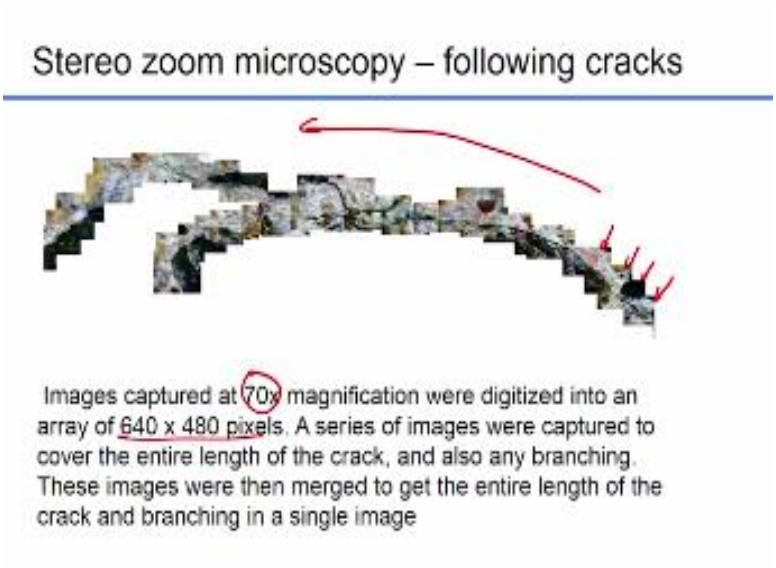
Characterization of Construction Materials
Prof. Manu Santhanam
Department of Civil Engineering
Indian Institute of Technology – Madras

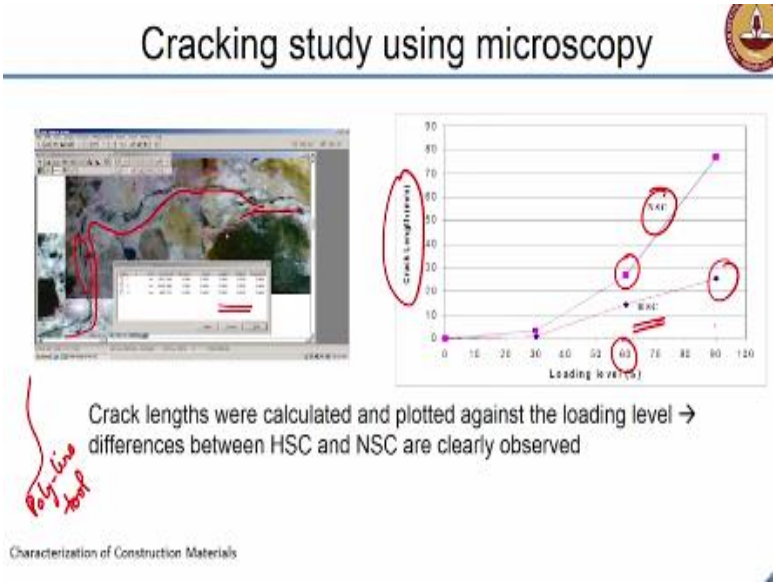
Lecture – 51
Image Analysis – Basic Operations – Part 2

(Refer Slide Time: 00:12)



So, let us see what crack parameters were actually measured in this case. So, what can you measure in this case? The most obvious measurement is you will make the measurement of the length of the crack. What else can you do? You can also measure approximate crack width in certain locations. So, that is what was actually done in this case.

(Refer Slide Time: 00:33)

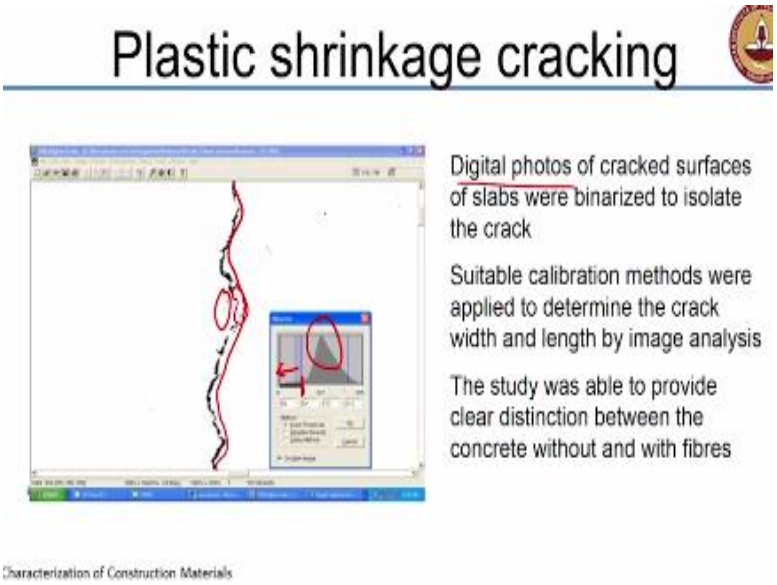


So, the cracking study using microscopy is shown here. This is a magnified view of the images that were stitched together. So you can see approximately how this crack is going. So now, in your image analysis software, there are these poly-line tools. All you need to do is trace the crack, if you see inside the crack, there is a faint white line that has been drawn just inside the crack. So that faint white line is nothing but the line drawn with this poly-line tool in your software. This poly-line tool is obviously even there in your regular Word and PowerPoint software.

So, this poly-line tool is used to trace the crack, but that still does not tell us the length. So, we still have to calibrate that length. So, in the same case, what was simply done was a ruler was taken and imaged at the same magnification, then the poly-line tool was used to trace a given length segment of the ruler. That gives us an idea about what length of the poly-line tool corresponds to a specific length on the ruler like 1 mm or 1 cm. Then, we were able to apply the same to the length of the poly-line tool exhibited by the software and capture the actual crack length in mm. So, you need to have a calibration. You need to have some sort of a calibration to ensure that you can ascertain the actual length of the phases. So, calibration and optical microscopy can be quite easily done by imaging at the same magnification, a scale bar or a ruler and then you can actually apply the same length to the number of pixels that is represented by the poly-line tool and convert that to the actual crack length.

So, as expected of course, normal or low strength concrete has shown a much greater extent of cracking as opposed to high strength concrete and even at lower load levels of 60%, the cracking is significant. In the case of high strength concrete, you have significant cracking only at about 90% of the load. Before that, it seems to have very less level of cracking. That corresponds quite well to our understanding of the behavior of how concrete cracks when you change the strength, it becomes more brittle. So, you have less amount of cracking and sudden cracking that describes failure.

(Refer Slide Time: 03:18)



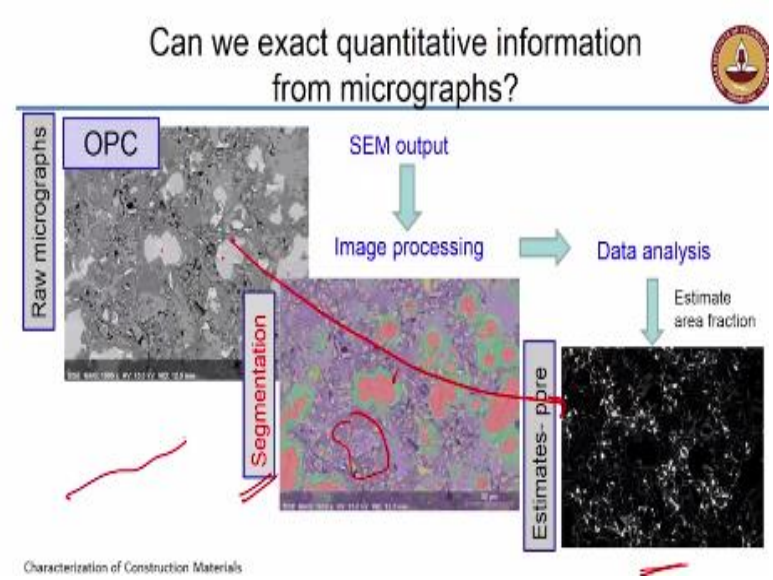
This is another example of image analysis - binarization applied to an image of a crack that appeared because of plastic shrinkage. So, image binarization has been done in this case. Of course, this was not a microscopic image, this is just a photograph, a digital photograph. These were binarized to isolate the crack. And, in case your features are large enough, macro features, for example, even in a loading of a beam, you see that the cracks develop slowly. These can be imaged easily using a digital photograph and calibrated fairly easily also because you can paste graticules or rulers right on the sample that has been loaded and you can easily get an estimate of that.

So, here of course, you can trace the length quite easily using a poly-line tool, but what is more critical in this case, we wanted to actually also look at the crack width. So, crack width in this case was calculated or determined by a crack-width microscope. You have all used crack width microscopes, I presume, to look at how the cracks get wider and wider as the loading becomes more and more. Then this was used to determine the overall cracking area that happened in this sample. So, you have length, you can determine the width at different locations and calculate an average crack width and convert the entire thing into an area.

Poly-line can be used, but again if the crack is very small, for example in these cases, you see that the crack width is not clearly observed in the digital photograph. So, you may have to actually image it using a crack-width microscope, so that you get much better magnification there.

So again, you can see the image histogram here. So, thresholding operation was done to convert everything to the left of this as black and to the right of it as white. Now, I will come back to this again because many cases, you may make this into some sort of an arbitrary choice, it may depend on the person who is actually doing the image analysis as to where they actually set the threshold. So, we need to apply certain rules to determine where should I get the threshold, and that I will come to in just a minute.

(Refer Slide Time: 05:43)



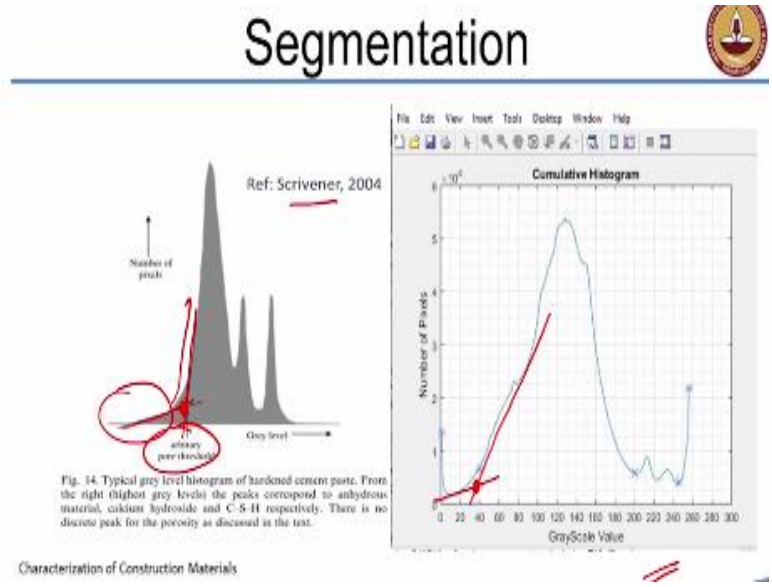
So, we will talk now about image analysis of SEM micrographs because that is where we need to really get a lot of information on the distribution of different types of phases inside a cementitious matrix. So can we get exact quantitative information from micrographs? So for example, here, you have an ordinary Portland cement paste micrograph which is showing you obviously the phases that you are quite familiar with. You have the unhydrated cement grains. You have the voids which are completely looking black. Then you have the much smaller pores inside the cement paste. In between this black and white, there are different levels of shades of grey that are actually being present.

Now, when you do image processing and thresholding and other operations after you actually determine the exact levels of the grey level where you can cut off one phase and describe the other phase, you can actually do what is known as segmentation. That means you are separating out the different phases that are represented by the elements of the image. So here, you can see that the unhydrated grains are now pink, the inner C-S-H is green, the outer C-S-H is violet-indigo type color, the pores remain black, and there are other shades of blue and violet that are governing the other phases like calcium hydroxide and outer C-S-H.

So, now for data analysis, this is also okay, you can actually count the number of green dots and get an estimate of the amount of inner C-S-H in a given volume of your sample or a given area and convert that to the volume. But of course for area fraction of porosity, for instance, you can actually binarize and give black to all the others and give white to all the pores or vice versa, you can also work with the negative image. So that is what is given here in this case, you can get an estimate of the porosity.

Now, the advantage of image analysis software and our understanding of mathematical algorithms is that you can actually train this machine to do the entire step of operations if you define your thresholding carefully. If you define at what point my grey level for the pore gets cut off, at what point does my grey level for the unhydrated phases appear and so on. If you know all that very clearly, you can actually set up these operations well in advance so that you can operate this in a number of images. But please remember one important thing, for all of this to be useful, you still need to satisfy this aspect that there has to be a large number of images taken randomly, only then you get a very good statistical representation of the overall mathematical calculations that you have in your system.

(Refer Slide Time: 08:34)



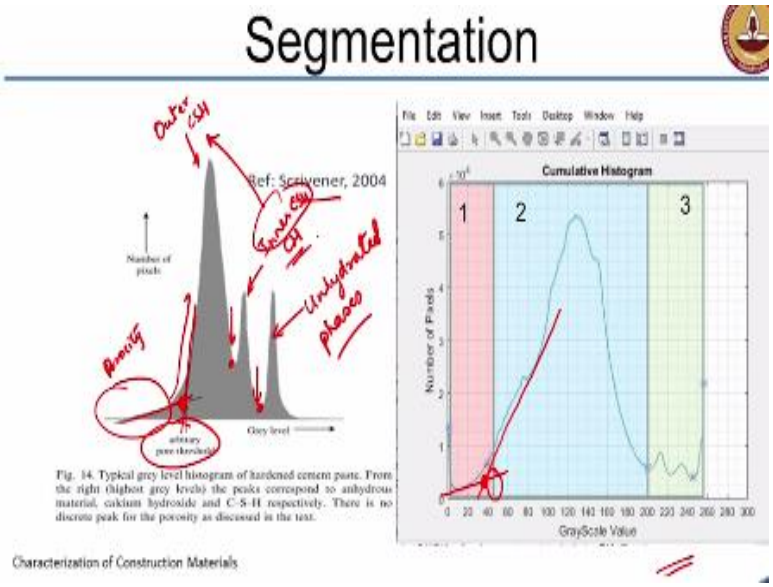
So, what techniques should we apply to do this segmentation in a manner that can be uniformly applied to different images? Now, there is no one particular technique that is correct or incorrect. On an image, you can actually go wrong even if you apply a particular technique, which seems to make some mathematical sense. But what you need to do is when you are comparing several images you need to apply the same technique across all these

images to ensure that you get a perfect match for all the sequences carried out on different images, so that you do not get errors between images. For that, this segmentation technique is actually defined by Scrivener. Karen Scrivener is one of the leading cement chemists in the world.

So, if you look at the grey level histogram that is represented by a typical hydrated cement paste, you see that your porosity, which is on this side of your histogram which represents all the dark phases, the changeover from that to this high level of frequency exhibited by certain phases like outer C-S-H for instance, that is a fairly sudden transition. So, if you draw a tangent here, and a tangent in this vertically rising segment of your histogram, the point at which those two tangents intersect can be defined as an arbitrary threshold for your porosity. That means, the gray level that is defined here, anything to the left of this grey level is now characterized as a void or a pore, and anything to the right is a solid phase.

So, for example, this is your cumulative histogram taken from a typical experiment. So, now what you can do is, in this case, if you apply the same sort of technique, you may draw a tangent to that point like that and then you have something like this for the tangent for the vertically rising segment and take that as a threshold for your porosity. So, again, there is no clear-cut way of defining where the porosity ends and the solid phase starts. In order to avoid differences between sets of images that you are trying to analyze yourself, you can apply this technique to determine what should be the cutoff point for your porosity.

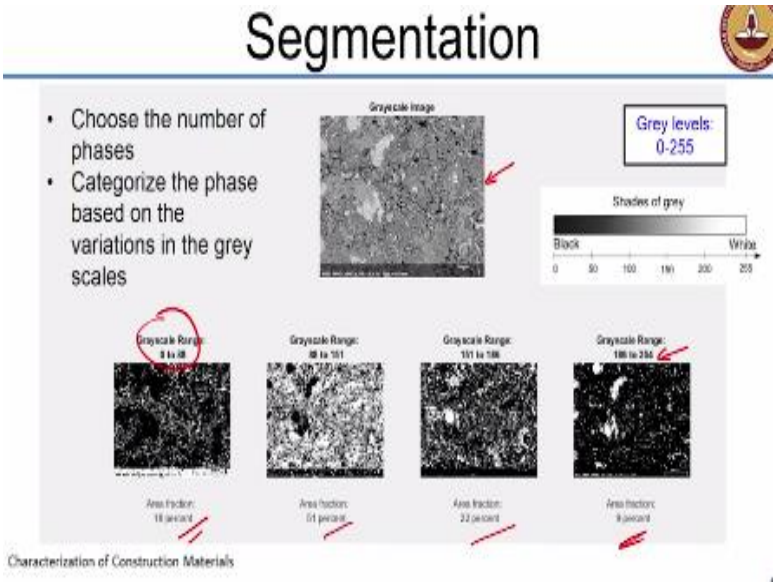
(Refer Slide Time: 11:12)



So again here, that is what is being done, this is the point that has been determined by the tangents. Now, the other aspect is you can clearly distinguish that there is a changeover that is happening in those locations and those could be other points of differentiating different phases. What do you think these phases are? So of course, this is porosity. This may be outer C-S-H (1^{st} peak), this (2^{nd} peak) could be corresponding to inner C-S-H or probably to calcium hydroxide and that (last peak) could be unhydrated phases.

Now, of course, you will be lucky to get a histogram like this, which has very specific peaks coming for each phase. Usually, your inner C-S-H and outer C-S-H will not be distinguished that clearly in terms of gray levels; calcium hydroxide maybe, but not inner C-S-H and outer C-S-H. Now again, please remember this again depends on how well you have prepared your sample, how well you have set the imaging characteristics - the brightness, contrast, focus, stigmatism correction and so on, because it depends a lot on all that, the kind of images that you actually end up getting.

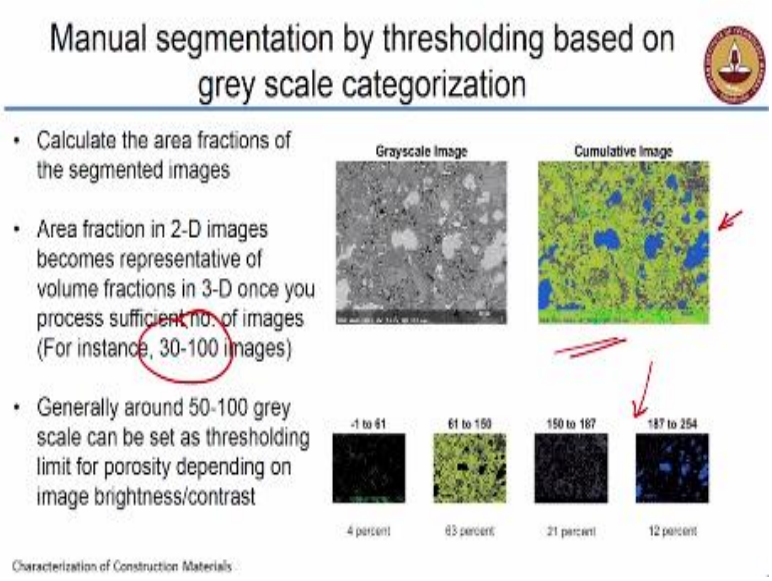
(Refer Slide Time: 12:38)



So again, this is an example of segmentation here. So, what you are simply doing is choosing the number of phases and categorize the phase based on the variations in the gray scales. So, in this case, for instance, for a typical gray scale image of a cement paste, gray scale range of 0 to 88, of course, in this case determined again by that thresholding method that I showed you in the previous slide. Area fraction comes to 18%. Grayscale of 88 to 151 is 51%. So, very large fraction of your sample is belonging to that grayscale. 22% is 151 to 186, again determined based on the histogram, and then you have grayscale range, which is representing the whitest of particles, which could be about 9%.

So, again, please remember, nothing is going to be perfect, none of these calculations would be perfect, but you have to ensure that the error that you have is the same across all the samples that you get, because ultimately you are going to be doing an internal assessment of different types of concretes, and you need to ensure that you do not have more error in one compared to the other. If you have a lot of error in one, you should also have a lot of errors in the other images. So in this case, it has turned out to be like that, based upon the histogram that was achieved, based on this sort of determination of the threshold. It is not the same every time. For instance here, the threshold selected in this example is about 45 or so, not 88.

(Refer Slide Time: 14:22)



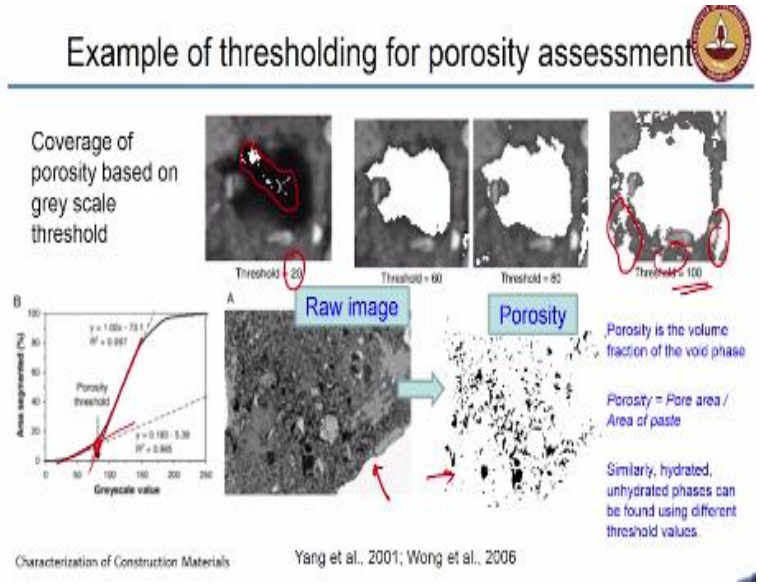
Now, again you can also do manual segmentation by thresholding, based on gray level categorization. Again just to give you more and more examples in this case, grayscale image, that is your cumulative image (on the right), which has been characterized by different colors for different phases. All you are simply doing is each phase has now been pseudo-colored. You can give a pseudo-color for each phase, again based on your original gray level histogram, and that pseudocolor can be directly used for calculation of your area fractions. You are not really worrying too much about doing the histogram and then finding out the specific area fractions based on the gray levels. Here, what you are simply doing is once you get the histogram and you define the thresholds, you are converting all the phases into a pseudo-color and determining the area fractions directly. Most image analysis software can directly look at this image and tell you the area of fractions of how many blue spots, how

many green spots are there and so on and so forth. You do not have to actually individually separate things out.

Now, one very important aspect is you need a large number of images to be statistically accurate, and if you have read your statistics well, you know that the smallest number to have a sort of a normal behavior across the entire population is 30, i.e., smallest number is 30. So if you want to do image analysis operations on cementitious materials or any other characteristics for that matter, you need to have at least 30 images to work with. Preferably 100 images because only then you get a good sense of what is going on.

So, now modern microscopes and image analysis systems come with automated image capture techniques, where you can actually predefine an area across which you want to capture images, the magnification at which you want to capture images and the microscope automatically does the imaging at different locations and captures all those images, so that you can actually analyze much larger areas at high magnifications without too much manual work. So, you can actually set these things up in microscopes (some microscopes not all).

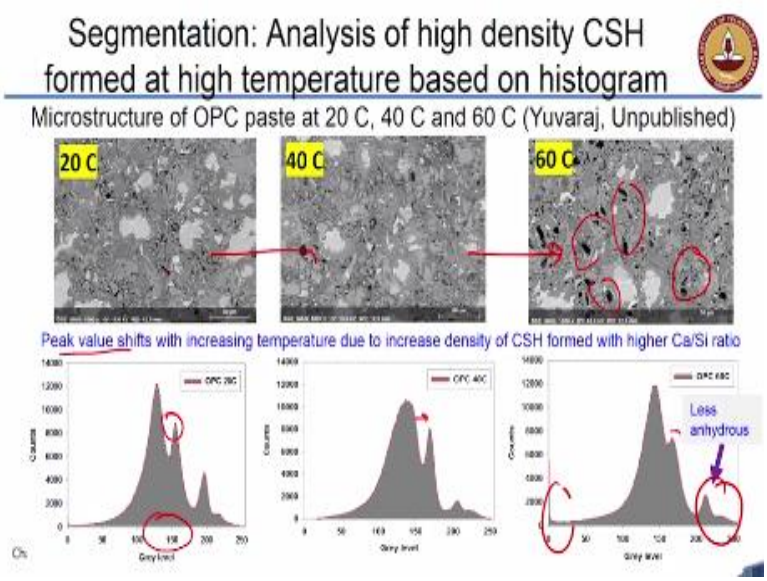
(Refer Slide Time: 16:41)



So again, this is thresholding for porosity assessment which has been done in a slightly different manner. So here, your coverage of porosity is based on grayscale threshold, the tangent is taken here and here (refer the bottom-left graph) and the porosity threshold is determined between 50 and 100 in this case. If you see what happens in this case when threshold is 20, you are only capturing a small part of your void. If your threshold is 60, you are capturing most of the void, but if your threshold is 100, you are also capturing other

points which are outside which may not be part of the void. So you can actually go completely wrong if you do not do a proper thresholding operation. So, again, this is the overall raw image and that is the porosity that has been extracted from that image.

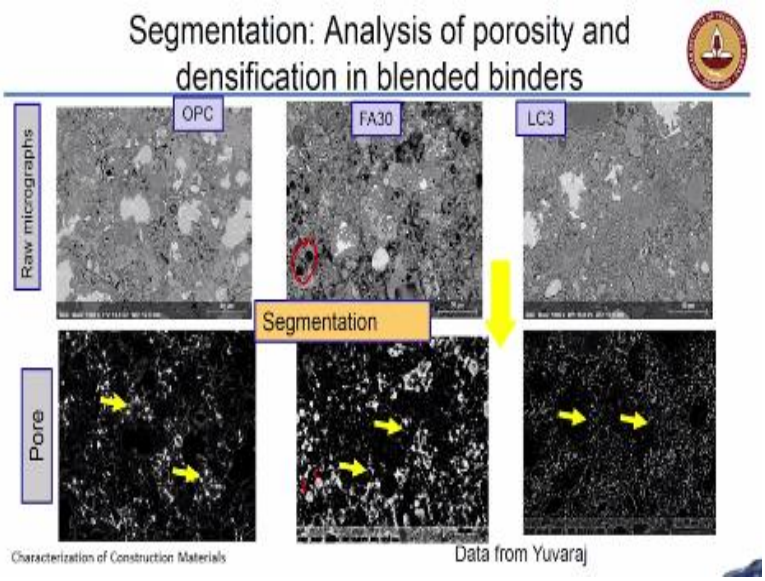
(Refer Slide Time: 17:35)



This is an example of a study that was done here to assess the influence of changing temperature on the system. So, I showed you some examples of this in the scanning electron microscopy section of our course also, but here quantitative information about the same is presented. I told you that when you increase the temperature of curing, the overall coarse porosity also increases in the cementitious system that may lead to a lot of problems with the long-term durability for instance.

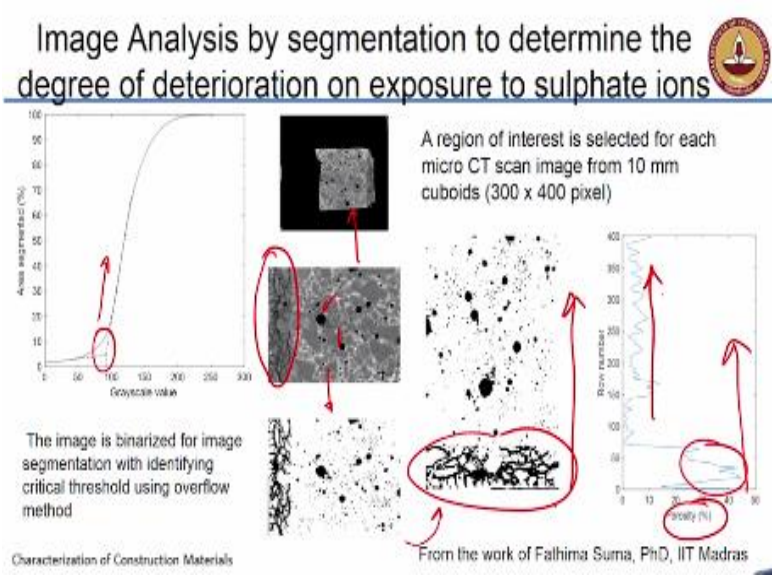
So, here as we move from 20 to 40 to 60 °C, what we are looking at is the extent of anhydrous phases that means, unhydrated cementitious phases, and as the temperature increases, it looks like there is lesser and lesser amount of anhydrous phases in the system. And the other aspect is the peak value also shifts with increasing temperature because density of C-S-H forming is also increasing with higher temperature. So, here for instance the peaks are in this region, let us say about 120 – 180 grey level. You can see this peak specifically has shifted to the right at 40°C and further to the right in this case of 60 °C. So, your inner C-S-H density seems to increase significantly with higher temperatures, but your porosity also increases of course, in this example, I have not shown you the calculation for the porosity which is at the lower levels of your histogram but the area fractions of the pores which you can clearly see from the image, are much greater in the case of the 60 °C sample as opposed to the 20 °C sample.

(Refer Slide Time: 19:13)



So again, this is effects of different types of binder systems, ordinary Portland cement (OPC), fly ash at 30% replacement (FA30) and limestone calcined-clay system (LC3). Again, I have shown you some images like this earlier. If you do a segmentation, you can actually assess the kind of porosity that exists in your systems. Only problem with fly ash is, sometimes the fly ash particles which are hollow spheres, when you are actually preparing your polished sample with this fly ash based systems, you may actually cut across these hollow spheres and they will start appearing like porosity to you. So, you need to ensure that you are trying to avoid these sorts of phases in doing your calculation for the overall porosity. So there again you need to apply certain kernel filtering type of operations to fill up those holes and not include those as porosity. So, you can say here for instance that any hole which is greater than a certain diameter can get filled up and avoided in the calculation of the porosity.

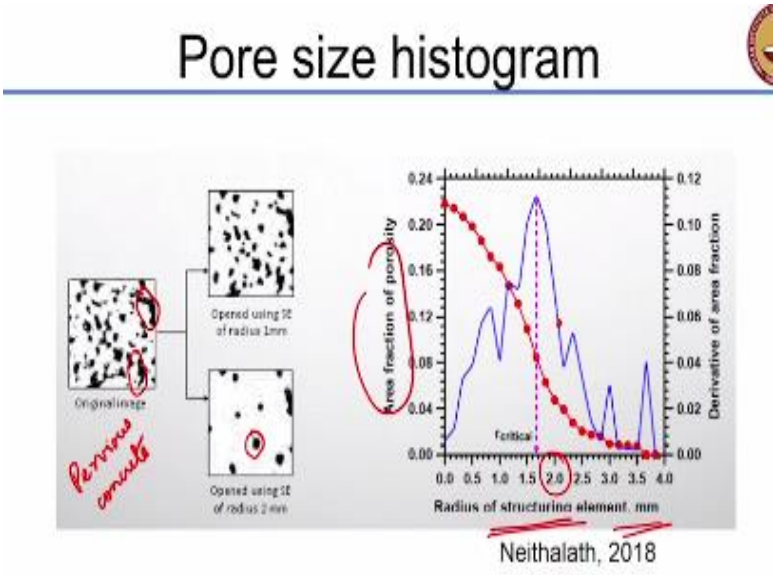
(Refer Slide Time: 20:18)



Now, this is another sort of a technique, which is again useful to determine the threshold that needs to be set for the porosity. So, here this is called overflow technique. So, what we simply do is, we are essentially determining the gray level histogram, and overflow is just defined as the point at which there is a sudden increase in the greyscale value or sudden increase in the area that is representing higher grayscale values. So, that is simply called an overflow technique. So, again, this was applied to some of our images collected from X-ray tomography. These are images collected from X-ray tomography and then you can see that the surface is completely cracked and has lots of cracks and voids. There are internal voids also present in the system. So binarization leads to determination of exactly where your voids and cracks are.

So again, this image has just been flipped by 90° and what we are showing here is just the porosity fraction in terms of the depth from the surface of the specimen. So, these specimens were actually stored in sulphate solutions. The external part of the specimens are completely damaged and attacked. As we go to the internal parts, you do not see that damage significantly, you only see the actual porosity that is expected in a cementitious system inside. So, you see here, the porosity is much larger on the exterior surface, that is probably because all your cracks are getting imaged as pores, because they are also looking black. So, anything black is imaged together. So, pores and cracks are imaged together for the surface and is showing up nearly 40% peak and then as you go inside the specimen, there is more or less a uniform level of porosity that is exhibited by your sample.

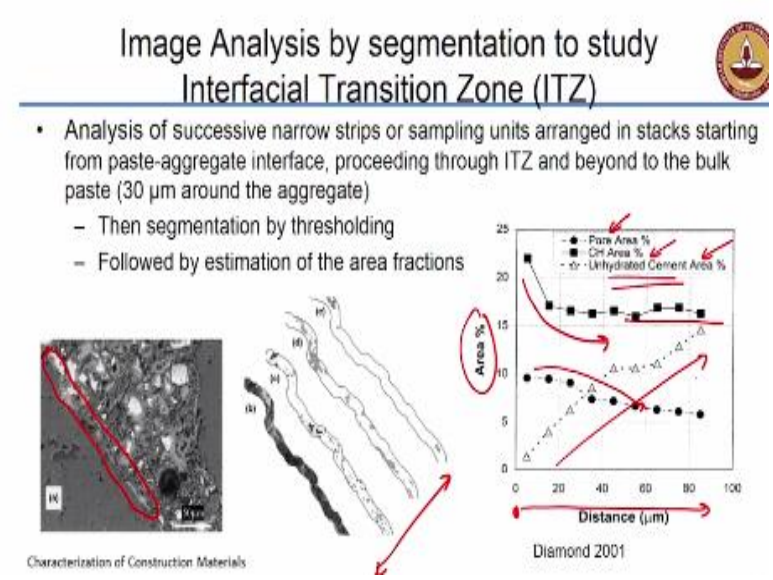
(Refer Slide Time: 20:08)



One more example here of a pore size histogram that can be actually created. Now, that is very important, because not only are we interested in analyzing the overall level of the porosity, we also want to find out what is the size distribution of the pores. With the typical cementitious systems, the pores are so small that you cannot actually image those pores. So, we have to shift to techniques like mercury intrusion porosimetry, if you want to get a pore size distribution, but in this case, we are working with pervious concrete. This is again an example of a segmented image from a pervious concrete system. So here, the voids are fairly macro in size, which can be imaged quite easily using optical or SEM microscopy. You do not even need to go to SEM, optical microscopy is significantly good enough.

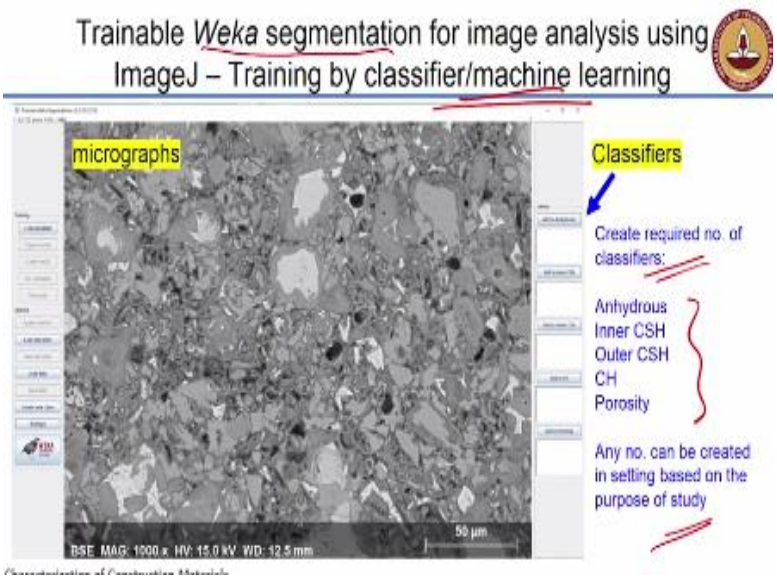
So here, what is actually done is you are trying to process all these individual voids and determining an approximate size of each of these individual voids and plotting against this area fraction of the porosity represented by each individual void size. So, we can actually do operations to determine what the exact size of these voids is and you are simply saying that based on a 2 mm, let us say I am looking for a 2 mm element, I have nearly about 12% of area represented by elements that are 2 millimeters in size and that is an interesting characteristic for me to take back because now I can actually define the range of pore sizes I see in the system.

(Refer Slide Time: 23:40)



Again, you can extend the study to much more complicated systems also like the interfacial transition zone between cement paste and aggregate and interfacial zone is the zone which is present from 20 to 50 µm away from the surface of the aggregate. And you can see that when you do a binary segmentation of these phases, you can actually calculate the amount of area in these interfacial transition zone strips around the aggregate that are either completely porous or completely calcium hydroxide or representing unhydrated cement. So if you take the area fraction of these phases as you move away from the surface of the aggregate, 0 µm represents exactly the start of your ITZ. If you are moving away from the surface, you see that the pores reduce as we go into the bulk paste. Your calcium hydroxide reduces to a stable level as we go into the bulk paste and your level of unhydrated cement increases as we go to the bulk paste. Near the ITZ, there is more water, there is more porosity. So, hydration happens more significantly in the zones at the ITZ and you also get more calcium hydroxide deposition in the ITZ area. So this is nothing but the same common knowledge that we actually have gained, which can be applied to quantify the extent of phase formation near the ITZ.

(Refer Slide Time: 25:06)



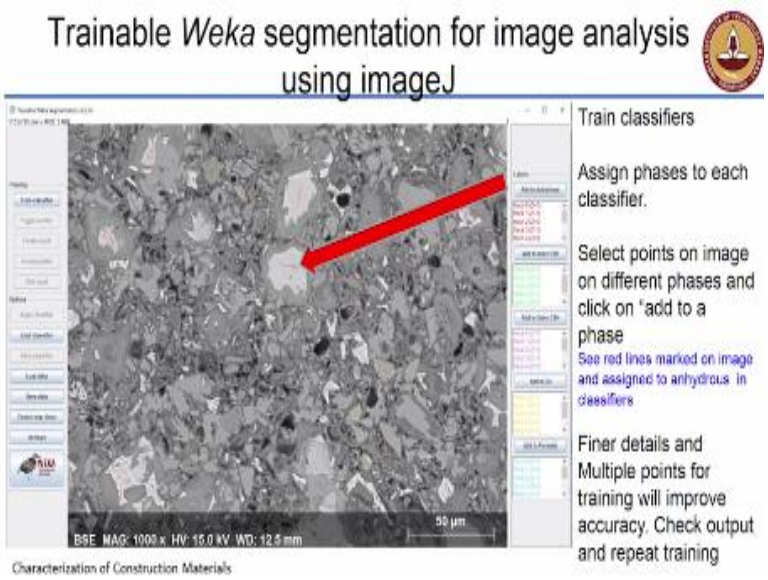
So, again, I was talking about the fact earlier that image analysis software can also help create macros and create training for the program itself to ensure that it has the same sequence of operations applied to multiple sets of images so there you can cut down the overall manual time that you need to actually put in. So this is called machine learning based system, Weka segmentation, you can actually do a Google search for this word. It has got applications in several different aspects of imaging.

So here, what you do is essentially, you are creating several classifiers for different types of phases that you are observing inside your image. So, classifiers in this case would mean the range of gray levels that you want to put in for the different sets of phases that you are observing in your specimen. So any number can be created in setting, based on the purpose of the study. So, all you are doing is creating the right level of gray level values representing each phase. You tell the machine or you tell the computer or you devise an algorithm that will apply these classifiers to all your images at the same time.

But what is important here is that all your images should have been collected with the same type of setting. For instance, if you choose a particular phase in your image, like quartz aggregate for instance, the best example is to use quartz aggregate, because it has a gray level of close to about 150 to 160. So, all you need to do is in every image that you take, you adjust your contrast and brightness in such a way that you ultimately end up getting that level of gray level for your quartz samples. So that will help you fix the overall imaging

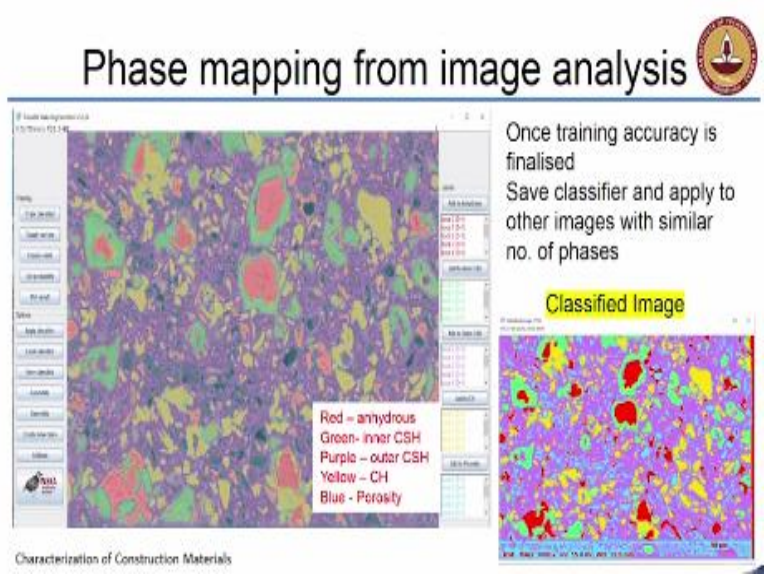
characteristics for all your images and then you can apply these classifiers carefully so that you can actually extract information on the phases.

(Refer Slide Time: 26:57)



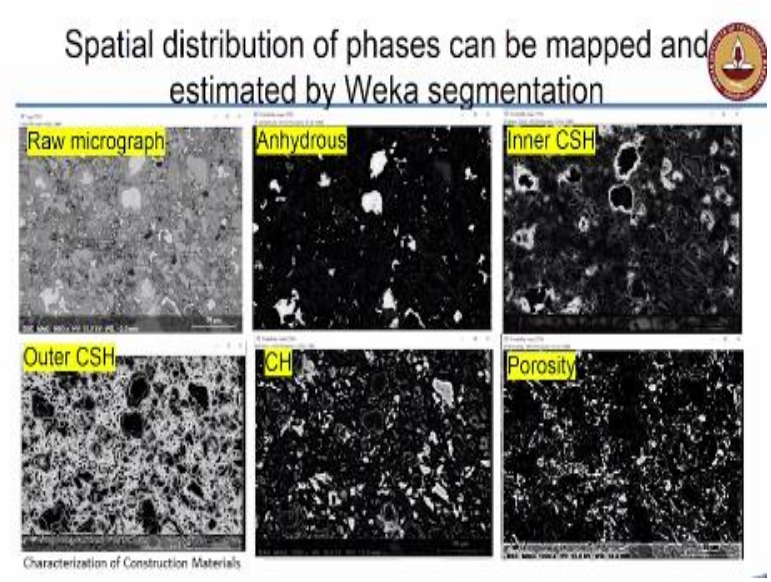
So again, this is just an example you can go through these slides, it is not really that difficult to understand. The idea is simply that you are now creating an algorithm in the system that can be applied multiple number of times to images. Now, what will happen as a result of multiple application here is that you are also training the computer to understand which one of these phases it is actually observing. So that is where the machine learning part comes in. The computer is now next able to perform this set of operations easily on the next set of images that you feed into the computer.

(Refer Slide Time: 27:34)



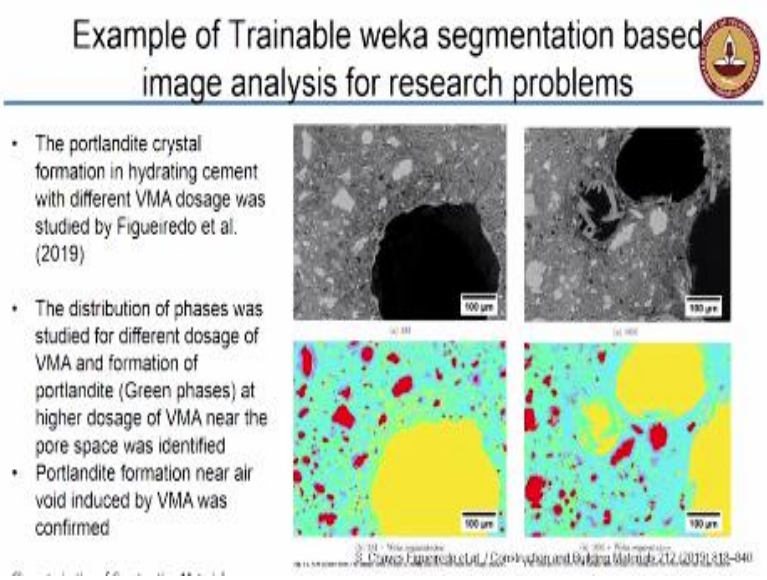
So, again, phase mapping can be done from image analysis, where you are basically giving a pseudo-color to each of the phases after applying the classifiers that have been defined in the machine learning algorithms.

(Refer Slide Time: 27:48)



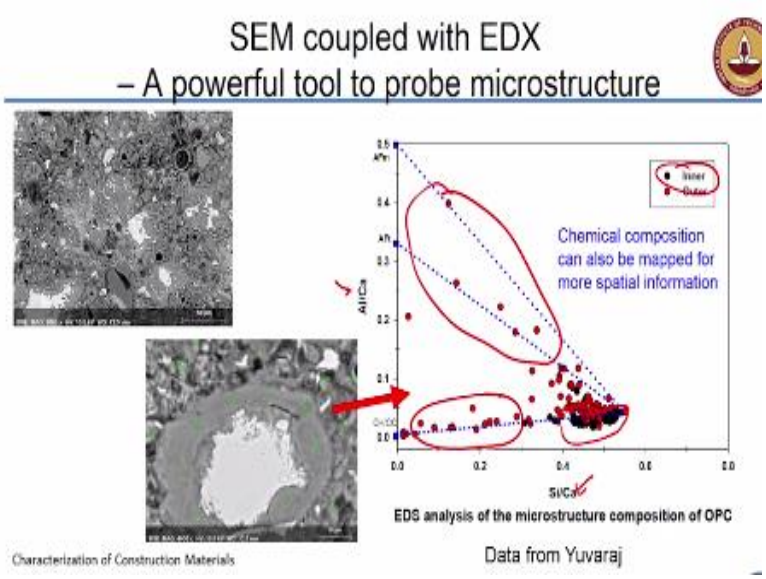
Again, this is more binary segmentation on the same image that was shown. So spatial distribution is mapped and estimated by the segmentation process that was described earlier.

(Refer Slide Time: 28:00)



Again, you can actually train the computer to actually undergo these operations and operate on new images which you do not really have to again write algorithms for. This is from a research paper that is published in construction and building materials.

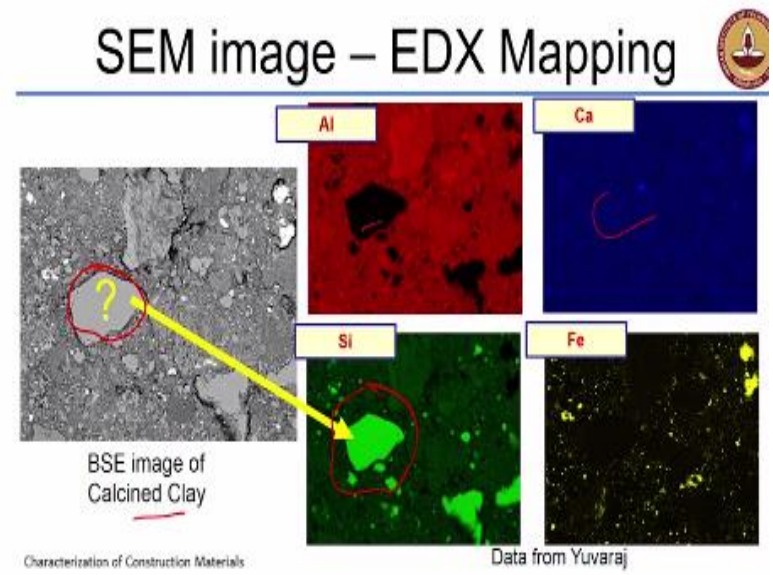
(Refer Slide Time: 28:20)



An important aspect is to understand how scanning electron microscopy coupled with EDX can be used to actually understand the microstructure features. I showed you some examples earlier also. So, here, your inner C-S-H is being imaged. I told you that the typical way of representing inner C-S-H is to plot the Si/Ca atomic ratio on the X-axis and the Al/Ca atomic ratio on the Y-axis, and for inner C-S-H what you will see is mostly all your points are lying very close, the black points are all inner C-S-H.

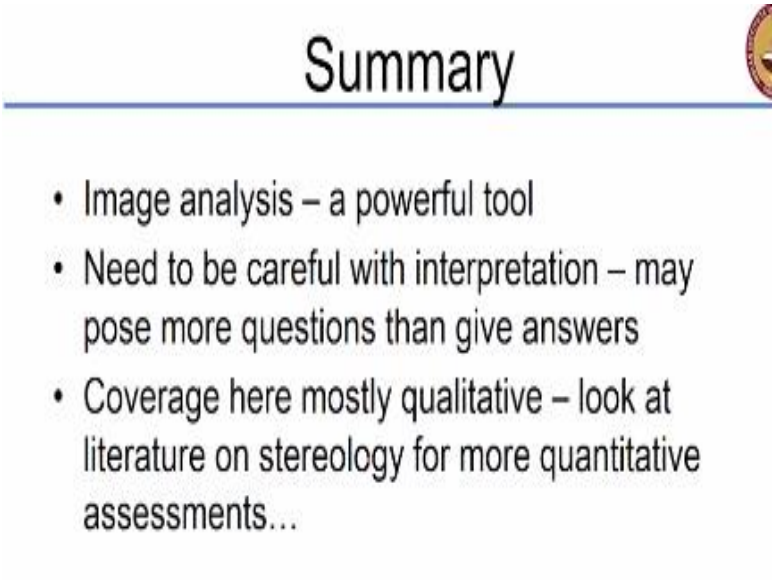
And the outer C-S-H depends on what phase you are actually setting on, you can get a range of values and some of these values will be for calcium hydroxide phases. Some of these values may be for calcium sulphoaluminate phases like ettringite or monosulphate. So, this is the way that you want to represent most of your microstructure features if you are using that coupled with Energy Dispersive X-ray Spectroscopy.

(Refer Slide Time: 29:20)



Now, the idea here is, you can also use mapping in Energy Dispersive Spectroscopy to see what elemental phases are present across the area in your sample. So this is called EDX mapping. So, for example, here a calcined clay image is presented and we want to understand what these macro features are in this system. So, if you do a mapping of this, everything appears dark, aluminum is not very clearly seen in that feature, no calcium appears there, but the silicon is very bright in that feature. That means that you have a grain of quartz present inside your sample of calcined clay. So, image mapping can very quickly help you to distinguish areas of the image that have specific chemical compositional characteristics.

(Refer Slide Time: 30:08)



So just to summarize, image analysis is obviously a powerful tool, which has to be used very carefully, because ultimately you can make grave errors if you do not have statistically right number of images first of all, and secondly if you do not apply the same kind of operations to all the images that you are trying to study.

Interpretation is very important, you need to be extremely careful with it and ultimately many of the interpretations may lead you to more questions than give you answers about the entire process that you are trying to analyze.

So what we have looked at primarily is a qualitative coverage of image analysis, I really did not get into the depth of stereological calculations. You have to look at literature on stereology if you want to understand these quantitative assessments much better, as to how the different aspects are related to each other, which means, how the 2-dimensional entity is is related to the 3-dimensional quantities and so on. So, thank you all very much.