Advanced Topics in Science and Technology of Concrete
Dr. Manu Santhanam
Department of Civil Engineering
IIT Madras
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Recycled Concrete Aggregates: Properties and Performance - Part 3

As I said earlier, workability is too complicated to measure with just one property. So very often you have people going for a measure of rheology which gives a lot more understanding about the flow behaviour of concrete and other construction materials. So rheology, especially when it comes to flowing concretes like SCC or sometimes even very stiff or harsh concretes, can become quite useful to study and in some instances you can actually study these with simple test methods without the need for very complicated rheometer type approaches. So instead of workability which gives only a one parameter like a slump or a compaction factor, rheological studies will tend to give you two parameters. One is called shear yield stress which talks about the initiation of flow, shear yield stress and the other is viscosity which relates to the resistance to flow. Once the material starts flowing what is the resistance to the flow ability and that is determined by the viscosity of the material.

So shear yield stress and viscosity typically are achieved using rheological measurements. So let us see what these physically also mean and before that let us look at some models which define flow behaviour of construction materials and other polymeric gels and all kinds of flowable materials. You know that water follows a Newtonian behaviour as soon as the shear water it starts flowing and there is a constant viscosity of flow. So typical rheology plots are drawn between shear stress and shear strain rate and a Newtonian behaviour starts at the origin and is a straight line with the slope which is equal to the viscosity of the material.

Water, oil all of these things are viscous with a Newtonian behaviour. Bingham fluid is a material that has to overcome some initial shear stress which is represented as tau naught or shear yield stress. Once you overcome that initial shear yield stress you can then start the particles to flow and once it flows in a Bingham model the flow happens with a constant viscosity. But this need not always happen with systems which are suspended solids in a liquid medium like concrete. You can also get some nonlinearity and for such instances Herschel bulkly fluid model is often used for concrete.

In such cases you do not have a constant viscosity but the viscosity then changes as a function of the shear rate. In concrete mostly what we see is a shear thinning behaviour where as the shear rate increases the viscosity tends to drop. On the other hand for certain gums and glues you may end up having a shear thickening behaviour where when you increase the shear rate viscosity tends to go up. But in both these cases the curve may or may not start from the origin indicating that the suspensions may have some inner shear yield stress that needs to be overcome for flow to initiate. Now in simple terms let us take a look at what this means physically for concrete.

Concrete is the composite material where aggregates that is coarse and fine aggregates are suspended in the cement paste. As we said earlier cement paste flows the aggregates basically will be carried by the cement paste. So, the more the aggregate the more difficult it will be for the cement paste to carry the materials that is why when you have more paste the workability is more. So, shear yield stress relates to the minimum stress needed for flow to initiate and it is a function of the intergranular friction between the aggregate particles. So, if there are a lot of aggregates, aggregates are going to be close together and they will be brushing past each other to really make them move past each other you need to apply some level of shear only then they will completely move past each other then the system will start flowing.

So, this is the physical meaning for instance when you put concrete into a formwork it just remains there but when you put the vibrator inside the vibration basically causes the aggregate particles to start moving makes it mobile and that is what gets the concrete to start getting compacted. So, the obviously shear yield stress will depend on the volumetric fraction of the aggregate particles the liquid phase that is cement paste phase it defines the average distance between the particles. So, it may not directly affect the shear yield stress but when you change the characteristic of the paste let us say when I add a super plasticizer then the paste becomes so mobile that it is now able to push the aggregates much more easily. So, in such cases when super plasticizer is used yield stress gets lower yield stress becomes lower but more often the yield stress will become lower and lower when you keep on increasing the paste content and reduce the aggregate content. On the other hand, the plastic viscosity basically is defining the resistance of the concrete to flow so in general if the fluid remains in the laminar regime while flowing between two solid particles its contribution to shear resistance will be proportional to the overall strain gradient.

So, that is why we get this sort of a relationship here that viscosity is more or less constant for a laminar flow. Now, the plastic viscosity can be defined of the concrete can be defined as the plastic viscosity of paste mu naught multiplied by some sort of a function of the volume fraction of the aggregate particles. The more the aggregate again the more difficult for the paste to carry this aggregate along with it. So, here if the paste is less viscous it still has to carry a lot of aggregate with it so the overall concrete viscosity will then suffer if you have too much aggregate in the system. So, for a flowable concrete like a self-compacting concrete both yield stress and plastic viscosity will be lower but plastic viscosity cannot be lowered beyond a certain point because that will lead to segregation.

So, rheological control can help design workability of the concrete in a much more efficient manner and this can be done with simple experiments of course that is not the target of our understanding here. What we would like to see now is what does recycled aggregate do in the system? When we replace conventional aggregate with recycled aggregate does it affect our rheological parameters or not? And to this effect there have been studies proposed or done by several researchers which shows that the increase in the content of recycled aggregate for instance here on the x-axis what is plotted is the amount of recycled concrete aggregate as a function of the total aggregate as it increases you have an increase in your yield stress and you also have an increase in your plastic viscosity. Now, why is this happening? When you compare the texture of the recycled concrete aggregate as opposed to a natural aggregate you may you can imagine that there will be a lot more roughness on the surface because of the adhered mortar the shape will not be as well defined because of which the intergranular friction is going to go up. Now, this adhered mortar which is porous will also tend to absorb some of the water and cement paste from the surrounding paste. Now, as a result, the viscosity of the paste also will go up and that will lead to a higher plastic viscosity also in the system.

So when normal aggregate is replaced by recycled concrete aggregate you can expect a change in the rheological behavior of the system in terms of both an increase in the yield stress and an increase in the viscosity. Now, depending on the water to cement ratio this behavior may or may not be very significant. For instance, when you go for a high water cement ratio you can see that the increase in the yield stress and the increase in the plastic viscosity is not very significant. In fact, in terms of increasing water cement ratio you see that the increase in plastic viscosity is still not very significant when you go for a higher amount of coarse aggregate replacement by recycled concrete aggregate. But when you have

, when you consider the yield stress there is distinctly an effect of increasing the, at lower water cement ratio there is distinctly an effect of increasing the yield stress when the extent of replacement of normal aggregate by recycled concrete aggregate goes up.

So, if your concrete is already too wet, a lot of water is present then your effect on rheology is not as significant as when you start concrete designing with lower water binder ratios. So, again you need to consider the grade of the concrete for which you are designing with recycled concrete aggregate. The effect on rheology may not be consistent at high and low water cement ratios. Now, there have been studies that have defined segregation levels with different types of concrete. There was one study by Koo and Poon where they looked at replacement of conventional aggregate by recycled concrete aggregate both in the coarse and fine aggregate regimes.

In such cases what they wanted to determine was, how much was the potential for segregation of the concrete mixes when they replace normal aggregate with recycled aggregate. Now, the results which are presented on the slide are quite mixed. You can see that in some instances you do not really see a major change in the segregation ratio. Now, just to give you an understanding of what this is, so in self-compacting concrete because of the extreme flowability there is a tendency for the aggregates to settle or segregate as compared to the paste. If you do not design your concrete well that is likely to happen because of the extremely flowable nature of the material.

So, in segregation test what is typically done is the fresh concrete is poured into a bucket. You then wait for 15 minutes then separate the top one-third of the bucket and bottom part of the bucket and determine the extent of aggregate that is present in the two locations. So, if there is a lot of segregation the amount of aggregate that is actually present in the top one-half of the bucket is not going to be equivalent to the amount of aggregate that is there in the actual mixture. So, you can then define what is called as the segregation ratio. So, here what is seen is segregation ratios depending upon the extent of fine aggregate replacement by recycled fine aggregate did not really vary that much.

But in one more case at a higher water cement ratio they found that with an increase in the extent of recycled fine aggregate the segregation ratio increased. But it is still going between only 8.9 and 11.1 it is not really that much. So, results seem to indicate that the segregation ratio does not really get altered significantly when concrete aggregates or conventional aggregates are replaced by recycled concrete aggregates.

Now, when it comes to bleeding we know that bleeding happens when there is a lot of free water that tends to rise up to the surface. What will happen when recycled concrete aggregate is there? If this recycled concrete aggregate has adhered mortar it will tend to also absorb the bleed water. So, as a result what you can expect is when normal aggregate is replaced by recycled concrete aggregate you should see some level of reduction in bleeding. Indeed that is what is being shown by the study by Yanger Tal where the amount of bleeding was measured with respect to the elapsed time. For the control concrete you can see the extent of bleeding is significant.

As you use different types or different grades of recycled concrete aggregate the extent of bleeding seems to come down significantly. So, what this goes to show is the adhered mortar is beneficial with respect to reduction in bleeding. Again this is also showing the total amount of bleeding with respect to the relative water absorption in the aggregate. As the water absorption in the aggregate increases the relative amount of bleeding gets reduced. This again says that the porosity caused by the adhered mortar in the recycled concrete aggregate leads to higher water absorption and this water is also absorbing the bleed water thus preventing additional water from rising to the surface.

Now this can have positive and negative connotations. For instance when you use concrete with recycled concrete aggregate you need to be aware that since bleed water is now not reaching to the surface you have to protect the surface early in the case of a flowable concrete for instance self-appacting concrete. In such cases since the setting is slow you have the tendency for plastic shrinkage cracking. So, if the bleeding content is reduced as compared to normal aggregate then you need to start thinking about covering the top surface to prevent evaporation that causes plastic shrinkage cracking. So, a lot of complications can arise here and there positive and negative because of which you need to be wary of the fact that your bleeding characteristics are not similar when concrete is prepared with recycled concrete aggregate.

Again air content you have more fissures and cracks and pores present in the adhered mortar and because of which you can see a minor increase in the air content of the concrete with respect to conventional aggregate. And you can see from this data that the effect is not really significant. You can see some increase but it is not really that significant as long as you are designing air-entrained concrete with proper distribution of air bubbles caused by the presence of the air-entraining admixture you do not really need to worry too much about the fact that you are replacing conventional aggregate with recycled concrete aggregate. It is not going to totally throw away your result of the air content too much. Now in some instances for instance this was a very interesting paper by Huda and Alam where they have looked at the generation of the recycled aggregate.

What do you mean by generation? So, they have from the landfill they collect aggregates which is the first generation recycled aggregate and they prepare concrete with it. They then crush this concrete and prepare the second generation of recycled aggregate and prepare one more concrete with it. Then they crush that concrete and one more prepare one more recycled aggregate with it. So, this is like a three generations of recycled concrete aggregate and what they wanted to see is how is the property of the concrete changing when you keep changing this generation of the recycled aggregate. So, here what they saw is there was a minor increase in the air content as compared to the control when you go for additional cycles of recycling you are tending to increase the air content and reduce the slump.

Your slump is reducing somewhat because again there will be a change in the absorption characteristics of the aggregate and you are probably going to be introducing more air. So, there will be an increase in the adiabatic content as you go for further and further generations of your recycled concrete aggregate. And because of the continuous crushing and reforming you are probably increasing the roughness of the RCA also which is going to lead to this increase in air content and decrease in slump. But of course this is only a study which is done out of interest you do not probably know when you collect aggregates from a dump yard. You do not know how many times they have been recycled you have no idea.

But you need to obviously study if the aggregate characteristics are good enough to be used in concrete and then design your concrete accordingly. Now, when you replace conventional aggregate by recycled concrete aggregate it is expected that the density of the concrete will drop. Why is this? Because adiabatic water is present there will be water absorption there will be higher porosity because of the water absorption and so on. Of course, water absorption is not the critical factor for density it is more the porosity introduced by the adiabatic water that will lead to the lowering of the overall density. So, you need to be aware of the fact that your density will change when you replace conventional aggregate with recycled concrete aggregate.

When you do better processing of your recycle aggregate obviously the differences in density will not be that significant. Now, let me just show you a case study of the use of recycled concrete aggregate in an application that is at the other end of the spectrum. I talked about flowable concretes, I talked about high workability. But let us now talk about a very stiff concrete such as roller compacted concrete. Roller compacted concrete is where the concrete is dumped and then compacted with rollers.

Primarily it is used for roller compacted concrete pavements. Roller compacted concrete pavements basically are zero slump, that means workability is zero or very harsh mixes, water content is low. Typically, even the cement content is quite low because you do not really need so much cement to produce the workability. You just need to control water to cement ratio to get the strength. But the entire concrete is getting compacted to a very high level of densification.

There is typically no reinforcing steel in such concrete because you use it for applications like pavements and dams. And you can actually make it strong enough because of the kind of compaction process that you give. And because of using lower cement, you are obviously going to be reducing the cost significantly. And because there is less cement there is also going to be less of heat emanation from the concrete. So, there is a lot of advantage of roller compacted concrete pavements as opposed to typical concrete used for pavement quality construction.

So, what essentially can be done in the case of roller compacted concrete pavements because you do not need much slump at all, you can then think about utilizing recycled concrete aggregate in such purposes. But the issue is now you need to figure out whether the roller compaction, that means the application of pressure by the roller, is going to be as effective in the concrete with recycled aggregate as it is with conventional aggregate. So, that is the primary challenge when you try to design such special types of concrete. So, now is your recycled concrete aggregate affecting compaction? That is the challenge in roller compacted concrete pavements. We earlier talked about workability but compaction, as you all know, is also a feature which defines workability.

So, let us take a look at what happens when recycled aggregate is used in roller compacted concrete and whether we can achieve the same level of compaction or not. So, now what we can try to do is design the roller compacted concrete pavement with an optimal choice of your gradation of your aggregate. We typically work with coarse aggregate of two sizes: 20 millimetres, 12 millimetres, and then one fine aggregate which is less than 4.75 mm. So, now you have three different blends of material, three different materials that need to be blended or proportioned in a way that can give you the maximum compaction and that generally can be achieved by maximizing what is known as the packing density of the aggregate.

Now, what you are simply doing is let us say you have a container, you are filling the container with coarse particles first and then you know that there are voids and gaps between these coarse particles which you have to identify properly in terms of understanding what is the efficient, what is the voids that will remain after efficient packing of this size particle and that those voids you start filling up with smaller particles and then you recognize the voids in that mixture and fill it up with even smaller particles and so on. So, essentially what you are trying to do is adjusting your sizes in such a way that the voids left behind by one size are nicely filled up by particles of the smaller size and so on ad infinitum. For instance, when you have a 19 mm aggregate, a 9.5 or 10 mm aggregate and a 4.75 mm fine aggregate, then in what proportion should you blend it so that you get optimal packing.

What is optimal packing? Optimal packing is when you actually have, when you do, you get the maximum density which is equal to the mass of the solids divided by the volume of the container, the mass of the solids in the system divided by the volume of the container. So, that is the packing density of the system. Of course, when you do the same experiment with roller compacted concrete, you have to also simulate the fact that you are going to be using a roller to do the compaction. So, in such cases, you cannot just measure the density by simply mixing and putting into the container, you also have to simulate the compaction action somehow. But what we are trying to do is maximizing the proportion of aggregate in the system.

So, maximizing the density of packing of the particulate inclusions in the system. And what you see here through this ternary diagram is that you are now able to achieve for certain compositions, you look at this 0.81 as the packing density, that is a contour of packing densities that can be obtained by combining aggregates and proportions which are leading to this packing density of 0.81. So, what you need to do is understand the particle gradation of your recycled concrete aggregate, design the proportion appropriately so that you get the maximum packing density.

So, what is done in this study is that for normal aggregate, packing density obtained was 0.81 for an optimal choice of fine aggregate, coarse aggregate for instance, here it was 19.5 millimeter aggregate was about 35 percent, 9.5 aggregate was 15 percent and the fine aggregate was about 50 percent. At this level, they got an optimal packing density of 0.81. That means if you take a volume of container, 81 percent of the volume is filled up by solids of the aggregate or you get 19 percent voids in the system. So, you can think about maximizing packing density as also the same function as minimizing the void fraction. So, now when you have recycled concrete aggregate of different proportions, for instance here, only recycle coarse aggregate was used of two different sizes of 19 mm and 9.5 mm, you can see that for 40 percent 19 mm aggregate and 15 percent recycle concrete aggregate of 9.5 mm and natural fine aggregate at 45 percent, they are able to get now the same or even better packing density as compared to natural aggregate.

Similarly, for proportions of normal concrete aggregate, normal coarse aggregate at 30 percent and about 25 percent in the case of coarse aggregate and about 50 percent of the recycled fine aggregate, you are now able to get the same packing density as the normal aggregate. Similarly, both coarse and fine aggregate in the last case were from recycled sources. So, here again at 35 percent of 19.5 mm, 10 percent of 9.5 mm and 60 percent or 55 percent of fine aggregate, you are able to now get the same packing density of 0.81. What does this tell you? This tells you that if I design my roller compacted concrete pavements with mixtures of coarse and fine aggregates that are from recycled sources, depending on an optimal choice of the blending proportions, I can then find a way to actually compact these to the same density as I would compact a normal aggregate mixture. So, here we are taking advantage of the fact that we do not need workability, so we can pack in as much of aggregate as possible, but the degree of compaction is absolutely important for me to achieve because that determines my overall performance of the roller compacted concrete pavement. So, that degree of compaction through appropriate particle packing approaches, I can show that now I can use recycled concrete aggregate also to the same extent as natural aggregate by optimally designing the proportions. So, it is very important for us to ascertain all the characteristics that could be altered because of the presence of recycled concrete aggregate as opposed to conventional aggregate and design appropriately.

Now, you can also optimize moisture states of the RCA. We know that because of the adhered mortar content

, the recycled concrete aggregate may have a lot of surface moisture and that needs to be compensated by achieving a saturated surface dry state. But when you design concrete with it with chemical admixtures like super plasticizers, which tend to then absorb on the surface of cement particles and also aggregate particles and lead to a repulsion effect, does that help us in achieving better compaction in roller compacted concrete? We saw that packing densities could be achieved, but when you actually do the concrete mix design with the cement and chemical admixtures and water, are we able to get the same level of compaction or not? So, generally the use of super plasticizers will improve the lubrication effect not just in cement or cement paste, but also in concrete because super plasticizers also tend to get themselves coated around aggregate particles and provide some level of steric repulsion. So, in this study, what was done was the Vb density, Vb basically is the apparatus which is used for determining the workability of very fresh concretes which are harsh, fresh concretes which are very harsh. So, in such cases, what was seen was for the control mix with natural aggregate, the Vb density was nearly about 2500 kilograms per cubic meter. When the moisture state of the aggregate was dry and the same concrete was prepared, the Vb densities were then lowered.

But when SSD was used, Vb densities could be increased, but not to the level of the control concrete with normal aggregates or natural aggregates. When super plasticizers were used, the degree of compaction could be achieved significantly so that the densities achieved were now closer to that achieved with normal aggregate. And this is very good because now it tells me that I can now design roller compacted concrete pavements with optimal control of my super plasticizer dosage to produce compaction levels which are equivalent to my normal aggregate concrete. So, again, this is showing you the density ratio in terms of the concrete density with the recycled concrete aggregate and concrete density with the normal aggregate. So, of course, this one indicates that it is equal to that of the normal aggregate.

So, as I change from dry to SSD to dry plus super plasticizer and SSD plus super plasticizer, I am going closer and closer towards the density level which I can achieve with normal aggregate or natural aggregate. So, what it goes to show is compensation for the moisture absorption by making the aggregate saturated surface dry and use of super plasticizer together are now able to achieve recycled concrete characteristics that are equivalent to normal concrete. So, please remember when you use recycled concrete as an aggregate to avoid any ill effects on the workability or compaction, make sure that you are saturating the aggregate well enough so that you get complete saturated surface dry state and you are using a super plasticizer to get the required degree of compaction. So, again, in this study, interestingly, what was also seen, now, of course, you can also see that your effect on the cement also is going to be significant because as you can readily imagine when the polymer chains of the super plasticizer adsorb on the cement grain, they lead to either electrostatic repulsion or a steric repulsion depending upon the type of chemical that we add, the same characteristics hold for their coating on the adiabat mortar surfaces of recycled concrete aggregate also. So, what happens here is this aspect of use of super plasticizer not only affects the density and gets it to a level which is equal to conventional aggregate, it also tends to help you, sorry, let me just rub this off so you can see the next graph, it also tends to help you in actually achieving a good property from a concrete in terms of the tensile strength.

So, here indirect tensile strength or split tensile strength by the Brazilian technique was determined for concrete with normal aggregate and concrete with recycled concrete aggregate, roller compacted concrete. So, you can see that as you are changing the moisture state from dry to SSD to dry with super plasticizer to SSD with super plasticizer, you can see that you are actually leading to an increase, significant increase in your indirect tensile strength and that shows that you can then really optimally design roller compacted concrete pavements with the help of recycled concrete aggregates when you take care of this SSD condition and also use a super plasticizer in your system. So, this effectively leads you to the fact that you can effectively design concrete mixtures with recycled concrete aggregate keeping in mind majorly the fact that the adhered mortar leads to an increase in water absorption, compensating for that becomes the primary target. So, I think we will finish up with that, I have reiterated this aspect significantly over the lectures that, over the lecture today that the presence of the adhered mortar is what makes for the difference in the workability levels of concrete with normal aggregate and concrete with recycled concrete aggregate. Now, the levels of change may be quite different when you are using recycled coarse aggregate or recycled fine aggregate, but in most cases the effect or the cause of that effect is the same, the cause is primarily the adhered mortar and the cement paste that is along with the adhered mortar that brings about a change in the behavior of concrete with recycled aggregates.

So, all that has to be understood by a proper mix design process and designed for before you go into using the recycled concrete aggregate for a particular project. But there is nothing to fear in terms of not being able to design concrete with recycled aggregate, there is sufficient knowledge at our disposal, there is sufficient understanding of the subject and all you need to do is take in that understanding by designing your mixes appropriately. Thank you very much.