Advanced Topics in Science and Technology of Concrete
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Recycled Concrete Aggregates: Properties and Performance - Part 5

The way that we treat the recycled concrete aggregates also matter. We find that wherever we remove the adhered mortar, say in the case of heat treatment and mechanical grinding, the strength goes up. Another way to increase the strength is improve the interface. Make sure that there is not lot of water being absorbed, say with some sort of pozzolanic solution, some sort of a coating that is given or we carbonate the aggregate such that they become, the interface becomes denser. So, this would also increase the strength. It increases the strength, one of the reasons being that there is less water absorbed by the adhered mortar.

How do mineral admixtures help and can mineral admixtures compensate for this decrease in strength that we see? One of the good ways to compensate or to have higher strength is through silica fume. So, with silica fume, silica fume is an amorphous, very fine state of micro silica. It comes from the ferrosilicon, silicon industry, very fine. We are talking about particles of 1 micron or less and they are, the particles are so fine, they are almost 10 times less than the size of cement.

They fill the spaces, the pores of the adhered mortar of recycled concrete aggregates. They form this, they try to impermeable the surface of the adhered mortar and they increase the bonding very much. So, in high strength concrete, we generally use silica fume to improve the interface and to fill up all the spaces between the hydrating cement particles. So, here we see that there is, when we have recycled aggregate, we find that when we use silica fume, there is a slight increase or at least there is no negative effect. However, when we use blast furnace slag, there is not much improvement.

When you replace a 60 percent of the cement with GGBS, ground granulated blast furnace slag, we find that there is not much improvement because it is reacting less than the cement. So, depending on the aggregates we use, the admixtures we use, we can have a much beneficial effect or not. How about chemical admixtures, especially super plasticizers? Now, we know that there could be a lot of fine material along with the recycled concrete aggregates and therefore, the workability drops. So, we can use water reducing admixtures, high range water reducing admixtures or super plasticizers to increase the workability and here we have a chart showing how dosage of super plasticizers increases the strength and this strengthening is because of better mixing. It is not that the super plasticizer itself is increasing the strength, you are able to mix better, we are able to remove the air better.

So, therefore, the compactness, the workability is better and therefore, the compactness is better and therefore, the strength increases. So, you might see that as we increase the recycled aggregate content in concrete, we might have to increase the super plasticizer dosage or go for a better super plasticizer. So, here again, we have two types of super plasticizers. This is the control concrete with the blue dots, the strength is lower, you go to a lignosulfonate based plasticizer and you have some strength improvement but if you go to a PCE polycarboxylate, you have much better strength improvement because the workability is better, we have been able to compact the concrete better and we have been able to remove all the air and make a better concrete, better quality concrete. So, that is where the super plasticizer comes in.

So, again, we have, we are talking about the stress strain relationship, we talked a lot about the strength, what are the parameters affecting strength, we should also look at what happens before we reach the peak, in the pre-peak, in terms of the elastic modulus and what happens when we have failure. So, generally we will find that if we test different strengths of concrete, for different strengths of concrete, we would find such behavior. With higher strength, we have more brittle failure because the interface has become so strong that you will have cracking. Now, in for recycled aggregate concrete, I would expect that you will have less brittle failure because you have a weak interface which is going to absorb some energy. You compromise strength but you gain in terms of brittleness. So, brittleness is where you have this sharp drop in the stress strain curve. So, if you have a lot of adhered mortar, especially the adhered mortar is weaker than the new mortar, I would expect that you will have a more brittle failure. But if you have removed all the adhered mortar, then you will have behaviour that is very similar to that we will have with pristine adheres. So, let us see what happens if the elastic modulus, elastic modulus as a function of the attached mortar and water cement ratio, similar to what we did, saw with strength, we find that as the attached mortar increases, you may have a slight drop in elastic modulus. Because the elastic modulus of concrete is basically a sum, a weighted sum of the elastic modulus of the stone, the aggregates plus the mortar.

And here now when we are using recycled concrete aggregates, we have some mortar which has a lower stiffness than the original aggregate. So, therefore, more of the adhered mortar, less will be the elastic modulus, but it is not that much, it is not that much, we do not have to worry a lot about stiffness, especially when there is lower adhered mortar content. More on the elastic modulus, so it also depends on the water cement ratio. This is the elastic modulus of concrete with different coarse recycled aggregate concrete. Here the C is for coarse recycled concrete going from 0 to 100 and this is the elastic modulus.

And as we saw before, more recycled aggregate concrete, more recycled concrete aggregates with adhered mortar, less will be the elastic modulus. This is what we see in both of these charts that more of the aggregates which is coming from demolition waste, we can find that the elastic modulus would be slightly lower. What happens if we treat the aggregates and remove most of the adhered mortar? So, this is work where we find that there has been thermo-mechanical treatment on both the sand and the coarse aggregate. Here the F is fine and C is the coarse. Stress strain curves under uniaxial compression, this is uniaxial compression.

We find that the curves are similar, curves are similar, but there is a difference in the peak. The concrete without any coarse aggregate is here, it has a strength of say about close to 40 mega Pascal, but when we have complete adhered mortar, all the aggregates replaced with just crushed recycled aggregate concrete, you have a lowering, the curves are very similar and in between we have the treated aggregates. So, the treated aggregates would be something like the aggregates that are coming for crushing, heated and the adhered mortar is removed. So, when we remove the adhered mortar, the behaviour becomes better as I have said several times and in this image at the bottom, bottom right you see explicit evidence of why this could be happening. So, we have recycled concrete aggregate here, where there is the natural aggregate which was originally there, then we have a part which is the old, this is the adhered mortar which is there.

So, all this will be the adhered mortar, the old cement paste, the old inter-patial transition zone and then you have the new one, this you have the new paste here. So, this becomes the new interface. So, you have the old aggregate with an interface here, then you have the new interface forming with the new mortar. So, the thicker this is, the thicker this is, it becomes worse and worse because cracks can go along this, water can penetrate and so on. So, if we can treat the aggregates to remove as much as possible of this, the adhered mortar, then it becomes much better.

Curing matters always in concrete. Again, we find that if we cure more, we cure more say 90 days with respect to 28 days, you get better strength, especially as we increase the recycled aggregate content because recycled aggregate content as I have said several times would absorb water. So, if you supply water during curing, you are not drying the concrete internally. So, similarly, we find here this is mixes with 0.55 water cement ratio, 0.45 water cement ratio. Obviously, if you have more water, the effect of dry curing is not that important or shorter curing does not become that important because internally you have supplied enough water. Now, let us talk about shrinkage and creep before we finish. And before I show you information or data on the shrinkage and creep of recycled aggregate concrete, I would like to step back, do a revision of the different types of shrinkage and discuss which type of shrinkage would be critical in the case that we are discussing. So, there are five types of shrinkage or five mechanisms that can cause shrinkage of concrete.

And when we are talking about shrinkage of concrete, it is a volumetric change, it is a decrease, it is a contraction of the concrete because of drying movement of water within the concrete. The first thing that occurs in concrete is the plastic shrinkage. Plastic shrinkage is shrinkage that occurs in the fresh state, concrete is still plastic, we are talking about a few hours, especially at very high evaporation rates. You have a hot day, low relative humidity and lot of wind, then you can have a lot of evaporation from the concrete, the concrete ends up with cracks still in the plastic state. So, there curing is very, very important.

The best way to handle it is proper curing, cut down the evaporation. So, this is also important for recycled concrete aggregates because the recycled concrete aggregates would tend to absorb water from within. So, you are drying inside and outside. So, curing is very, very important. It is very like we saw in the previous slides, curing is not only important for the properties like strength and elastic modulus, but also to prevent cracking. Otherwise, you will have a surface that is severely cracked. Then comes autogenous shrinkage, which is a combination of chemical shrinkage, that is the lowering of the volume of the hydrates as cement hydrates and self-desiccation is where you have the water being taken away from the cement paste by hydration, during hydration, which causes an internal drying. So, this is very important in high strength concrete. So, high strength concrete with very little water cement ratio, lot of binder, this matters. The more important type of shrinkage is drying shrinkage and in before that, we have thermal shrinkage or thermal contraction.

Thermal contraction also happens in concrete that are similar to where you will see a lot of autogenous shrinkage, where you have a massive element probably with high cement paste, low water content. So, the hydration is pushing up the temperature. As we all know, all cement reactions are exothermic. So, the temperature goes up as the cement hydrates. Now, when the concrete sets at this high temperature and cools down to ambient, then there is shrinkage. So, this is thermal shrinkage or thermal contraction. So, this again occurs when you have low water cement ratios, lot of cement, mass concrete, then this could be a problem. So, if you are making a raft, raft foundation with recycled concrete aggregates and a lot of cement, then this could be a problem and we will have to be concerned about. But what is more important is drying shrinkage and we will spend more time on drying shrinkage. This is what has also been characterized more than any other shrinkage mechanism in recycled concrete aggregates or concrete with recycled aggregates.

Drying shrinkage is the classical mechanism that we study about, which has been researched a lot, where you have water going out from the concrete out into the environment because of a dry environment. And here again, we should remember that there is absorbed water in the adhered mortar of the recycled concrete aggregates. So, this could also be released and there is this movement which can lead to more shrinkage. The other mechanism, the final mechanism that we will have to talk about is carbonation shrinkage. So, as concrete carbonates, the carbonated, the carbonate products or the products of carbonation decrease volume and release some water. So, this gives rise to shrinkage. So, if we have carbonatable adhered mortar and this is going to carbonate later and it is going to shrink later, then we will have some effect. But otherwise, mostly what happens is the adhered mortar is carbonated because it has been, the aggregate have been stockpiled, have been outside in the environment and they are carbonated. So, we should not have much worry about carbonation shrinkage in recycled concrete aggregates, concrete with recycled aggregates with respect to concrete with pristine aggregates or natural aggregates. The sequence of how these different shrinkage mechanisms occur is important and this is something that a concrete technologist should be aware of and always if you go to a site and there is cracking, you should always ask when it happened. If it happened very early, first few hours, it is plastic shrinkage.

If it occurs over days, initially because of the heat, then it is thermal contraction and if it is occurring during hydration weeks to months, then it is autogenous shrinkage and if it occurs over a longer period of trying, time it is drying and much later carbonation comes in. So, this is the sequence. Generally, drying shrinkage would be the most in normal concretes, in concretes that we talk about day to day concretes, drying shrinkage would be most. But as we are going towards higher binder contents, higher grades of concrete, these other three become important and carbonation shrinkage becomes less important because you are talking about more compact microstructures. So, this gives you a picture of what are the different shrinkage mechanisms that you should be aware of when we are looking at concrete technology.

Now, what happens in shrinkage, what happens during shrinkage? Let us say if we are, we are talking about drying shrinkage, water from inside which is held in the pores, see if this is, this is a large pore, this is drying, this is drying because water is going through the interconnected pores through the cement paste is diffusing out. So, these pores now have a meniscus that is forming and this pulls, this pulls on the pores, this pulls on the pores. So, the meniscus because of capillary stresses pulls on the pores and the whole material shrinks as we have more and more diffusion, more and more drying, then this material is shrinking and as it is shrinking, the microstructure deforms and stays there. So, this is how shrinkage occurs. We have basically the capillary stresses inside the pores which are pulling on the pore walls and trying to, and trying to contract the concrete.

What about creep? Creep, again, is because of sustained load, long-term load on the material, and you have two types of creep. Creep that occurs without any loss of moisture to the environment, what we call basic creep, and then drying creep is the additional creep which happens when there is also drying. So, basic creep, it is without loss of moisture to the environment; drying creep is that creep component which is due to the loss of moisture or drying. Creep can also be recovered when you remove the load; some creep is recovered. You see this in the graph below that I have taken from the book of Neville, where you see that when we apply load, you have an instantaneous strain, that is the elastic strain, and if the load is kept there for a long period of time, then we have the strain increasing.

So, this is what is creep. So, creep is happening over and above the instantaneous strain or the elastic strain, and under load now you have this red line. Suppose I suddenly remove the load, then I will get an instantaneous decrease in strain because that is the elastic part, and then slowly there will be more recovery which is the creep recovery. So, this is what will happen when you put load, keep the load on for a long period of time and suddenly remove. This is a case of cement mortar that is been under about 15 megapascal stress. So, this gives you a picture of the different aspects of creep.

How do we measure? How do we measure in the lab? So, we have to do an elaborate set of tests to determine the shrinkage and the creep characteristics of concrete. We suppose we have cylinders, usually we use cylinders or they could be prisms, prisms also, usually cylinders or prisms and these would be sealed or unsealed. Suppose we want to measure autogenous shrinkage, we would take a specimen, seal it right away as soon as it comes out to the mold and monitor the strains that would be the autogenous shrinkage. What we determine would be the autogenous shrinkage.

Specimen is sealed but still it is shrinking. It is shrinking because during hydration the cement products are shrinking, the volume decreases as cement plus water react to form hydrated cement paste and so on. Then there is some drying internally because the capillary pores are emptied out. So, that is autogenous shrinkage. Now, suppose after curing, I allow the specimen to dry, so the sides are exposed. Generally, the top and bottom are covered so that we have drying only from the side.

This value of strain over and above the autogenous is the drying shrinkage strain. So, autogenous is occurring and there is an additional drying shrinkage. So, together this is what is happening in this specimen. Now, suppose I apply load, see after curing, I apply load.

So, I take this specimen and load. So, this is sealed and under load. Then you have the instantaneous strain that is the green line. So, as soon as I apply load over and above, what is happening, what has happened to during the autogenous shrinkage, I have this elastic strain and then if I keep the load constant, then I have the additional strain which is basic creep. So, when it is sealed, I have at any particular point the autogenous shrinkage, drying shrink, autogenous shrinkage, and basic creep which is occurring and the instantaneous strain. So, I have already some autogenous shrinkage occurring because it is a sealed specimen.

I have the elastic strain which is due to the load applied and then there is basic creep. Suppose it is a specimen that is drying. So, here it is drying and under load. Then I will have all the four components occurring. I will have autogenous shrinkage, drying shrinkage, basic creep, and drying creep.

So, this is how it is measured. These strains are measured in the lab. You will have to do these four different types of conditions on similar identical specimens and determine what are the strains in order to decouple and find out what these values are. So, let us look at some of the values. So, this is data on concrete with recycled concrete aggregates.

We look at shrinkage. So, we find that as you increase the recycle aggregate ratio within concrete, the shrinkage is slightly increasing. This is for different types of concrete, but you see that there is a trend. So, there is a there is an increase of about 20 or 30 percent when you have recycled aggregate because again you have less stiff aggregates. So, it is resisting shrinkage not as well as pristine natural aggregates and you also have water that is being released. So, that is what is shown in the diagram here that if we have lower porosity say by this two-stage mixing and you have slurry actually filling up all the pores, then there is less diffusion, there is less water that is absorbed and therefore it becomes better.

But in general, we should understand that if you have a lot of adhered mortar, you are going to have slightly more shrinkage in the concrete. Again, the quality matters how well you have removed the adhered mortar, how less porous the adhered mortar and the aggregate are. If you have low quality recycled concrete aggregates, low quality meaning lot of adhered mortar, porous adhered mortar, you will find that there is more shrinkage, more shrinkage in this case than in good quality aggregates and the water cement ratio also matters. More water within the concrete, more water to evaporate, more porosity and weaker less dense concrete.

So, always we find that the water cement ratio matters. It does not matter that much if the aggregates are very of very good quality that means there is not much adhered mortar or the adhered mortar is very compact and not weak or porous. Parent grade again matters because why parent grade determines how compact the concrete was and how good of a quality the recycled concrete aggregate is. So, if we have higher strength grades, higher strength grades, we have less shrinkage. We have less shrinkage because the adhered mortar is also very compact, less water absorption and less shrinkage. So, always better quality parent concrete will give us better properties and lower deformations.

Shrinkage reducing admixtures can also come in handy to compensate for this. Shrinkage reducing admixtures are mostly say polypropylene glycol or similar products which decrease the surface tension of water. So, if we go back to our high school physics, the capillaries forces, the capillary stresses depend on the surface tension. So, if you have water with lower surface tension, there is less, there are lower capillary stresses and therefore there is less of contraction or shrinkage in the concrete. And what we find is that if you have higher grade parent concrete and a shrinkage reducing admixture, this will give you the least amount of shrinkage.

So, we can compensate to some extent how this happens. So, we have decreased by so much the shrinkage in case of having parent concrete of 80 megapascal strength and an SRA, we can decrease it. Similarly, 30 megapascal concrete that is crushed and used in new concrete, again we can decrease the shrinkage using an SRA. So, there are ways to compensate for any limitations or disadvantages that we can see when we use recycled concrete aggregates. And this is an example where if you have very high shrinkage because of poorer quality, we can think of a shrinkage reducing admixture to compensate.

Let us look at creep. So, as I said before, there are two types of creep, basic creep which is occurring without any loss of moisture to the environment. And here we find that the basic creep is very similar for recycled aggregates. So, it is not much of concern, basic creep does not increase very much when you have recycled concrete aggregates. However, drying creep does, drying creep increases. So, this is drying creep and you see that it increases as we increase the replacement ratio with recycled concrete aggregates.

Again this is because of the interface, less stiff material, more water absorption and so on. So, curing matters or the condition of drying matters. So, if it is sealed, that means we are looking at basic creep, if it is drying or in the air we are looking at drying plus basic creep and drying creep and we will see that if you have a sealed case that is basic creep, you do not see much of change. However, if you have 100 percent recycled concrete aggregate and the concrete is drying, air cured and not saturated, you will see that there is a major increase in the shrinkage. More curing helps, more curing helps reduce the creep, but this is something that we have to be aware of that drying creep would increase just like we saw that drying shrinkage increases, drying creep will also increase.

Especially if you have poorer quality recycled concrete aggregates, that means with a lot of adhered mortar, poor quality adhered mortar. So, in general we can, we find that the creep would be higher if you have lower parent concrete strength and higher replacement ratio of aggregates. So, this is in line with what we have discussed. Better parent concrete, lower amount of adhered mortar will always help us in terms of mechanical response and this is due to porosity. So, here you see how porosity is higher in concrete with more recycled aggregates and therefore, you have a higher creep.

More porosity, higher would be the creep. Basic creep does not matter that much, but drying creep it does matter. In drying creep it does matter a lot because water is removed, water is moved out into the environment, diffuses out and therefore, if you have more porosity this diffusion is facilitated and there is more of deformation. So, again more data of curing, how curing can help, better curing can help decrease the creep, but there are practical limitations we cannot cure for many months because we have to move on, have the structure constructed and so on, but better curing always will be important. Maybe we have to look at it the other way. Poor curing will have bigger effect, bigger negative effect on concrete with recycled concrete aggregates rather than with pristine aggregates.

So, this is something that we have to be concerned about. How about compensating creep? One way to do it is with fly ash. Substituting cement with fly ash can help and these are cases where we have different fly ash percentages, replacing cement at different water cement ratios and we find that having fly ash replacement at replacement levels of 25 to 35 percent, we can have a 12 to 20 percent reduction in creep simply because the cement paste is mainly creeping, is mainly deforming and if you have fly ash which is slowing down the reaction and you can decrease the amount of cement paste because of the fly ash, you have less amount of creep that is happening. So, this is also some way that we can compensate for the higher creep that we might see in recycled aggregate concrete. So, to conclude, what I have been emphasizing is that the properties of new concrete made with recycled concrete aggregates depends on the amount of adhered mortar. If we have been able to remove the adhered mortar better or if we have been able to improve the quality by decreasing the porosity and the strength better, the degree of saturation matters.

It is always good to have the adhered mortar with some water, with some moisture. It should not be bone dry, should not be oven dried, it should not be very dry because that reduces the strength in the modulus and can also increase shrinkage and so on. So, it is better to have not necessarily saturated but some moisture in the aggregates. It could be done through two-stage mixing, it could be done while stockpiling, but better to avoid dry recycled concrete aggregates in new concrete. So, if we can remove the adhered mortar, make it more compact with coating or some treatment, then we will have much better properties in the new concrete. So, with that I conclude. Thank you very much.