**Advanced Topics in Science and Technology of Concrete**
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**Week - 02**
**Lecture - 10**
**Recycled Concrete Aggregates: Properties and Performance - Part 4**

Thank you for being with me while I discuss the hardened properties of concrete with recycled aggregates. I am Ravindra Gettu from the Indian Institute of Technology, IIT, Madras. So, when we talk about hardened concrete characteristics, strength first comes to mind. Strength is the maximum stress that occurs in a material before failure happens. Strength in the context of concrete is usually the compressive strength; the grade of concrete is also defined by the compressive strength. So, that is what comes to mind when a designer specifies a concrete or someone who is checking the quality of concrete refers to.

However, strength can be determined in many modes: compression, shear, tension, and so on. Also, we should note that the behavior of concrete as many other materials is time-dependent. In concrete, two time-dependent strains or modes of deformation, harsh shrinkage, and creep. We will talk about this in detail a little bit later.

Shrinkage is what happens when water is lost from the microstructure of concrete and therefore, there is deformation. Due to this loss of moisture, there are stresses, internal stresses that decrease the volume of concrete. So, shrinkage is volumetric. Creep occurs when there is a sustained load, load that is on the material for a long period of time and therefore, there is strain in the direction of the applied stress. So, this is also time-dependent and often these two occur together.

So, we should remember that there are time-dependent strains in concrete, time-dependent deformations in concrete which should be taken care of. Apart from the strength, there are other parameters such as the elastic modulus and the Poisson ratio. Elastic modulus is important because it determines the deformations, the stiffness, deflections of a concrete element during service. The Poisson ratio determines how much expansion there would be and the Poisson ratio also dictates how much of effect confining reinforcement would have. So, the Poisson ratio is the transverse deformation relative to the axial deformation due to an applied load.

And as we also mentioned, the sustained load, repetitive load, fatigue and so on can affect the deformation of the hardened concrete. Now, look at, let us look at different aspects especially of recycled concrete aggregates when they are put into new concrete how they can affect the behaviour especially strength. So, here we have a sort of a flow chart or a relation between the different characteristics of concrete and the properties. So, mainly we are looking at concrete strength. So, as I said strength is what affects the design and the grade of concrete or the quality and when we talk about concrete this is the most important thing that we consider.

Now, what affects strength? Obviously, how we test matters. Therefore, there are standards, there are standards for how we test. So, the standards determine the dimensions of the specimen, what is the type of specimen used, what is the moisture condition, how should it be cured for testing. Then we also look at how to load the specimen. Usually, we are talking about uniaxial compression.

So, you have a cube or a cylinder under uniaxial compressive stresses. So, this is how the specimen is loaded at a certain stress. Generally, when we do a test under what we call quasi-static conditions, the failure occurs in about 3 minutes. This is a rule of thumb to decide what would be the rate of stress that needs to be applied during a test. When we are doing a new type of test, we often say that this is the rate of loading that should be applied.

If the failure occurs in say about 3 minutes, that means the test can be considered as quasi-static. So, once we take care of how to test the characteristics of the material, the components, their strength and other characteristics come in to determine the concrete strength. So, these could be the different phases, this could be coming from the different phases in concrete. The matrix for the binder, so this would be the cement paste and basically the binder for the matrix, this is the matrix. So, the porosity of the matrix, the characteristics of the matrix, so the porosity would depend on what the matrix has, what the binder has, the water cement ratio, the different admixtures that go in, how well it has hydrated, which would depend on the curing time, the temperature, humidity and so on.

Air content in terms of the air that is entrained or entrapped. Entrapped is air that we wanted to get out, but it did not come out. Entrained is mostly intentional because we want to increase say the freeze-thaw resistance or we want to decrease the density of the concrete and therefore we can entrain air. So, these are common to all concretes not only recycled concrete aggregates in concrete or concrete with recycled aggregates, but for all concretes we have to understand that the matrix governs significantly the failure and the strength of concrete, especially since the aggregates are quite strong. If we compare the strength of the mortar and the concrete, mortar and the aggregates, the aggregates are always stronger.

We would only choose aggregates that are stronger than the matrix in order to get good quality concrete. In some cases, we intentionally choose aggregates which are lighter, porous for other reasons, but normally in general concrete the aggregate is stronger than the hydrated cement paste, the binder in order to give us good quality concrete. So, as I said the aggregate also matters. Generally, we would choose a strong aggregate, a stiff aggregate, low porosity aggregate in order to get good strength and durability in the concrete. Then when these two mix, when these two phases mix, so the main phase in terms of volume in the concrete are the aggregates.

These are held together, bound, the space is filled with the hydrated cement paste and the binder. So, when I say the hydrated cement paste or the binder or the matrix, it is the cement and water it is reacting plus there could be mineral admixtures, chemical admixtures and maybe some fines that are put in as filler or pozzolanic material which are reacting. So, all this together is the binder, the matrix or very simplistically the hydrated cement paste that is modified or unmodified. Now, when these two phases are put together, there is an interface and often like in most composites the interface is of concern, because failure originates, cracking often occurs in the interfaces. When you have an ingress of water, chemicals into the concrete also it could happen through the interface.

So, the interface is very important and we want to always strengthen the interface, make sure there is good binding across the interface. So, these are the different parameters that affect this interface or what we call the Interfacial Transition Zone or the ITZ. The ITZ or the Interfacial Transition Zone depends on all these things, the water cement ratio, whether we have pozzolanic admixtures or not, whether we have done compaction well, curing well and so on. So, all this affects the strength of the concrete. Now, we can start to imagine, suppose we have recycled concrete aggregates, instead of pristine aggregates we are having recycled concrete aggregates.

Let us assume that the matrix is exactly the same, but we have only changed, we have substituted pristine natural aggregates with recycled concrete aggregates. So, the aggregate porosity now could be of concern, because we have taken aggregates from old concrete and this could be covered with hydrated, partially hydrated cement paste or we call adhered mortar. So, the aggregate now in recycled concrete aggregates has the aggregate plus mortar that is adhered to it, stuck onto it. So, this changes both the strength, strength of the aggregate as well as its porosity. Also, remember that the aggregate coming from old concrete after we demolish and crush, since it has an adhered mortar layer on it, it already has an interface between that mortar and the old aggregate.

Now, when we are going to put this into concrete, then you are going to have another interface. So, now we have two interfaces. So, if we compare concrete with natural aggregates, pristine aggregates with that concrete which has recycled concrete aggregates, we should understand that what we call the aggregate before, now is aggregate with some mortar stuck on it and the interface therefore becomes wider and you will have sometimes two interfaces, the interface between the original aggregate and the adhered mortar coming from the old concrete and the interface between the new cement mortar and the old cement mortar. So, this is what changes and when we go through the rest of the discussion, you will find that the origin of the differences in the characteristics between concretes comes from these two aspects. The aggregate itself has changed, the interface is now changing.

So, keeping that in mind, when we look at the stress strain behaviour of concrete, say in compression, we have here the curve of axial stress versus strain and on the right there are some cartoons which show what happens in the concrete when you have compressive stresses applied. Initially, there may be some defects or if it is a very good concrete, normally the high-strength concretes will have very few defects and as we load the concrete, as we load the concrete, we have some of these defects opening up, some of these defects will open up, will propagate, but it is quite few, quite few of them which are doing this, so we have basically an elastic behaviour, elastic behaviour. So, this is basically elastic response and if you unload it goes back to 0. Then what happens, the aggregates, the interfaces around the aggregates, other defects in the mortar start to pick up, start to open up and then the interfacial zone, especially in recycled aggregate concrete starts to open up and you start getting some non-linearity, we get some non-linearity because of these cracks developing. These cracks develop further, say by the time we reach about 70 percent, then the interfacial cracking has already started and now you have more of non-linear behavior and the cracks start to connect, cracks starts to connect and you have a reduction of the load.

So, the maximum load is the strength. In the post-peak, what happens is that these cracks connect and you have strain softening. Strain softening is where you have a reduction in the load-carrying capacity as we increase the strain. So, this is basically what occurs and you see here that I have emphasized a lot the interfacial transition zone and as I said a few minutes back in recycled aggregate concrete, we have now a broader, thicker, wider interfacial transition zone because you have the old mortar stuck to the aggregates.

So, there is one interface. We have put this aggregate into concrete. So, there is another interface now coming between the new cement mortar and the old cement mortar that is stuck on the aggregate. So, this behaviour or this, these characteristics or this phenomena changes the way that concrete behaves when you have recycled concrete aggregates. So, to summarize, the characteristics that would affect the strength when you have recycled aggregates is first the parent concrete, the original concrete that was crushed through demolition or whatever and then we put it into new concrete as aggregates. So, if that concrete originally was very bad, then the mortar coming from that if it is still adhered to the aggregates, then that would cause pockets of weakness, it would be more porous, strength would be compromised and durability.

How we crush matters? How we crush matters because some crushers are more effective in removing the adhered mortar, in making sure that we have reasonably rounded size particles, so that is being covered in other lectures of this module. Do we do any treatment afterwards? Again with the intention of removing the adhered mortar, making sure that all weak material is removed from the waste concrete when we are making it into aggregates or if we are going to make sure that the adhered mortar does not absorb water through some coating or some way to block, improve the bond. If we use such techniques, these are called treatments. Then the size of the aggregate matters, the size of the aggregate matter generally larger aggregates should be used in concrete because as I said in the beginning, aggregate is stronger, we choose aggregates, we use stone to become to be made into aggregates because they are stronger than the rest of the concrete and they have fewer defects, they do not undergo creep or shrinkage.

So, the size of the RCA matters. As a rule, we would use the largest pieces of aggregates that we can have and here you must keep in mind that when we are talking about recycled concrete aggregates, it is the idea is to reach as much as possible the old aggregate, removing the adhered mortar. So, if you have a large piece of, large chunk of recycled concrete aggregates, which is mostly the original stone plus a little bit of adhered mortar, then that would be better than having a chunk of old concrete which has some pieces of stone and lot of cement mortar or if you have a very small aggregate with a layer of adhered mortar, that would not be good either. So, the adhered mortar comes up a lot. The strength durability really is affected by the adhered mortar and that is something that is also ways of concern. If there is no adhered mortar and we have the same aggregate as before, then we do not have to worry about anything at all.

We can talk about this new concrete as good as the original concrete. The adhered mortar content, how much is still left matters. The water absorption, which indicates the porosity, how much water is going to be taken up by the aggregates when we put into concrete matters. The mixing, because we want to be able to saturate the adhered mortar, the surface of the new aggregate, new aggregate meaning the recycled concrete aggregate should be saturated, should be coated with cement paste. So, we want the mixing to be proper.

We will see later how two-stage mixing where a little bit of saturation time is given to the aggregates comes out much better and curing conditions always. When we cure concrete, we are allowing time for the cement to hydrate, for the interfaces to become stronger and therefore, concrete behaves much better. The strength is better, shrinkage is less and creep would be less. So, let us look at some results from the literature on different aspects of recycled concrete aggregates that affect the compressive strength. So, on my left, I have the relation between compressive strength, water-cement ratio, and percentage of adhered mortar or attached mortar.

We find that always, with more adhered mortar, the strength is less. This is in line with what I discussed earlier, that the adhered mortar is a layer of weakness generally because it is coming from older concrete. Mostly, older concrete would be of lower grade, lower strength than today's concrete or more modern concrete. So, we find clearly that as you have more adhered mortar, strength comes down, and as we know from concrete technology, more water, lower, higher water-cement ratio also decreases the strength, and this is data where concrete has been made with all the aggregates being recycled concrete aggregates. Now, on my right, we have the attached mortar content in the coarse aggregates versus the maximum size, and we find that when we have smaller aggregates, generally the relative, remember that this is a percentage, relative amount of adhered mortar is more.

So, that is why I said some time back that it would be good to have large aggregates used. We also have to do something with the fines to replace the sand, but generally we will find that as a percentage, there will be more adhered mortar on smaller aggregates than larger aggregates. The larger aggregates you are able to remove more, and that layer which is stuck will be relatively less in the larger aggregates than in the smaller aggregates. What about the moisture condition? So, here we are going to review what we call saturated surface dry. So, what is called SSD, SSD in terms of aggregate is saturated surface dry.

That is that we have saturated the aggregate until the surface is dry, that is the inside is saturated, but outside you do not have extra water. So, that is called SSD, and this is the condition that we usually design a concrete mix for. And here on my left, you see that the compressive strength is less when we have oven dry. So, these are, this is dry concrete than when it is, when it has some water in it. Because when the aggregate is dry, it absorbs water from the cement mortar, the new cement mortar.

And therefore, you are left, you are leaving the interface a little bit drier because some of the water has been removed, there is not enough water for the cement to completely hydrate. So, it weakens the interfaces, and this is what we see here also. That the strength, if it is slightly wet rather than having a lot of extra water. So, when we talk about SSD, I said that it should be surface dry, but often there will be, there may be some extra water, which could weaken the surface. So, that is the effect we are seeing here, that the best is slightly less than surface dry, slightly less than saturation surface dry, and obviously some water rather than having oven dry concrete.

So, if you have oven dry, oven dry aggregates, very bone dry aggregates that are put into the concrete, then they absorb water, remove water from the cement paste, and therefore, you have a weaker interface. So, the moisture content of the recycled concrete aggregate matters. And what I would like to reiterate is, it should be wetted, it should be wet before we put it into the concrete. If it is very dry, then you end up with a weaker interface, because the aggregate absorbs water from the new cement paste. So, this is what is shown here in these cartoons, you will, suppose you have very dry aggregate and you put the dry aggregate into fresh concrete, into new concrete, then you will see that this aggregate absorbs, absorbs water. So, this what we see here in this animation, you see that the water is going in. So, the water goes in, fills up, the pores, the porosity of the adhered mortar. So, here the adhered mortar is what is shown in lighter colour. So, the pore, pores of the adhered mortar, cracks in the adhered mortar get filled with water. But now this water, if it is removed from the interface, so the interface becomes drier and therefore the bonding is not very good and therefore the strength can decrease.

So, that is why we would maybe want to start off with aggregates in this condition. So, this is better, it is better to have some moisture in the recycled concrete aggregate, better to have some moisture in the recycled concrete aggregate. And this we see again further in these scanning electron microscope images where we have dry recycled aggregate concrete with or I would, I should better state it as recycled aggregate concrete made with dry RCA. So, this should be, it is better to say RCA, recycled concrete aggregate. So, RCA made, RCA made dry or dried and put into concrete, you find that there is an interface that is weaker porous. So, there is a porosity when you use the RCA that is dry. Whereas, if you have saturated surface dry or sub-saturation, then you find that there is no such weak interface, you do not see any porosity here in the interface. This is the aggregate, the RCA and this is the remain and this is now adhered, this is the hydrated cement paste and the microstructure here. And you find that you do not have this porosity that we see in this image.

The way that we mix can also matter. So, here we are talking about two ways of mixing, the normal mixing, which would we just treat the aggregates as you would pristine aggregate, mix everything together, say for a couple of minutes, that is what we call normal mixing. Then the two-stage mixing is where we have the sand and the coarse aggregate mixed with a little bit of water, allow the water to be absorbed by the aggregates because remember now we are talking about aggregates with some old cement mortar, adhered mortar. So, we allow it to be absorbed, water to be absorbed instead of absorbing from the cement mortar, then we add the cement and then mix. In the microstructure images, we find that when we do the normal mixing, we could have some cracks in the interface that are not filled, whereas if we do better with this two-stage mixing, it is because that we are able to fill these cracks and pores. And on the left, we see a idealization how compressive strength as a function of the recycled aggregates used in the concrete could be improved with two-stage mixing.

So, again two-stage mixing would be longer, it will take more time, but it will give us better quality because you allow the aggregates to absorb water before the cement is added into the mixture. As it is obvious, the parent concrete, the original concrete grade does matter, the water-cement ratio does matter. Especially at lower water-cement ratio, higher the strength of the parent concrete would give us better strength. So, this goes back to what I told you about aggregates. When we choose stone aggregates, we choose stone that is stronger, less porous for use in concrete. So, similarly, if you had concrete of 80 megapascal strength that is crushed and we are using it as aggregate, certainly that would be better than say using a 20 megapascal concrete strength. So, this is the parent concrete strength as it increases, the new concrete strength also tends to increase, especially when the water-cement ratio is low. When the water-cement ratio is very high, that means the mortar itself is weak. So, the aggregate does not come into the picture much. We have made the new mortar so weak that failure is going to occur through the mortar and not through the aggregates.

Therefore, it does not matter that much. So, this is often a very important problem when we are using recycled concrete aggregates. We do not know what the parent concrete strength is and it would be a mix. So, you have to see if we can take samples and get an average strength or say some sort of a characteristic strength or ideally we know where the demolition waste is coming from. So, the use of recycled concrete aggregates works fantastic where you have a certain structure that is being demolished, a large structure where we know the parent's concrete strength grade, we can determine the strength of the parent concrete and we crush and use all of that in making new concrete for the same project or for some other project. More knowledge of the parent's concrete strength and characteristics will help us use recycled concrete aggregates in a better way. Thank you.