying that it is irregular specimen. So, you see there are 2 things, that are irregular and egg shaped.

So, what we do here is how to make this egg-shaped irregular specimen? See, the specimen can be like this, it may have some sharp edges here and there. So, what we do is, we give this specimen light hammer blows and we try to get this kind of specimen more or less this kind of a specimen which is egg shaped, okay, from this. So, we need to give the light hammer blows and we need to prepare 15 to 20 specimens with mass difference of ± 20% which are tested parallel to the longest axes.

That means, it should be tested like this. The load is applied along this and the planes of lamination should be perpendicular to this, that is like this it should be like that. So, the sample is to be prepared keeping these 2 things in mind and the ratio of the dimension can be 1.5:1 that means, if this is 1.5 times let us say d. So, this dimension should be d and roughly the volume should be about 100 cm^3.

So, we prepare this type of specimen and then we test it. So, in this case like for UCS, I mentioned to you that you need about at least 5 this specimen, but in case if you are carrying out the test on the irregular specimen, one needs to go for 15 to 20 specimens for that testing. But then one needs to keep in mind that more or less they are mass differences ±20% they should be tested parallel to the longest taxes and perpendicular to the plane of laminations.

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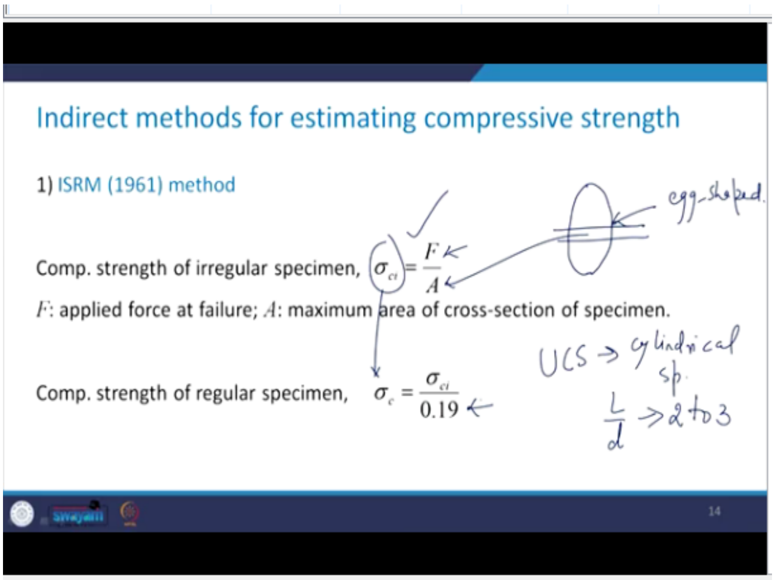

So, in this case, the compressive strength of the irregular specimen can be obtained as like $\sigma_{ci} = F/A$. So, this F is the applied load at which the failure takes place and A is the maximum area of the cross section of the specimens. So, you see that, if you have a specimen like this, so, egg shaped. So, in that case it will have the maximum area somewhere in this zone.

So, this area is this one. So, this is what that you will get for the irregular specimen. But what we want? How have we defined the UCS? That means cylindrical specimen with *L/d* varying between 2 to 3. So, the correlation was developed to convert these compressive strengths of the irregular specimen to the compressive strength of the regular specimen, that is whatever that you get from this step divided by 0.19.

$$\sigma_c = \frac{\sigma_{ci}}{0.19}$$

And this is what is going to give you the irregular specimens compressive strength. So, this is about the method that was given by ISRM in 1961. So, we have discussed about the failure mechanism or the reason behind that why we obtain such type of failure mechanism of the intact rock in compression, and confined compression or uniaxial compression, then we saw that using the stiff machines, we would be able to capture the post peak behaviour.

And the complete stress strain behaviour of the rock under compression can be divided into 8 distinct zones. And I explained you that, what is the physical significance of each of these zones? And then, we started our discussion on the indirect methods for estimating the compressive strength. These are useful when it is not possible to make the regular specimen as per the requirement given by ISRM.

Then we can go for the testing on the irregular specimen. So, we discussed one method that is ISRM method. How we can find out the compressive strength of the irregular specimen and how we can convert that to the compressive strength of the regular specimen? So, in the next class, we will continue with this and we will discuss the next method, that is, point load strength index method, which is again another method for the indirect determination of compressive strength of the rock in the laboratory. Thank you very much.