Advanced Topics in the Science and Technology of Concrete
Indian Institute of Technology, Madras
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Developments in the Performance Approach for Durability and Service Life Prediction for Concrete Structures

My name is Mark Alexander from University of Cape Town and I am currently visiting at IITM address. It is a great pleasure to be able to with you this afternoon and to present this lecture. And the title is the developments in the performance approach for durability and service life prediction for concrete structures. I appreciate the opportunity to give this lecture because for me it is a great honor simply to be here in IITM and to being asked to give this lecture. So I appreciate that very much.

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Just a bit of background, that is the city where I live and work, it is called Cape Town. It is the most south-west tip of the continent of Africa and it is a very beautiful city. As you can see, it has a water front, it has this iconic mountain called Table Mountain in the background. And that structure right in the front is the soccer stadium that was built to host the 2010 soccer world cup, the semi-final was played in that stadium. And so what you are looking at there is a picture of the city.

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But of course today, we are in Chennai. And this is another iconic structure here in Chennai, the old central railway station, a beautiful building. And this is very interesting city as well, I have thoroughly enjoyed being here.

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And in particular we are at the Indian Institute of Technology, Madras here in Chennai, for this particular lecture. So that is enough background.

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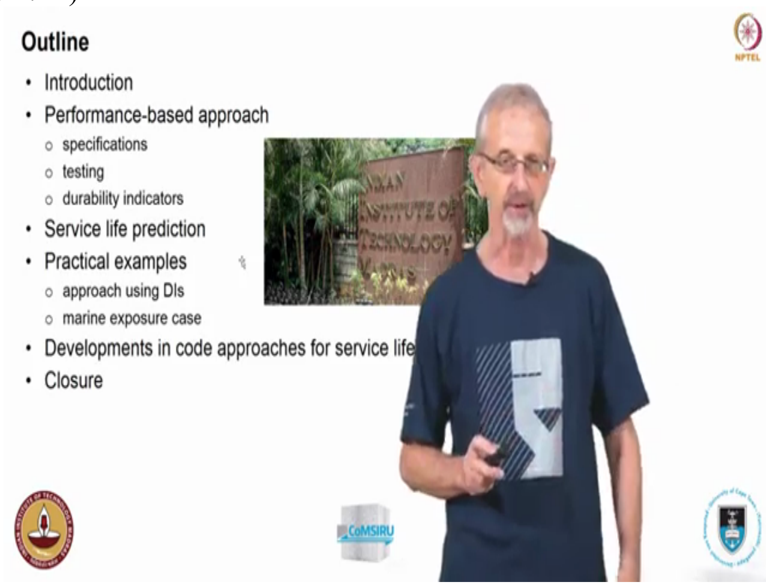

This is what I like to cover in my lecture today, an introduction, just setting the scene and something around performance based approaches for trying to achieve durability in concrete structures, that will allow us to move onto talking a little bit about service life prediction. And then I am going to give you some practical examples drawn from our own experience and also some work that was done in Canada. And then briefly talk about what is happening about code approaches, developments in code approaches for service life and then I will bring the whole thing to a close at that stage.

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We know that concrete is the material of choice for infrastructure and construction worldwide. It is functional, it is efficient, it is universally available.

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There again in those pictures you can see it on the left hand side is that same soccer stadium that I showed you in the first picture under construction. On the top right there was some very elegant free-cost concrete panels that would be used in high-end or high-tech application. And then on the bottom right in fact is just ordinary construction going on in the very rural or very low-technology application. And that is the marvel of this material called concrete. It can be used in all kinds of applications from the high-tech to the low-technology and people can use that as a material that will help them to improve their lives.

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It is the development, developmental material par excellence. It is the material we use to develop our world in which we live. So here is an example of block construction which is based on of course on cement.

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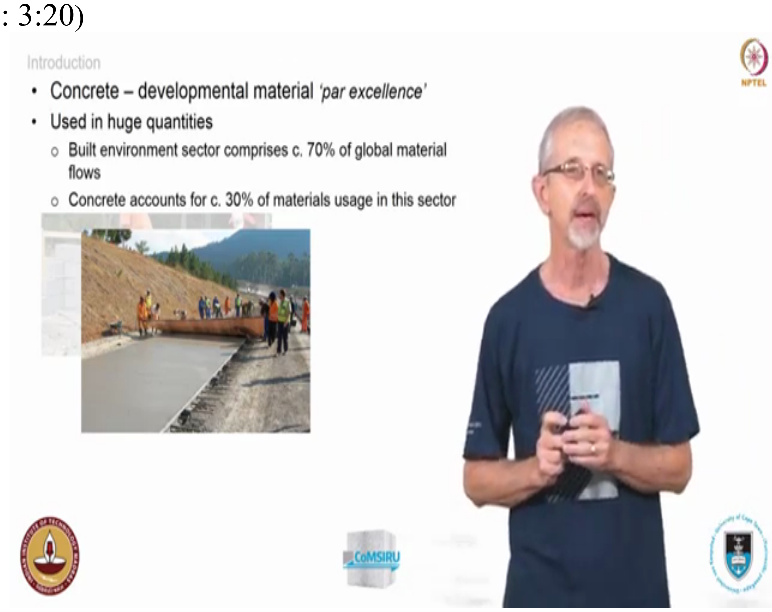

Here is in fact a high-tech concrete road. This is a continuously reinforced concrete pavement built in our country in South Africa but being built with relatively low-tech methods. So it is a high-tech application built with low-tech methods. These are largely labor-based construction, so you can do high-tech construction even using labor-based kind of construction. You do not always need the very high-tech staff.

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Here is an example of another application, this is one of the newer dams that we recently built with roller-compacted concrete. This is called the (())(03:56) dam and it is part of a pond storage scheme, electricity pond storage scheme on one of our mountainous regions. It is a very beautiful structure as well.

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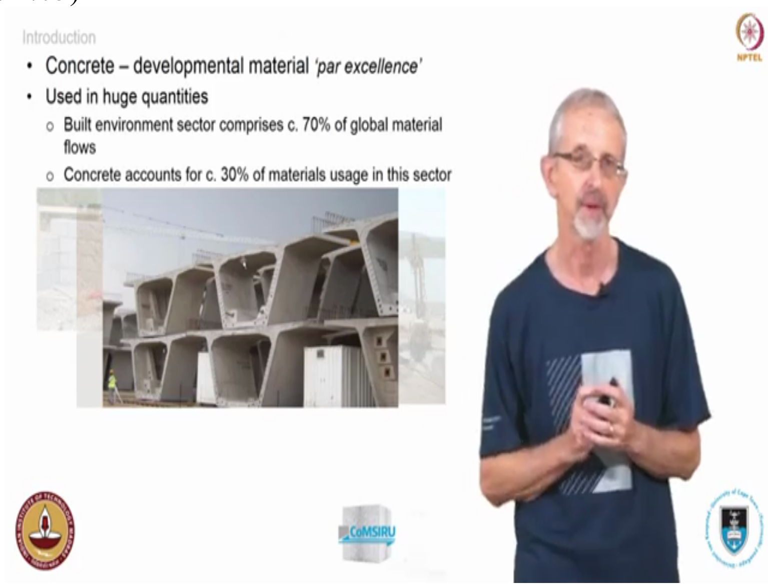

And these were the precast viaducts that were cast in segments in a huge precast factory the time it was one of the largest in the world. This was at the time that the high-speed rail link in Johannesburg and Victoria was being built about in time in fact for the soccer world cup. So this is for a very high-tech application. Those were stitched together as viaducts for the high-speed train. So this is how we can use concrete in all kinds of applications and for all kinds of usages.

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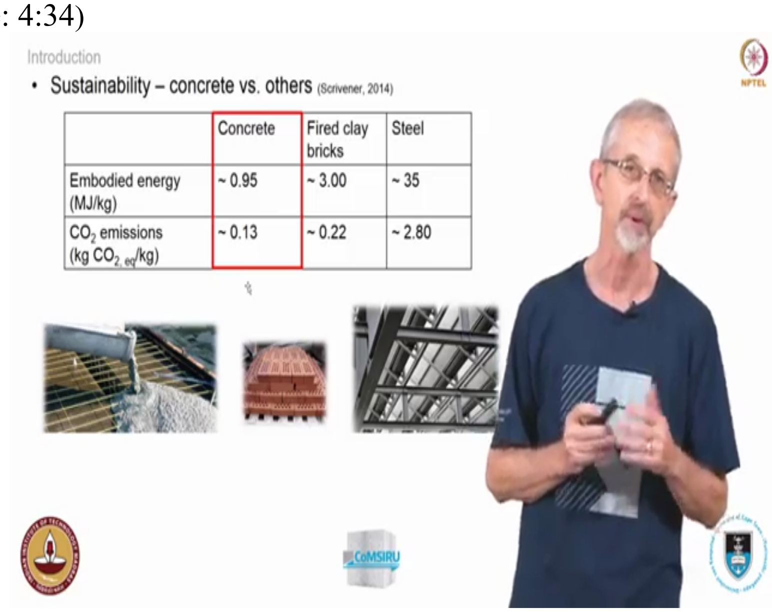

Also a concrete is surprisingly a very green material. People think of it as not but if you look at the figures there, you can see that concrete has relatively low environmental impact factors. Whether it is embodied energy or CO2 emissions, the figures look extremely good. The reason why of course we have an issue with this is because concrete is produced in such huge quantities. So you have so much of it even multiplying it by relatively low figures means in the end there is a large environmental impact but not because the material itself is unfriendly, if you like environmentally unfriendly.

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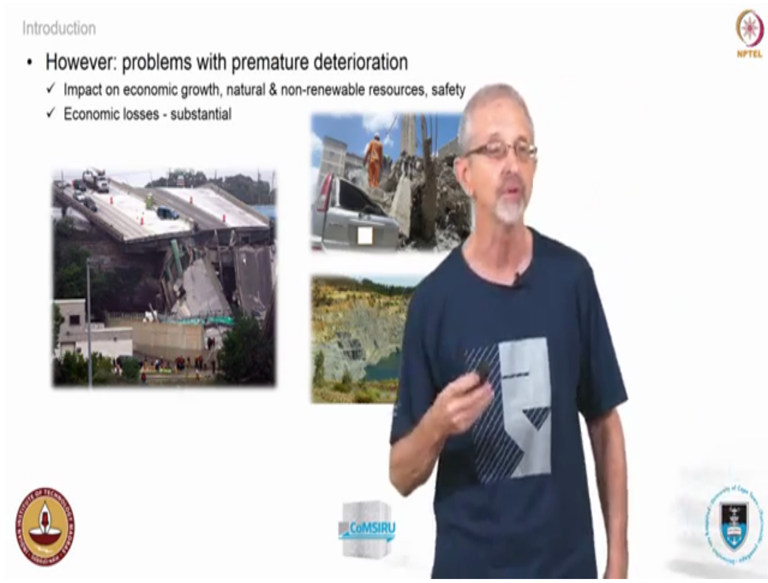

But having said that we do know that we have problems and the problems that we have are largely around what we call premature deterioration. In fact, the concrete on occasions deteriorates more rapidly than we would like it to do. So we live with this problem of deteriorating infrastructure sometimes collapsing infrastructure, sometimes infrastructure that is not fulfill the need for which it was designed. And so it comes to the end of its design life relatively early with useful life and that impacts on the economic growth, that impacts on losses to the economy as well. And of course, it uses that resources that we could well use elsewhere.

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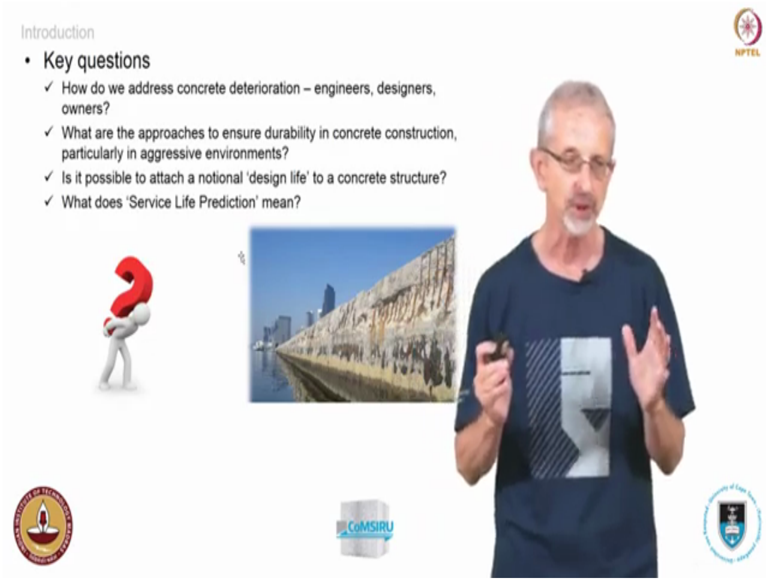

So the key questions then that we need to ask are the following: how do we address concrete deterioration? That is largely what I am going to be speaking about today; as engineers, as designers, as owners there are number of people involved in this whole picture. Then what are the approaches to ensure durability in concrete structures, particularly in aggressive environments? And then is it possible to attach a notional design life to a concrete structure? And if so, how much? And what do we mean by service life prediction?

I am going to explore some of those topics today. This is relatively high-level, we are not going to get into huge amount of detail. I am trying to sketch a philosophical picture within which our framework, within which we can understand these problems that I am talking about.

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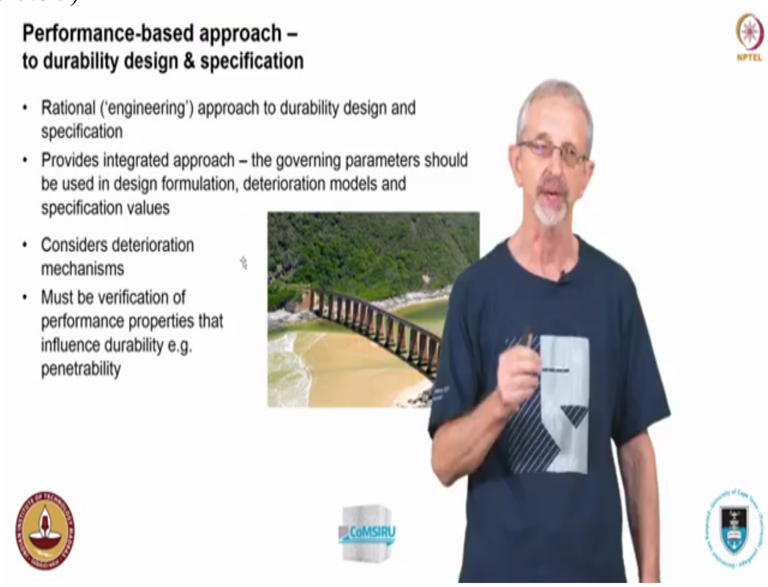

So with that as background, let me talk a little bit about performance based approaches to durability design and specification. I will try and help you understand what this means. In the absence of what we call performance based approaches the possibility of rational or engineering approach to design durability design specification will elude us, we will not be able to do then. Performance based approaches provide an integrated approach. Last two have an integrated approach in which we use governing parameters and I will talk about some of those just now.

In all kinds of different ways, in design formulation, in deterioration modeling and then in specification college control on sites, so you can see the big picture can emerge from this kind of thing. Also in a performance based approach we have to consider deterioration mechanisms, we have to understand what deterioration is occurring, how it is occurring and what rate at which it is occurring. And very importantly if we do have what we call a performance based approach there must be verification of performance properties that influence durability. We have to be able to verify that we get what we hope we want to get.

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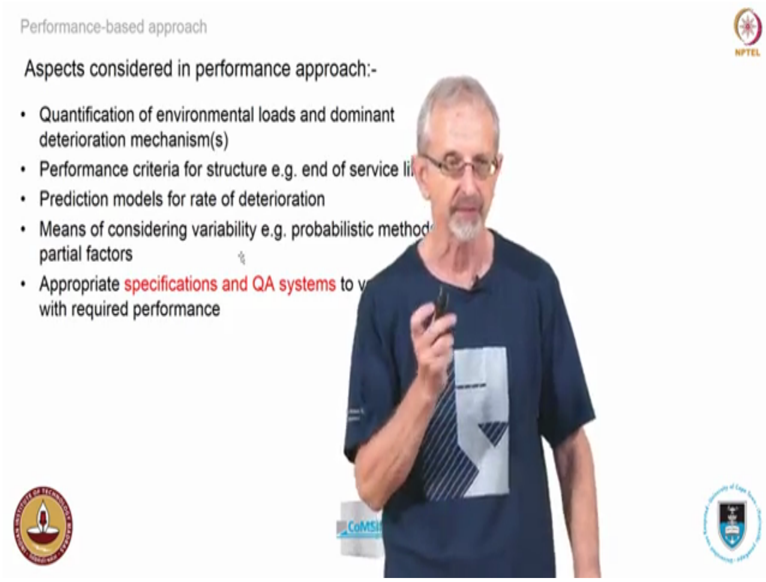

So that is a bit of background. So the thing of the aspects that we consider then are quantification, so quantification of the environment, in this case environmental loads and dominant deterioration mechanisms. How can we quantify these things? They are very difficult actually to quantify. We need performance criteria. For example, what will be the end of service life criterion that we will use? Will it be a certain amount of let us say corrosion occurring, a certain amount of cracking, a certain amount of discoloration, a certain amount of loss of surface of the structure or whatever. How do we decide when the end of service life has been reached?

We need prediction models or really these are deterioration models to give us rate we need the rate equations. And very importantly we need ways of considering variability. Concrete is itself a variable material, it exists in highly variable state of environmental circumstances. The weather, the environmental loads, they all differ all the time. The structure varies with time and so variability is with us all the time. So we need to be thinking about probabilistic approaches and other possible ways. And then as I have said we need appropriate specifications and quality assurance systems to verify compliance. Of course, that is a very essence of performance approach, is the verification that you get the performance that you wish to have.

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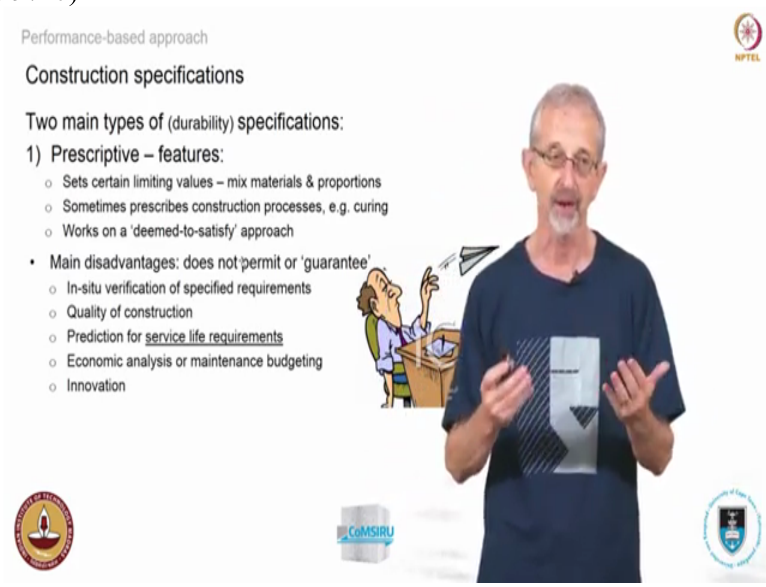

And that brings me to issue of how we do specify concrete for in this case particularly for durability. There are two main types of specifications that we use in engineering. The one is the prescriptive approach, this is the common approach, the one that you will find just about everywhere throughout the world. This is the norm if you like at the present time. And the features of a prescriptive approach are that it sets certain limiting values for the concrete: mix materials, mix proportions and things like that.

It might prescribe construction processes, it may or may not but often does. For example, how you should care, how you should finish and things like that. And it works on what we call a deemed-to-satisfy approach. So the specification says this sort of ratio, this minimum cement content, this minimum strength or whatever whatever cure this way, finish it off that way. And if you do all that, then the structure is deemed-to-satisfy the durability provisions.

Of course, what does that mean? It means very little because many of these things we cannot even check on site and if you have a deemed-to-satisfy durability criterion, we actually measure it very little, is really thinking is what we call find the sky, it does not actually work. So there are many disadvantages related to the prescriptive approach. There is no in-situ verification; we cannot guarantee the in-situ properties that they have met in fact up to the specified requirements. We cannot really control the quality of construction, not particularly well.

There is absolutely no way that we can do service life prediction because we have nothing to model this one. There is no ability to model in this approach. It does not allow us to do proper economic analysis, a cost analysis or maintenance budgeting because we just do not know when things may go wrong or when we will reach the end of a certain type of condition, deterioration condition. And of course, it stifles innovation because it is just a set of rules. Obey the rules and then everybody will be happy. It does not quite work that way.

So that is an approach that increasingly we are suggesting we should do a lot, we should put it where it belongs in the waste pack of basket. However, reality is with us today and it is going to take a long time before we finally manage to move propping away from this approach.

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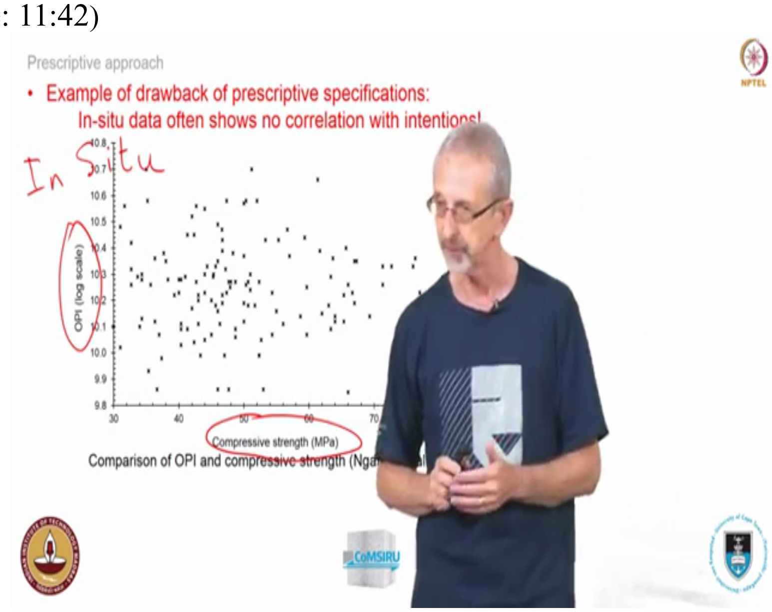

And this is just an example that we have from our own work, of this drawback of using prescriptive approaches. This is the set of data and what we are plotting is oxygen permeability index OPI which you probably mostly are familiar with on a long scale, on the y axis against compressive strength on the x axis. Now these were in-situ measured properties. So what I am saying is that the OPI we measured in-situ on the actual structures that we were working with and the compressive strength we measured in the lab on standard control specimens normally cured.

So we have got all the influence of construction on the OPI and we have got only the influence of standard curing on the compressive strength. And you can see that there is just no relationship whatsoever. You can kind of get any OPI value for any compressive strength and it simply indicates that when you come and when you start to measure real in-situ performance which is what you can do with OPI, you find that you simply do not get any correlation with say strength. And engineers tend to use strength as a parameter by which they control everything else.

If you do this work in the lab, you will get very nice correlations. But go on to site and this is exactly what happens. This is the problem of verification that I was speaking of earlier.

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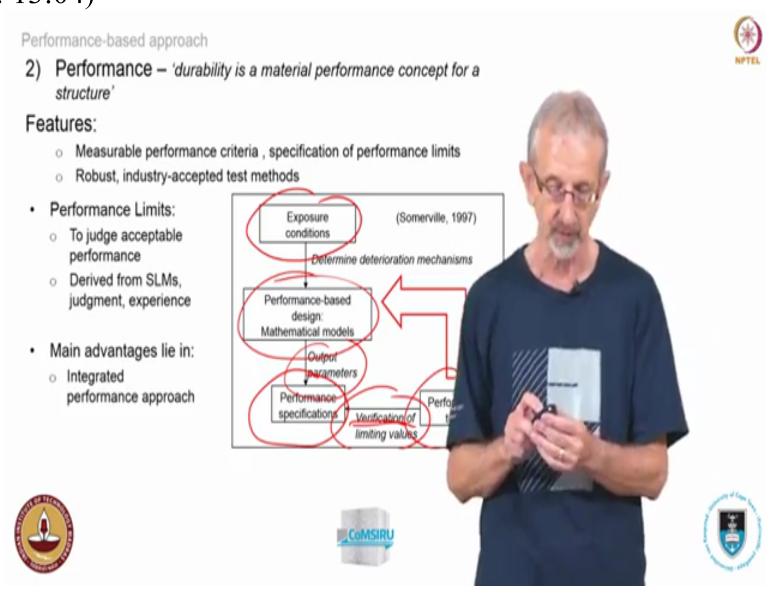

Okay. So if you move away prescriptive to a performance approach with durability becomes what we call a material performance concept, then what we need are the following things: we need measurable performance criteria. How do we specify an actual performance criterion? Specification of performance limits? What limits we work with? We need of course test methods. This is the big thing that we often do struggle with test methods. Then we need performance limits, as I said to judge acceptable performance these have to be derived not just from some sort of concept but from proper models like service life modeling.

Judgment can come in of course and in this way we can get what we call an integrated performance approach. Now this was a diagram that in fact Somerville way back in 1997 which is if I am assess correctly 20 years ago, came up with, they were really thinking along these lines and this was a good example. So we start with exposure conditions and then we move from that through performance-based design. Using mathematical models we come up with performance specifications as output parameters and then importantly verify, verify, verify.

You have test and of course you have the feedback loop as well. So that was advanced thinking at that time and we move beyond or moved in this round now considerably since then. But that is really what we are talking about.

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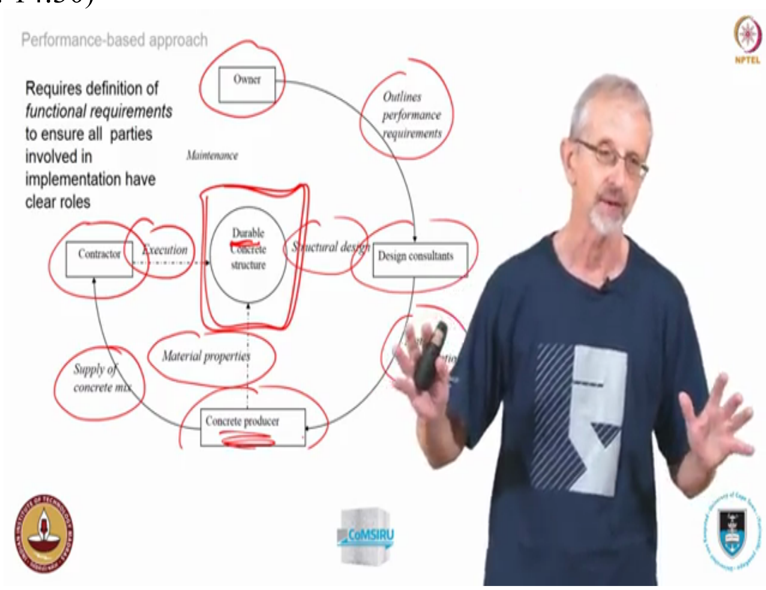

And here is another diagram, maybe also to help us understand it. Here we have a whole lot of different people involved. We have the owner of the structure who has to outline the performance requirements. Then we have the engineer or the design consultants, they work with a structural design because they produce the specifications which we are talking about. We then get the concrete producer, possibly a ready mix producer in this case who has to produce material with correct properties.

And then we produce the supplies to the contractor who executes it and finally what we want is a durable concrete structure. Notice that the durability has to occur in the final structure. It is not good enough to simply have durable concrete coming out of the ready mix plant, you have to prove that you get durability in the final structure. That is the critical key here. So we need a set of functional requirements here to ensure that all of these parties understand their roles and play their part effectively.

So it requires significant amount of coordination across the whole value chain if you like of the construction process which of course prescriptive approaches do not require.

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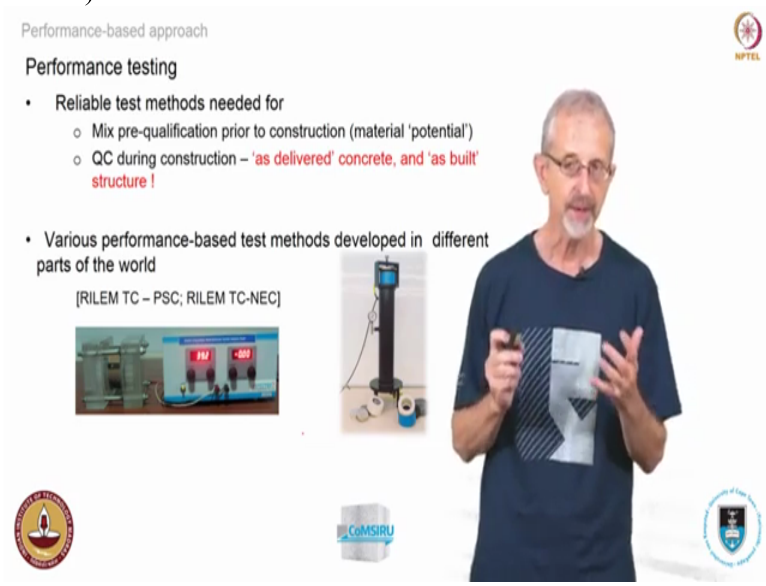

Then there is issue of performance testing. This is where we have struggled now for several decades, to find reliable test methods for doing things like mix pre-qualification and then actually during construction as built quality of the structure itself. And there is no shortage of tests, absolutely no shortage. RILEM has done lot of work here, I have my RILEM shirt on today by the way and RILEM has done work through many technical committees and that is really good work. But despite that we still do not have internationally accepted test methods.

Some have more or less achieved that status but across the board we struggle to get test methods that actually give us what we want. And so this is a major challenge because without the ability to test and verify in-situ we do not have a proper performance approach.

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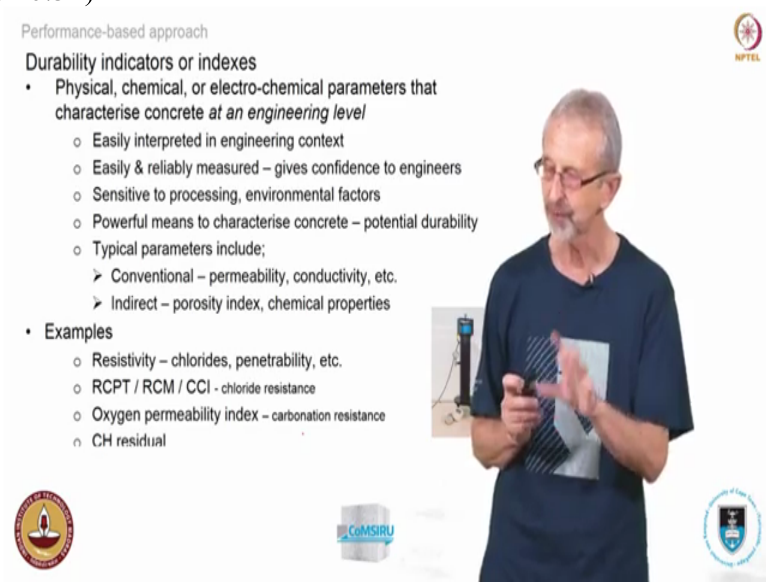

Just a brief word on durability and indicators of durability indexes. These are physical or chemical or sometimes electro-chemical parameters that characterize concrete at the engineering level. So they are easily interpreted in engineering context and they are easily and reliably measured. And in fact these things, these durability indicators can be a great way forward in terms of moving into this performance setup. They need to be sensitive to all the things that will affect the final structure, the processing and the environmental factors.

And they are very powerful means to characterize the durability, potential durability of concrete. The typical parameters may be things like permeability, conductivity. Indirect may be a porosity index or may be some kind of chemical property. And the examples are given here. Resistivity is the one that we often use now. We have different kind of chloride. Penetrability or prior resistance tests, RCPT and so on. We have the oxygen permeability test which is a very good indicator of carbonation resistance. And we might be things like calcium hydroxide residual which would also influence things like carbonation.

And so there are bunch of these things but we have not quite learnt yet how to integrate them fully into performance approaches. That is the challenge that still remains.

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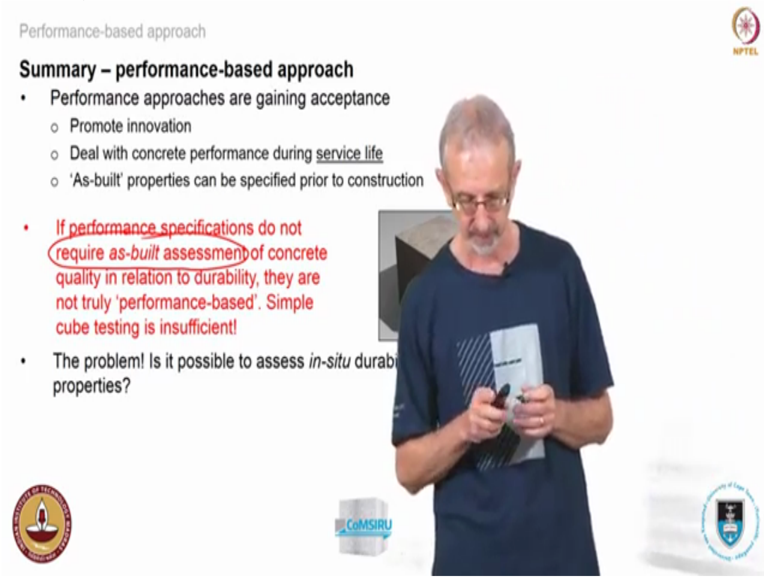

So let me try and summarize where we are at the moment about performance based approaches. To gain acceptance they promote innovation because now you can start thinking rationally, you can start thinking how to actually do rational engineering design, doing things that engineers do best that deal with concrete performance during the service life. We have to verify that the structure has achieved what we wanted to achieve and then we can do something about predicting service life.

The as-built properties are specified prior to construction but if we do not measure these performance requirements within the real structure, for example, in relation to durability, then in my view these are not truly performance based specifications. You constantly do keep testing. And some approaches that you find in the literature which are core performance approaches, in fact are not in my view because they do not go through this final very important step of requiring as-built assessment and that is always a trick.

And I showed you some of those pictures, that picture of the OPI testing earlier which was done on the actual structures. That is very important. So the problem is that is it actually possible to assess in-situ durability properties and that is a huge challenge which we are still grappling with today. This is what is largely held back, the full implementation of performance approach.

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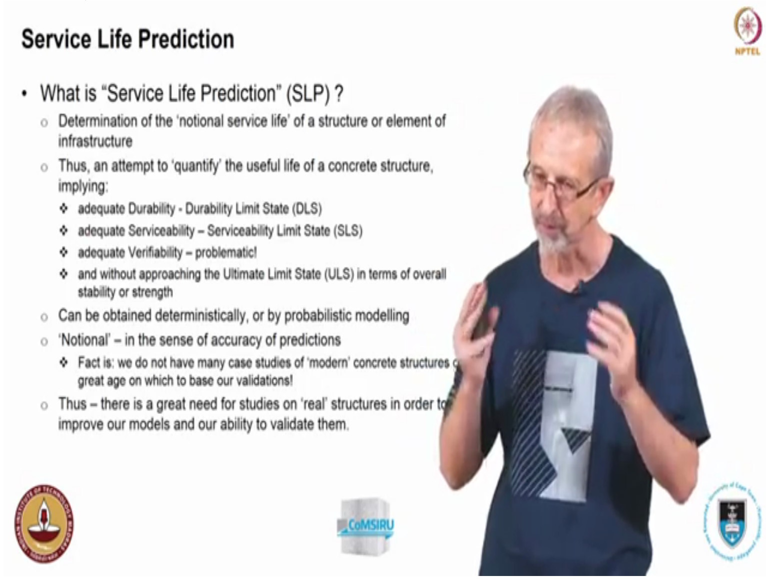

So with that as background we can talk a little about service life prediction. Service life prediction is determination of the notational service life of a structure. How much life can we get out of this structure in terms of decades or years whatever? So it is an attempt to quantify the useful life of a structure which implies then that we need to have adequate durability. So we need durability in the main stay. We need serviceability, serviceability limit states. We need verifiability, that is the problem as we often come up against.

And of course in all of these we should not approach the ultimate limit state. The engineers understand this question of limit states very well. So we can work with that. We can approach service life prediction either deterministically, in other words simple models which give us single value kind of answers or we can do probabilistic modeling. Preference for the latter because of this huge variability issue that I spoke of earlier. And the problem is of course is that we do not have many modern concrete structures with which we can actually verify that the approaches that we use in for service life prediction are going to work.

So somebody comes to me and says I want a structure that was lost for hundred years, I do not have a problem, so I can do that for you because now I want around 100 years to show that I managed to achieve it. So in a sense it is a little bit hysteric. How can I actually guarantee 100 years when I cannot retain the responsibility for ensuring that I actually get that service life. Nevertheless that is what people are asking us for these days. They say they want 100 years' service life and then as engineers we have to try and do something to prove that we might actually get that. So there is a great need for studies on real structures in order to see whether the approaches that we are using are actually working and this is of course difficult. This is hard work. It is easy to work in the lab and getting to real structure it is always difficult because there is the question of access, there is a question of responsibility, there is a question of safety, all kinds of things, difficult to do that.

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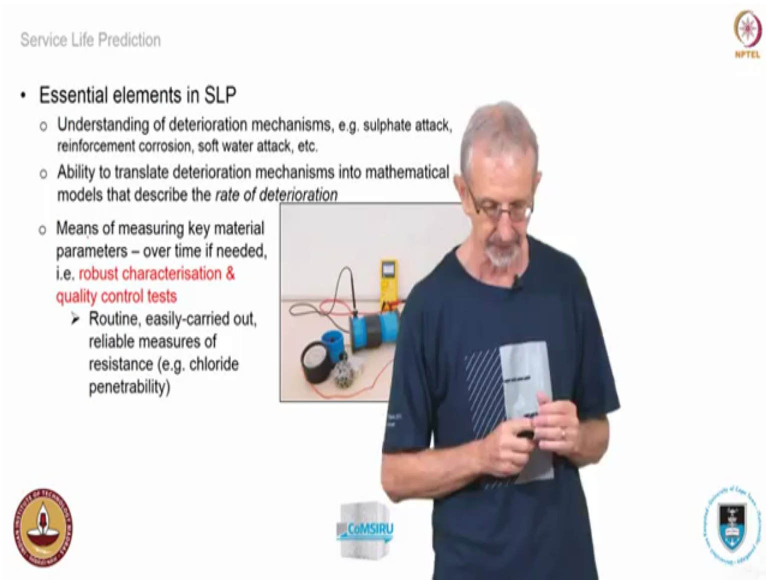

Essential elements in service life prediction are this understanding of deterioration mechanisms, dealing with sulphate attack or dealing with reinforcement corrosion or dealing with soft water attack or whatever. So we have to understand deterioration and the ability to translate those deterioration mechanisms into some kind of rate equations, mathematical models that allow us to predict things. And then as we have indicated ways of actually measuring material parameters, this robust characterization and quality control tests which have to be routinely carried out, easily carried out, we cannot take six months to measure these things.

We got to be able to measure these within space of hours or days at the most because we use them in quality control and quality control means that they want to answer tomorrow for the problem that they have today in terms of site construction. And I will refer to few of these later on and of course many of you are familiar with some of these tests.

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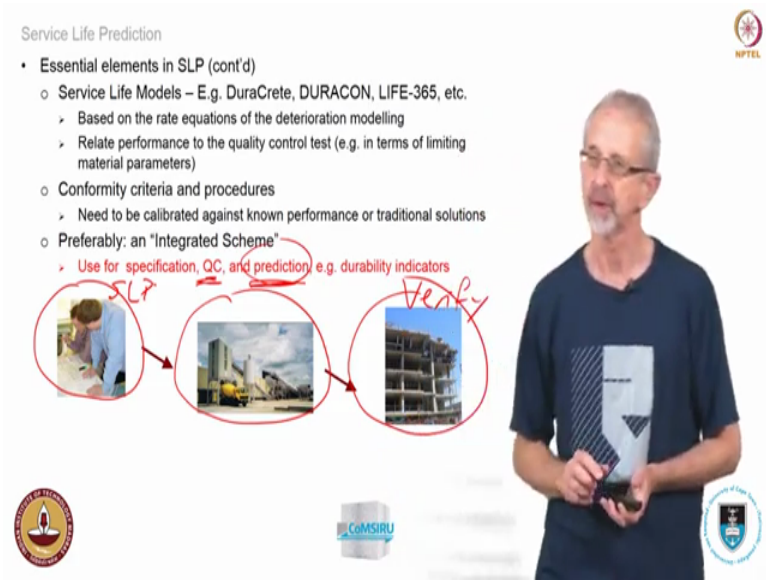

There are number of service life models out there in open source softwares, you get DuraCrete, Duracon, Life-365. They all have merits, they all have demerits. They are all based on rate equations one way or the other. And their relative performance to quality control test, but the conformity criteria or still issues that we grab always because we have to calibrate these against non-performance and that means studying real structures.

And I will come back to this question of integrated scheme. Many of these are not properly integrated, where we use them for specification, some specification limits. We use them for quality control. Can we measure them on the real structure to prove that we get it? And then can we use them in prediction? And that is a nice scheme because if we can use a parameter, let us say durability indicator or durability index for each of those three purposes, then we have an integrated scheme.

Say for example, we specify certain value. We find out on site that we did not get that value. So then we can go back to our prediction model and say okay, we did not get what we wanted. So what would the effect be on the service life? How much less service life are we likely to get because we did not get the performance we wanted? And then we can immediately start doing remediation. We can put coating on, we can put an extended maintenance warranty or something like that in place. It allows us to act far more rationally.

So really what we are saying is can we move from the intention of the designer to the production of the concrete through to the quality and the final construction that we really want. How do we bridge the gap through that entire range of activities? That is what performance approach allows us to do. And what we really want to be able to do is to say can we do service life here and can we do verification over here in some way or the other. That is the big picture.

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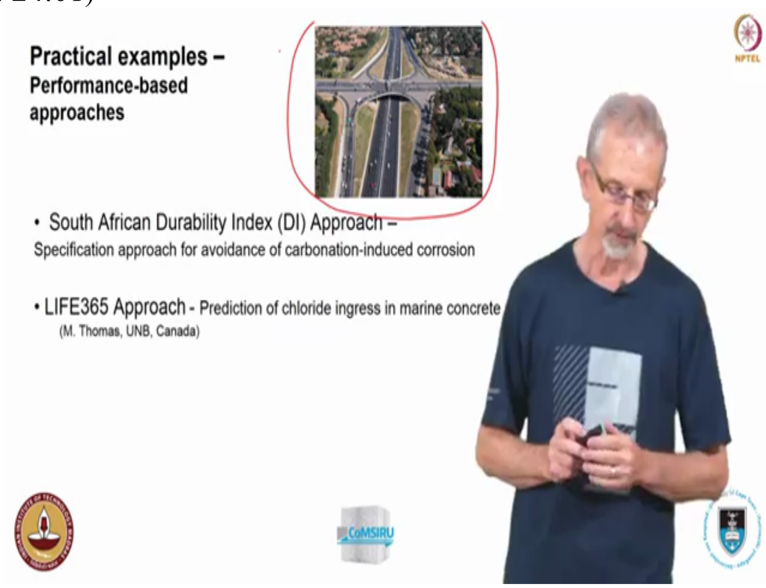

So let me then move, now I have really given you some of the philosophical and framework background to this whole problem of durability specifications, service life modeling, performance approaches and so on so forth. Let me now deal with couple of practical examples of these. And I am going to deal with two: the approach that we have developed where I come from in South Africa. And then the life 365 approach with some work done by Mike Thomas from (())(24:32) in Canada.

By the way these are some of the structures that we have studied in the approaches that I will be showing you just now. That was some major freeware upgrades that we did some years ago and we were able to actually being involved in site construction very extensively to try and implement this approach.

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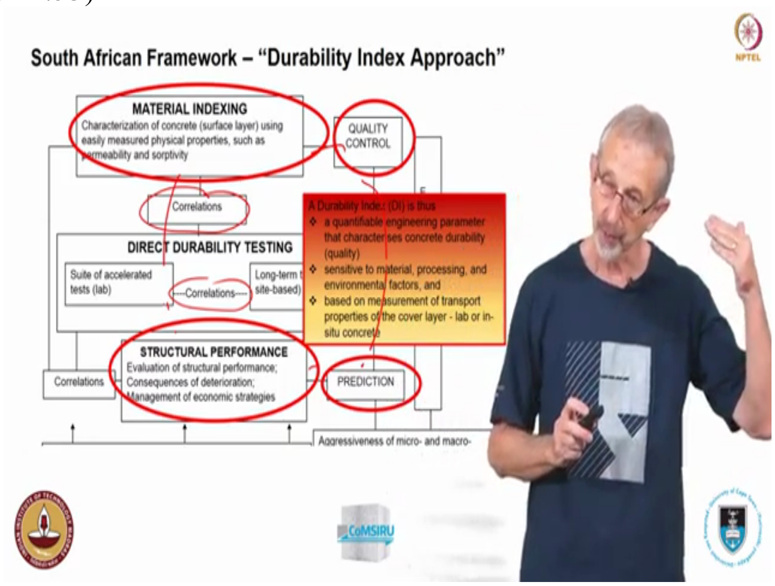

This is how the approach works in our setup. This is a framework which we have used for many years. And the important things, I do not want to go through this in detail because there is a lot of stuff here. But importantly we talk about material indexes or durability indexes and I have defined those, I will briefly refer to them again. We talk about quality control, we talk about structural performance, we talk about prediction. And we try and tie all of these things together in some way another through the approaches that we are using.

Say for example, you see things here like correlations, there and there and there and so on. So there is a lot there and importantly one of the things that we really have found very very helpful is to develop these things called durability indexes. With that defined here there are quantifiable engineering parameter that characterizes the concrete durability. In this case what we call the potential durability, how potentially durable is this concrete? There are sensitive to all the things that influence concrete quality: the materials, the processing, the environmental factors and they are based on the measurement of transport properties. And they can be carried on importantly either in the lab or in situ.

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And the two that I just want to show you is actually also (())(26:13) test and another therein action here in your own laboratories, or the oxygen permeability test and the chloride test.

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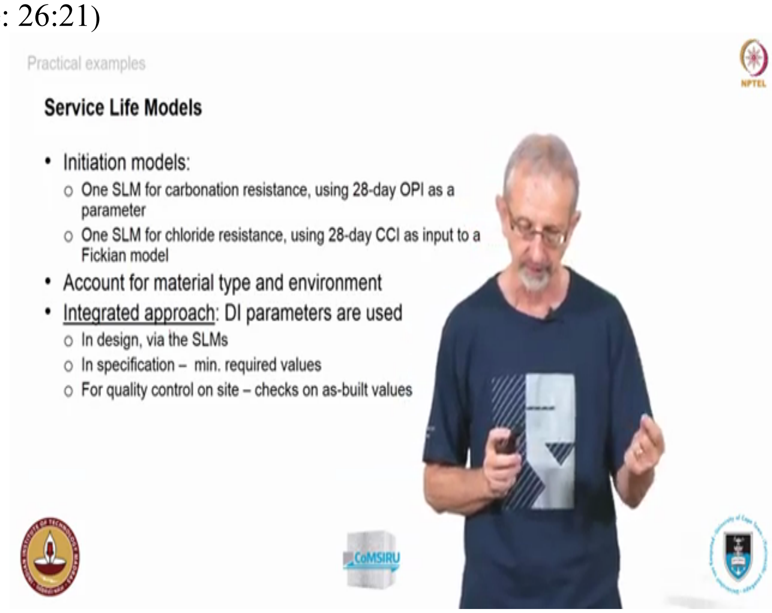

In the case of, I will come back to that now but they are also linked to service life models. So here is the link between material parameter and prediction or service life modeling. We have two initiation models, one for carbonation and one for chloride resistance which account for material type and environment. And it is an integrated approach as I described earlier. We can use them in design, we can use them in specification, we can use them for quality control.

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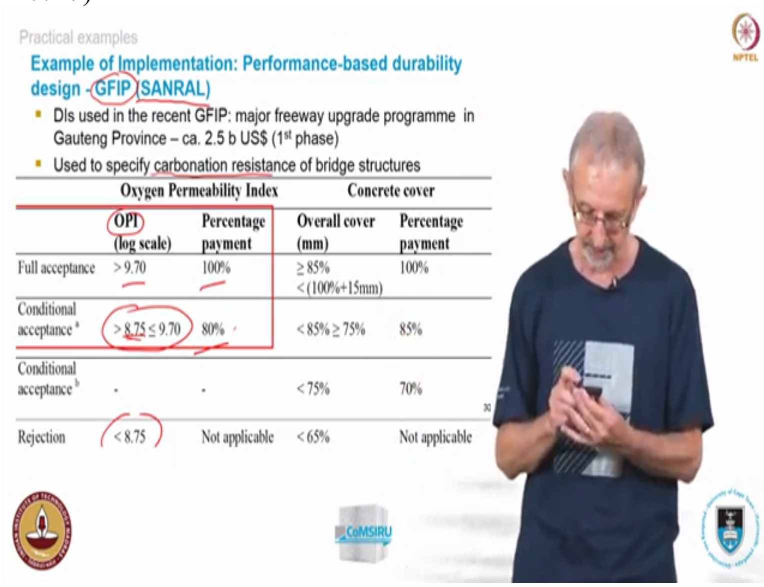

And here is an example of the implementation. This is from that, I showed you that 3-way structures earlier. This is, that was part of what we call hearting freeway improvement project which was rolled up by South African National Road Agency Limited, SANRAL. So this was a major piece of construction appeared in several years in that part of the country. And in this case the criterion, because it was in lab not at the coast, the criterion was a oxygen permeability index in order to control carbonation resistance. Another is our concern was reinforcement corrosion due to carbonation. And that was the, this is the specification. The contractors were required in-situ to achieve concrete with an OPI of at least 9.7 in which case they got paid 100 percent for the concrete.

If they achieved values that were less, they only got paid 80 percent and below that they got paid well, nothing at all. Now you will realize that with OPI this is a large range, 8.75 to 9.7 is almost a factor of 10 because this is a log scale. So they were being quite lenient here allowing the contractor to go quite far down and still giving them reasonable payment. So that was a specification. We also noticed that there was specifications around cover, but I will not deal with that now because that is just as important that you get the actual cover you specify.

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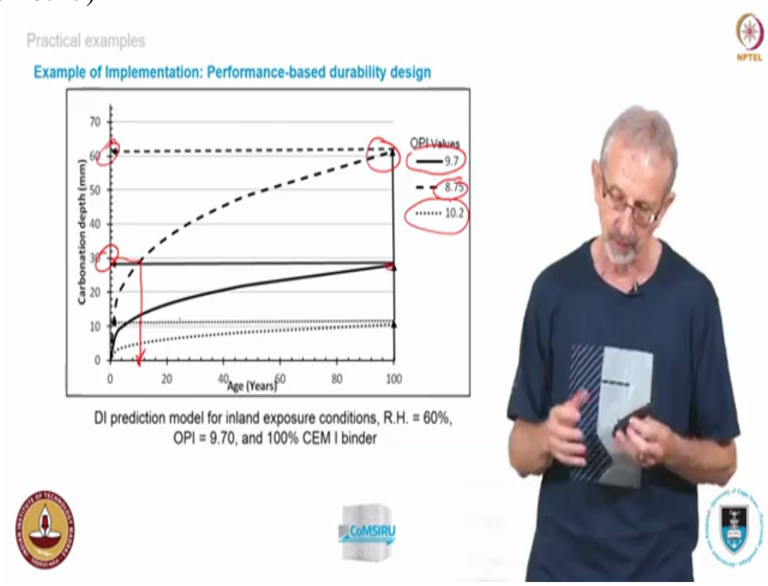

And this is just to show you how the model works. So for example, for 9.7 OPI at 100 years we would predict roughly 30 millimeters of carbonation. That is the model that is deterministic and I know that there is a lot of variability but that is roughly how it works. That is the basis for the 9.7. If you only get 8.75, you can notice that you can get about 60 millimeters of carbonation in 100 years and if you only have 30 millimeters of cover, then your service life is only going to be about 10 years before you get carbonation at the level of steel.

On the other hand, if you go up to really good values around 10.2 which is this curve at the bottom, then of course you get really very very good service life. So that gives you the sensitivity to the parameters that we were measuring in-situ on the real concrete.

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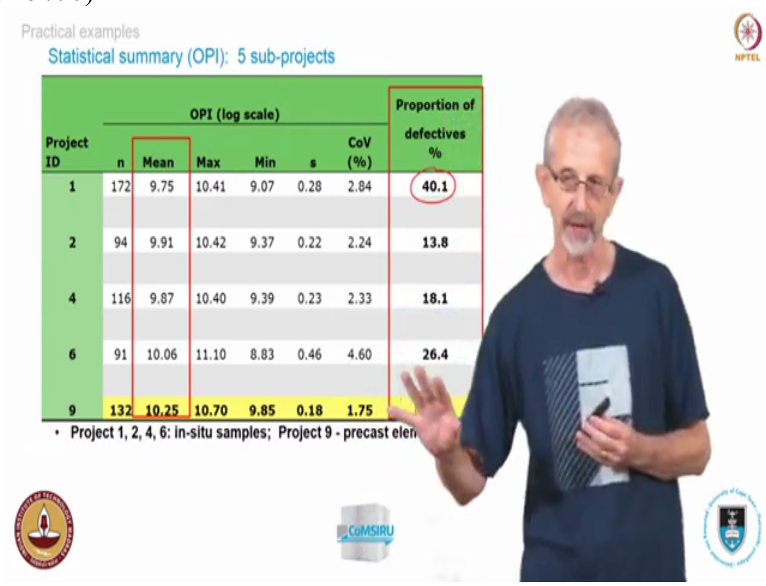

And this is what actually happened, we measured, we got data from 5 sub-projects, actually got from more than that but on any report on the 5 and what you can see here is that the mean OPI in all cases exceeded 9.7 in this column here. And you can see the number of data points in the column called n. Lot of data points and in every case we got at least the mean value, that is good. On the other hand, if you look at what they call the proportionality factors, that was not so great. We got as high as 40 percent, results not achieving the minimum and in one case we got 0. So they achieved that in every case with a whole lot in between.

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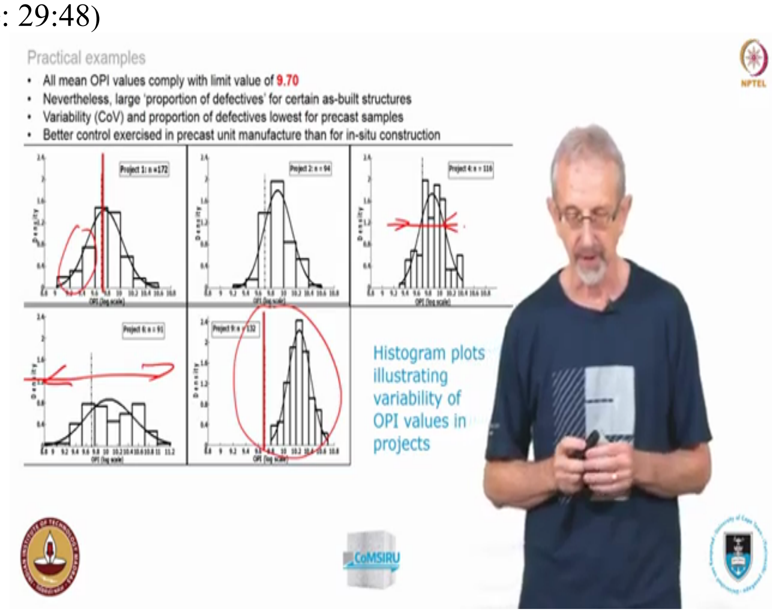

And if you look at that on sort of histogram basis, that just shows you what happens on site. This is really good example of what happens on real construction site. Basically the concrete going into these five sub-projects is all the same concrete, coming from more or less the same plant. However the difference is the contractors, the actual execution that was given out in five separate contracts to five separate contractors. And this is what the contractors did with the same input material. This is what they did on site to the concrete if you like. And so of course the best one was down here and you can imagine that way that was produced.

That was produced in on-site precast plant to make medium variables. So when you do stuff in precast operation, you can really get excellent quality. And here you can see those were the 9.7 values, I have not done them on every graph but you can see that in this case there was a huge amount of underperformance. You can also see that here there is a huge spread of data, here the data is much more well-confined. So the variability is now actually being able to be quantified. So that was a really interesting example to us of whether we could achieve this on site and you can on average but very often you do not get it in every case.

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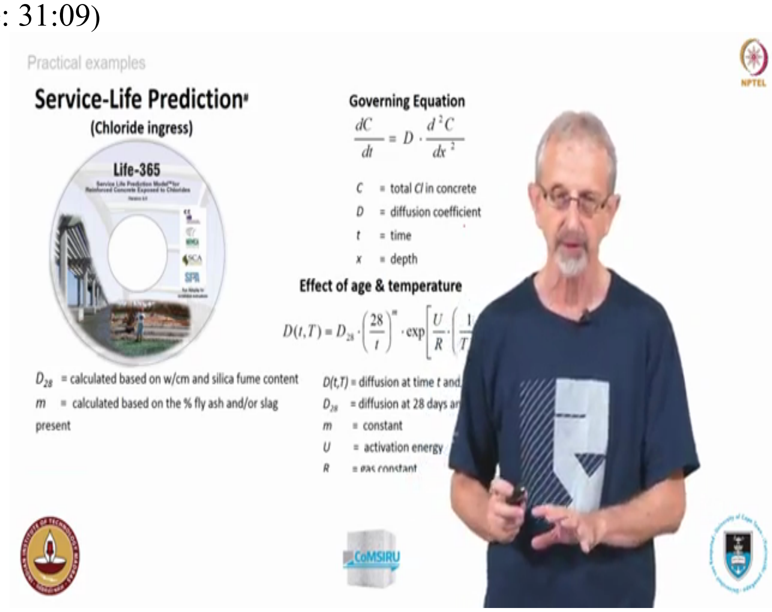

So that was the first example. The second one is from this work that Mike Thomas has done on service life prediction. He is using life 365. I am not going to go through all of these, this is chloride prediction.

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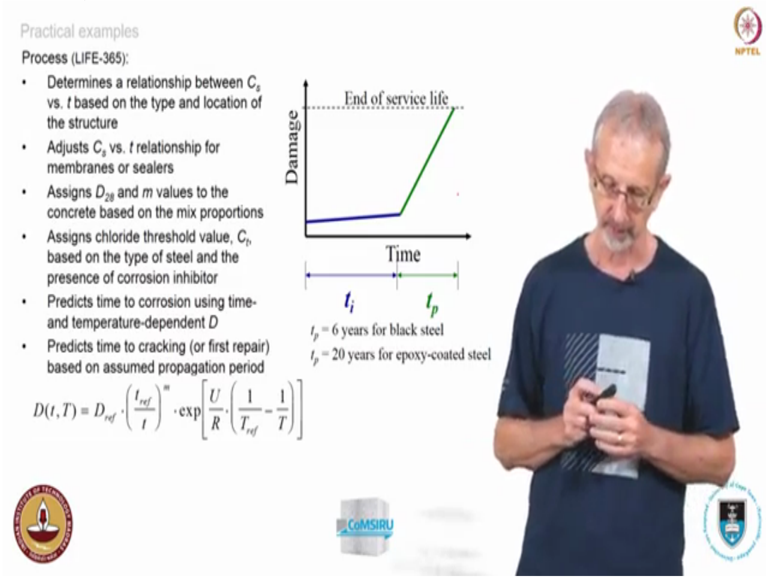

In the life 365, really what it does is it allows you to determine the rate at which chlorides enter into the concrete. So you have to do things like find the surface value of the chloride content. It assigns an apparent diffusion coefficient and from there you can calculate using this kind of equation at the bottom of the slide exactly when the chlorides will be at a certain point within the structure. So that is what the model does.

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And then they had this site at Treat Island in Maine where they have exposed concrete for long periods of time. And they looked at in this case at the forms of slag concrete. And so whether the measured chloride ingress that they were able to actually go and measure was not any way represented by the model. And well, yes, it was pretty well.

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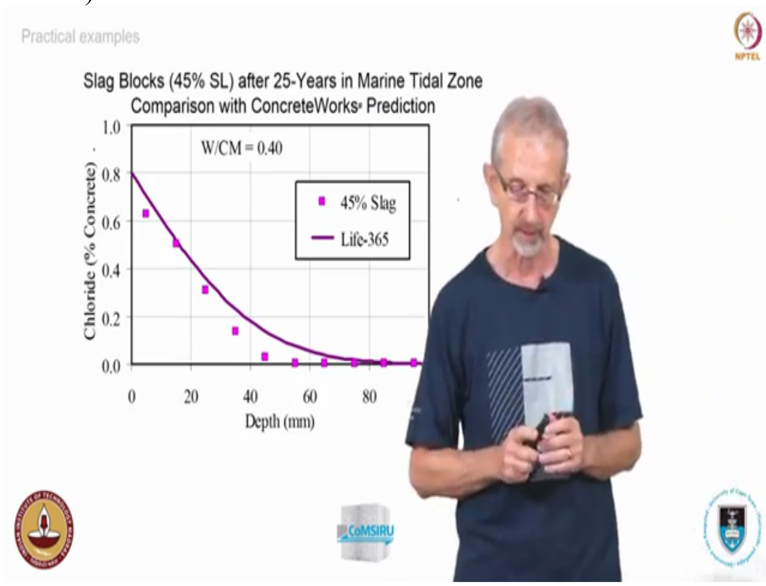

Here concrete blocks of the 25 years, there is no slag in them. And you can see that the model is predicting reasonably well. And then for slag concretes you would expect this steeper profile and there too the model was doing reasonably well. So these are very simplistic examples but the model was not calibrated by this data, it was calibrated by other data. And of course, when you have a model that is calibrated by certain data, then you apply to new data, that is the real test of model. Can it work with data that is not being used in its own formulation? So that was interesting.

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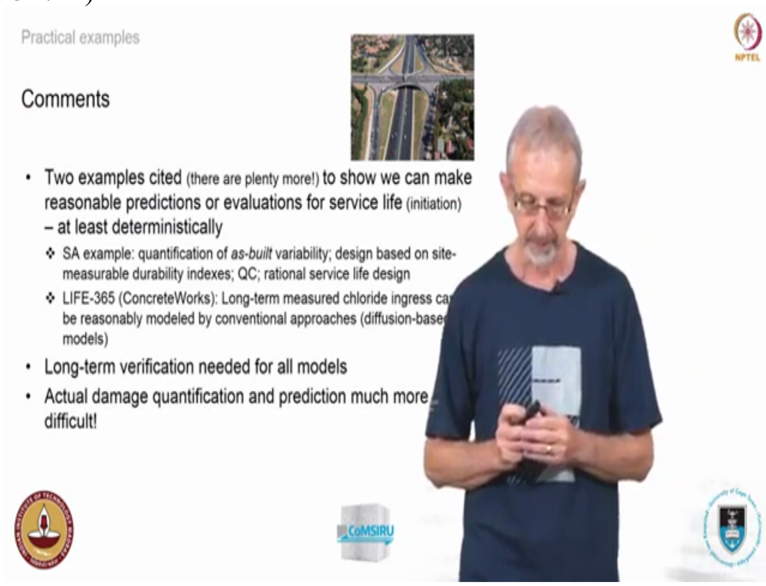

So what can we say from this? I had two examples here which shows that yes, we can make reasonable predictions for service life, at least deterministically. Probabilistically that is still quite a challenge. We have used this in South Africa for as-built quality and variability and in life 365 you can do to some degree some kind of prediction for that. However we need the long-term verification. This is really working over the long period of time. That means we actually need to go and study damage quantification and things like that.

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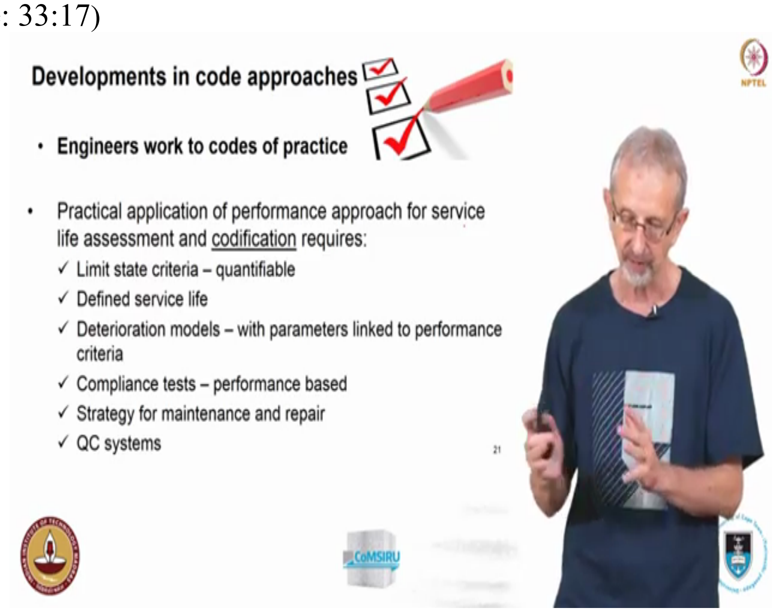

Very briefly then to bring the lecture to a close, what about the developments in code approaches? All of this stuff is very interesting, it is exciting as researchers we love this kind of stuff. This is what gives us oxygen and helps us to get out of bed in the morning and gives us a smile on our face. What about code approaches? Engineers, they listen to what we have just said. But that said, what is that really mean? I work to a code of practice, that is what an engineer would say to you.

So that is very important. And so if we are going to get practical application of what we do in research, we have to find that embedded. We will make sure that it gets embedded in codes of practice, codification. And in that case we need limit state criteria, we need defined service lives, we need this deterioration models, we need compliance test. All the things are in fact spoken of before. Strategies for maintenance and repair and also quality control systems.

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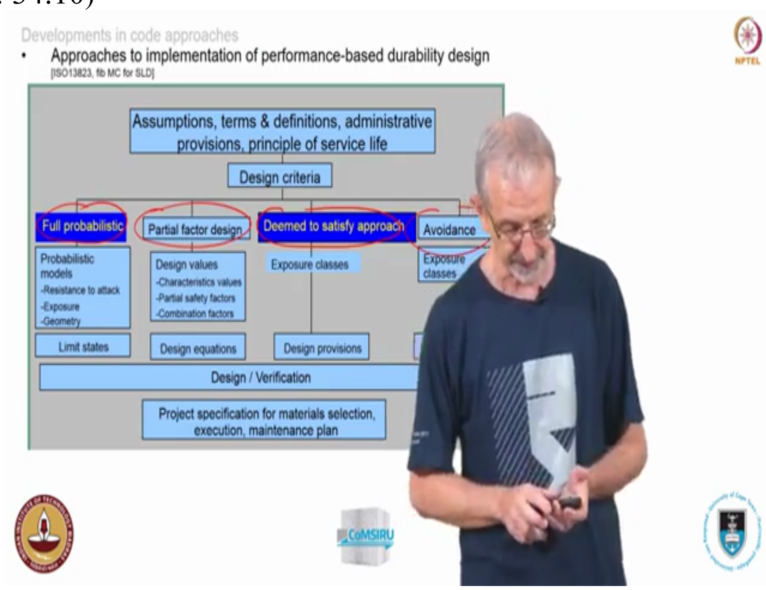

And there are different frameworks here. This is the framework that the FIB uses. It comes from model code for service life design. They are working on this. This is a new code coming out in few years. And here you can see that they have a number of different approaches to tackle this problem at the code level. There is the in fact, there is deemed-to-satisfy approach which is still there but there is the full probabilistic approach.

There is the partial factor design and sometimes if you have a real problem with deterioration concrete, maybe we should just try and avoid it. So use stainless steel reinforcement not black steel or cut the structure so completely that nothing can get in. That may be a valid approach if it is just a very small structure and very highly sensitive structure. That might be something we should do for example, for nuclear power stations maybe and so on. So it depends on which framework you want to follow.

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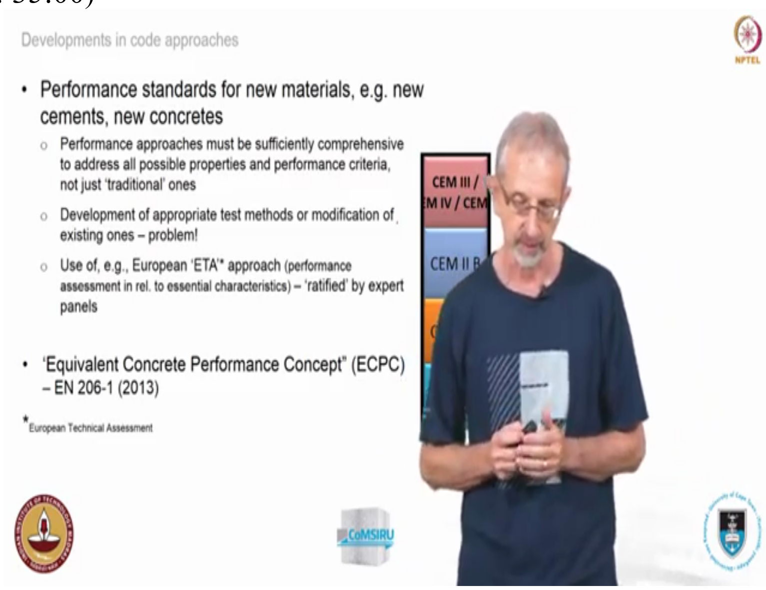

The problem is we are continually getting new materials. And that is where the prescriptive approach cannot handle this at all. Because the prescriptive approach is based on past experience, so when you immediately you get a new thing coming along, like LC 3, how do you handle this? There is no past experience to go on. So the prescriptive approach completely shuts you out of applications. And here so we need ways but the performance approach can get us there of course.

And there are different ways of doing this, I will not go through this in detail but in the European context there is the European technical assessment that you can use in the interim before you get into the full code approach. That sort of things can be done. There is also the equivalent concrete performance concept which is covered within the European approaches. Again one can read this stuff if you like. What I am saying is that all of these things are there from a performance approach perspective without which we cannot even begin to think of how we actually use these new materials in real construction because engineers want to know that these things will work.

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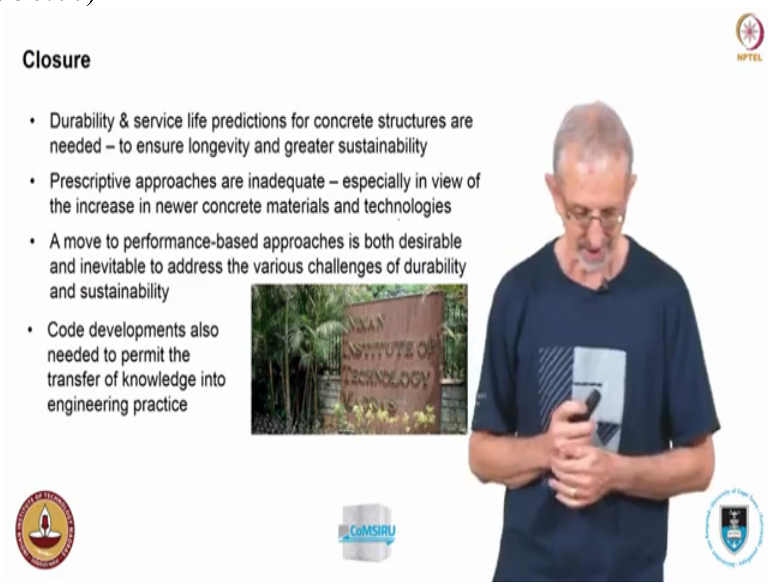

So let me bring this to a close. First of all, durability and service life predictions for concrete structures are needed. We have been required as engineers today by our clients, by the owners of infrastructure to provide proper and quantifiable service life. Longevity, sustainability, all are coming in there. The current prescriptive approach simply do not do the job because we have all these new materials, new technologies, none of that can be handled within a perspective approach. We need to move to performance based approaches. This is desirable inevitable to address these challenges that I tried to indicated today to you.

And the code developments are absolutely essential if we are going to be able to roll this out into engineering practice. So there is a lot of work to be done and enough for your life times I am sure.

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So with that I thank you. That is a city ton concrete (())(36:58) used for coastal protection on one of our new harbors. And you might just recognize the national flag, Nandri! Thank you.

Right, there is time for questions. The question is about that five sub-projects and we saw the different variability and the different proportion of defectives that we are getting. We did not manage to quantify that. All we know is that they were each let out to different contractors. But they receive concrete from central plant. So the concrete was the same, the specification was exactly the same but it went to five different sub- contractors if you like or contractors and sub-projects.

And they each had structures to build under the big scheme. And so it simply indicated to us different contractors had different ability to produce quality concrete, the quality control that they had the training of their labors, the methods they used on site all clearly differed and we we were able to actually quantify that difference, at least at this level of the material, quality of the material. But exactly we did not, we could not dig and dive into everything. Of course, we were working little bit for marketing, we were getting the data from the sites and then processing it. We were into ourselves physically involved on the sites.

That would have been another study, why that contractor do better than another one? Of course on the precast operation that you can clearly understand there. There they got absolutely zero defectives which is just again a real example of how really excellent work can be done in properly controlled environment such as precast. Other questions?

[Processor-Student conversation starts]

Professor: Other questions? Yes.

Student: When you have testing done at site and the concrete fails in terms of durability and the structure has been constructed at least partially, what do you do?

Professor: Yes. That is the key question, is not it? When you compare them at least to start with and then you have some money in the bank to do something, say to cut the structure, would you give it additional, maybe if there is very inadequate cover because the other part of this question is not just the quality of the cover, the quantity of the cover, I have not spoken about that. But if your cover is very diffusion you can already put in sacrificial anodes for example or something like that.

So that is one possibility. You can at least determine possible remedial work and decide whether this should be done now or in ten years time or whatever and you can put proper maintenance scheme. Of course in the worst possible case you may say well, please demolish and reconstruct. That never happened. Now I just mentioned that this was very much an experiment, I mean the agency the national roads agency were really very courageous I think, very bold in coming in with this entirely new approach. This is most unheard of that you find a national agency willing to go out on a limb. And I can assure you that I took may bullets for that. People discourage you, you cannot do this. What I say, we can do method.

So they took, they sort of took an education approach to this. They said look, this is new, the contractors have never done this before. We are not going to be too tough. So they use this opportunity to help, train and educate the contractors into these methods. And now it has become common practice within the agency to do this kind of stuff. So contractors have, initially they were very resistant because they said, this is yet another requirement that we have fulfill. But once they learnt how to do it, some of them abreast it and did very well.

So yeah, so in fact we have been talking to the agency about being a little bit tougher about some, because sometimes I think there are bit too lenient. I have lost my picture but anyway another picture, another question.

Student: You told about chlorides and carbonation, and limits for chlorides and carbonation and models based on that. Then the governing factor is mostly the transport problem. So problems like sulphates, acids or others are where it is more of chemical effect, so what sort of limits can be implemented?

Professor: Oh, that is extremely good question. You can see that the main concern we had was reinforcement corrosion because that accounts for the vast majority of the deterioration that we see in concrete structures. It is around corrosion. And you have a lot of corrosion which is going on here for good reason. The other kinds of deterioration, like ASR, sulphate attacks, softwood attack whatever would need their own similar approach philosophically but you would need the test methods, you would need the criteria to judge the limits that you would set.

And there are performance test here, I mean some of the sulphate testing is performance testing but how you relate that to the real structure is a big issue. And that is always the trick, that is always the challenge. Can we relate this to, sulphate testing has certain limits to it but is that really what is happening in the structure? These are the challenges that we face. So this all needs developing and if there was a particular criterion that you needed to set for a certain deterioration, you could do that.

For example, one dam that I showed you, that roller compacted dam, that is a pam storage scheme. So they have a dam at high level and dam at a low level, that was the low level dam that pump water up during periods of peak of excess electricity to the high level dam and then during periods of peak demand they leak that water out of the high level dam through very large tunnels. But 3 meter dam at penstock tunnels through the turbines to generate power for couple of hours at a time. Now those tunnels were aligned in concrete and we were asked to look at deterioration mechanism for and that would be softwood protect. So we did work on the softwood problem for that particular application. Yes.

Student: For different sub-project same concrete through different contractors, there was variability. Do you think that is because of the nature of the work that has been carried out in-situ? For example, if it is a small tank or small restoration (())(43:38) that has been built through a site where lot of public usage is happening, like for example, it is a main freeway or something. So because of the importance of the project that would be the variability or?

Professor: In this case bear in mind that this was all to do with freeway construction. This was the same kind of construction. Every contractor had so many bridges to build and so many covets to build and so many medium barrier walls to build, et cetera, et cetera. So this was all much the same construction. There was not variability in the type of structure being built in this case, there were all bridges and they were all within the same area using the same basic source of concrete and materials and so on. So this I think is a reflection of the construction practices, how well they compact in the concrete, how quickly they strip the concrete, whether they protect it properly, the degree of curing that they are carrying out and for how long and things like that.

So I think it was a reflection of their of how good they were doing, how well they were doing their construction, that is all I can put it down to. And that then further reflects on equipment, plant, training, understanding of processes, commitment to quality, all these kinds of things coming there.

[Processor-Student conversation ends]

Professor 2: Thank you very much Mark. It is always the pleasure talking to you and have you visit us.

Professor: Thank you very much. It is being a great pleasure. Thank you.