Advanced Topics in Science and Technology of Concrete
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Recycled Concrete Aggregates: Properties and Performance - Part 2

Hello everyone and welcome to this next lecture in the series on our lectures on Recycle Aggregates. As stated before, this is arising out of the SPARC collaborative project between IIT Madras, University of Pitt-Petersdorf in Johannesburg, South Africa, and University of Cape Town in South Africa. So, together we have set out to actually look at the aspect of how recycle aggregates are important for new construction, what are the kind of processing methods that are required to get these aggregates to a condition where they can be gainfully utilized in new construction, and finally of course what are the properties of concrete that has been prepared with using such recycled materials. In that segment today, let us take a look at the performance with respect to the fresh concrete properties. I am Manu Santhanam, I am a professor in the Department of Soil Engineering at IIT Madras. Now of course we all know that when we talk about fresh concrete, the first aspect that comes to mind is workability.

So let us just for the purpose of defining it, just define it and then get on with the talk. So workability is the ease with which concrete can be transported, mixed, placed, compacted, and finished. So it is actually a very complicated parameter to measure all at once. So if you look at the official definitions as per ASTM C125, it is defining workability as the property determining the effort required to manipulate a freshly mixed quantity of concrete with minimum loss of homogeneity.

If you look at the ACI definition, American Concrete Institute definition, it states that workability is the property of freshly mixed concrete or mortar that determines the ease with which it can be mixed, placed, consolidated, finished to a homogeneous condition. Now how do we actually define characteristics in terms of a parameter that will actually contain all of these things at once? It is very difficult to do so because of which workability is typically measured as a composite property which is a mixture of the consistency which indicates the mobility or the ease of flow of the concrete and the cohesiveness, stability or resistance to leading and segregation. So again we often when we go to sites, we see people doing the slump test to measure workability. Now slump is only one of the ways in which workability can be determined. There are several other methods that define workability.

However none of these can actually fully capture all of these aspects of mixing, placing, compaction, finishing, and all the properties that define the early age behavior of concrete cannot be captured by the single measure of consistency or cohesiveness. Now there may be other aspects to also consider. For instance when you are going to be pumping concrete over a long distance, there is also the aspect of concrete being pushed through pipes under pressure. So we call that aspect as pumpability. Compactability or self-compatibility comes from the perspective of the concrete being able to consolidate under its own self-weight without the need for additional vibration.

You can also start measuring a parameter like finishability but that is not very easy to define in terms of an objective parameter. So it becomes a very subjective aspect. So in most cases what you have seen in practice is that workability is looked at in terms of the consistency and in some instances cohesiveness. But more often than not we are actually testing just the consistency which relates to the mobility of the concrete or the ease of flow. In most cases, in most sites around the world the slump test is practiced. It is very easy to do and it gives you a quick answer and it is a good method to control the quality of the concrete that is arriving at the job site. So there are several factors that will affect the workability. First and foremost being the water content in the concrete. Because the more water there is the more easy for the concrete to flow. Only issue is can the concrete flow or get dispersed without segregation.

So that is where mix design comes into play. So it is not just the water content but other characteristics also that will affect workability. Mainly gradation of aggregate. Gradation of aggregate is a primary factor that affects workability because if you have a very good gradation the aggregates are packing quite nicely and because of the good packing you then need only a small amount of cement paste to fill up the voids and some additional cement paste to provide some degree of flowability to the concrete. Aggregate morphology.

You must have seen that aggregates natural aggregates come from various sources. You have riverbed gravels and then you have of course the quarried aggregate which is crushed to small sizes. When you crush aggregates obviously you make it angular and the texture also may become quite rough as opposed to the nicely weathered smooth texture of aggregates that you pick from riverbeds. So all of those aspects will affect the aggregate morphology and aggregate morphology will go on to affect the workability because rounded aggregates obviously give you better workability as opposed to angular and rough aggregates. The cement content also will affect workability but of course taken in combination with the water content.

If you have too much cement in your concrete your paste becomes a lot more cohesive because lot of fine powder is available in your system. It is not just cement but cementitious materials including the fine-grained mineral admixtures that are added alongside the cement. The concrete temperature and the ambient temperature can also have an effect on the workability. Why? Because at higher temperatures the workability tends to drop very fast and also at higher temperatures sometimes the initial flowability that you get in the presence of superplasticizers may be high. But it can rapidly drop because at high temperatures the cement will start reacting faster, efficiency of the admixture will go down quite rapidly.

The aggregate to cement ratio again I will talk about how this affects workability a little bit later on when we have some consideration of rheology also in our minds. The paste volume, how much is the extent of cement paste in the system because we know that aggregates are basically the particulate inclusions inside the flowable paste that we have which is the mixture of cement and water and admixtures of course. So that essentially is the flowable component and it carries along with it the aggregates. So the more the paste the better will be the workability for obvious reasons. And of course paste can be optimized by the use of chemical admixtures.

Presence of chemical admixtures like water reducers or superplasticizers can increase workability. Now in addition to these there are some of the factors that you would have to consider when you want to understand the workability of concrete with recycled aggregate. Now the extent of recycled aggregate replacement will play a large role because you can either go for a complete replacement of natural aggregate or you can go for a partial replacement. If you look at IS 383 again you know that today permissible limits of coarse and fine recycled aggregate as a function of the total aggregate content is only limited with respect to the kind of application, plain concrete or reinforced concrete and so on. In such cases you have to still assess the workability afresh when you have different replacement levels of your aggregate with the recycled concrete aggregate.

The moisture state of the aggregate plays a large role in determining the initial workability as well as the retention because we know that in some instances when the aggregate is completely saturated it will not tend to absorb any more water from the mix. So that means all of the water that you added in the mix is now able to provide flowability. But if you have not done a compensation for that moisture level of the aggregate then you will have a lot of problems in controlling the workability. So this in my opinion is the primary factor because as we discussed earlier there is adhered mortar which sticks to the surface of the recycled concrete aggregates. The adhered mortar is definitely going to be a lot more porous as compared to your natural aggregate and because of this adhered mortar there is a tendency for the recycled aggregate to absorb lot of moisture.

We will see some examples later on and you will see that the absorption of moisture with the recycled aggregates is the primary concern with respect to either achieving workability or not achieving workability. We will talk about that in more detail later. The effective water cement ratio that means the water that is remaining in the system after accounting for this absorption by the aggregate. And the mixing approach in some instances as I will show you through an example a two-stage mixing approach in which part of the water is added in the beginning and part of the water with the cement later and that approach seems to work better when you are actually doing concreting with recycled concrete aggregates. So we will talk about that also.

Now again just to revisit this you have seen this in several other lectures before the structure of the recycled concrete aggregate is quite different from that of a natural aggregate and primarily because of the adhered mortar which is stuck to the surface of the concrete. If you have done a proper processing of your aggregate it is quite likely that most of this adhered mortar has been removed. But if you really want to be efficient with respect to your processing if you do not want to put too much energy into the system in that case you will have to live with the fact that some of this aggregate has adhered mortar. So just to again come back to the structure as this was discussed before in one of the previous lectures. So you have of course the original aggregate, original natural coarse aggregate that is inside then you have the ITZ.

The ITZ between the adhered mortar and the aggregate from the original concrete. You also then have the ITZ between the new mortar and the recycled aggregate itself. And then you have the, this is the adhered mortar of course, old mortar is the adhered mortar which is stuck to the surface of the aggregate particle. And then you have these cracks and fissures that have come in into the structure of the recycled concrete aggregate because of processing. Because we are crushing it, we are heating it and so on and so forth.

All the processing will lead to some sort of damage to the aggregate. So those are cracks that have been introduced due to processing. And definitely there are pores and voids which are there in the older adhered mortar and pores and voids which are also there in the new concrete. So your system now becomes a lot more complicated as was discussed in one of the previous lectures. Now you have two ITZs, two Interfacial Transition Zones, one is the old one and one is the new one.

So it has been reported that the presence of adhered mortar and cement paste in your recycled concrete aggregate can increase the water demand by 3 to 12 percent. Your normal aggregate which is either granitic or basaltic coarse aggregate I am talking about will typically have a moisture absorption of less than 1 percent. But when you actually start using recycled concrete aggregate with the same parent raw material you may end up having 3 to 12 percent additional moisture absorption. So that is going to be the critical component when designing your mixture for achieving workability and strength. Now the rough texture that is coming out of the crushing process, the angular and irregular morphology once again which is created because of the crushing process and because of all these aspects you will have a higher water demand to satisfy the workability of such systems.

So because of this what you will end up having is that you need to design your mix considering this absorption by the aggregate in mind. Most of the issues that we talk about with respect to workability of concrete with recycled concrete aggregate arise from this singular fact that there is increased water absorption at the time of usage of recycled concrete aggregate. So just to show you the effect of the moisture states of RCA this is one of the studies conducted by a few researchers. So here what it says is depending on the moisture state the slump loss with respect to time can change. For instance if you look at this blue curve which indicates the aggregates were in saturated surface dry condition.

SSD means saturated surface dry. What does that mean? That means that all the pores all the accessible pores in the aggregate are saturated with moisture but there is no extra moisture clinging onto the surface. So that means SSD saturated surface dry. But you can have a state of the aggregate which is less than SSD that means not all the pores are saturated only some pores have water in it. So that is called a dry state or normal dry state.

Then you have the oven dry state in which absolutely there is no moisture inside at all. So when you use aggregate in these different forms in your concrete the loss and slump can vary quite a bit. For instance when you have the SSD state it is more gradual loss and slump that means with time the loss and slump is quite gradual. But when it comes to oven dry or air dry aggregate your loss and slump is lot more rapid it happens much faster. So again in most cases concrete mixtures are not only designed for an initial workability but also for the retention of this workability over a given period of time.

Let us say 1 hour or 2 hours some instances even 3 hours or more. In such cases you need to be aware of what is going to happen to the slump as I as the time elapses how much is the slump going to drop from the time that we mix the concrete to the time that we are going to be delivering concrete. So in such cases moisture state of the aggregate is playing a major role. Now again this is with respect to replacement level of the aggregate. So let us say we are replacing 20 percent or 50 percent or 100 percent.

So here what it tends to show you is that when you have an SSD state aggregate that means if all the aggregates are in their saturated surface dry state the loss and slump with time is more or less similar irrespective of the degree of replacement of coarse aggregate by recycled concrete aggregate. On the other hand if you have your aggregates which are oven dry or partially dry you may have differences in the rates of slump loss generally the slump loss with the 100 percent recycled aggregate will be much more as compared to the others which are a lot more gradual. So what I am trying to say is while mixing while designing a mix you need to ensure that you understand what the potential water absorption by this coarse aggregate is going to be and make sure that your mix is accommodating that particular level of water that needs to be added to the mix to compensate for the water absorption to make the aggregate saturated surface dry. Now as I said earlier there are instances where we can actually design our batching in such a way that we compensate for the water absorption early on and then obtain our higher flow or higher slump as desired. So if you go for a normal mixing process which is basically all the dry ingredients are mixed first then the water and superplasticizers are added next mix for a few minutes and then you measure the slump that is what it works out to.

If you have oven dry aggregate or partially saturated aggregate or saturated surface dry aggregate your slumps are typically low in concrete with recycled aggregate. But if you adopt this two-stage mixing approach for instance in this study by Brandeeter they showed that the two-stage mixing approach where the coarse aggregate and cementitious materials were first mixed first then half of the water was added and a further mixing for one minute was done. What does this do? When you add half of the water the water that is required to compensate for the absorption by the coarse aggregate first goes into the pores of the coarse aggregate. That means that it is completely saturating the coarse aggregate. Then you add the remaining water along with the fine aggregate chemical admixture and further mix for two minutes to prepare a homogeneous blend what you end up doing is getting a much higher slump when you have either oven dry or saturated surface dry or even partially saturated aggregate.

So why is that happening? Because you have now satisfied the demand of the aggregate to have its pores filled up with water. So because of the adhered mortar, this aggregate will act like a sponge and start absorbing moisture from the mixed water. So again, make sure that when you do the mix design, compensate for this additional water content. If you have not compensated, you need to then determine the effective water cement ratio of your concrete.

Now, sometimes we collect recycled concrete aggregate from concretes that have had different strengths. So what will happen? Let us say if I have a concrete of strength 50 megapascal, I break it into aggregate particles. I have another concrete of 100 megapascal, and I break that into aggregate particles. Now I know that from my understanding of durability and durability parameters of concrete, that the concrete which has higher strength will tend to absorb less moisture because the pores will be finer, there will be lesser porosity and so on and so forth.

Because of this when you actually prepare recycled concrete aggregate from different grades of concrete, there will be a difference in water absorption levels. For instance, here in this study by Koo and Poon, they had done and coarse aggregates recycled coarse aggregates prepared from 30 MPa concrete, 45, 60, 80, and 100 MPa concrete. These are the parent concrete strengths in megapascals at 28 days. So you can see that the strengths are varying from 35 to 100 MPa.

So you see here that the water absorption of the aggregate that you produce out of this 10 mm and 20 mm aggregate that you produce out of this is significantly changing. For instance, from this 8.6, it goes down to 5.1. From 3.6, it is going down to 2. That means the higher the grade of the parent concrete, the lower is the water absorption of the coarse aggregates that you produce from it. So this tells you that when you are having aggregates from different sources, coarse aggregates from different sources if you have not done a source characterization if you do not know what kind of concrete it is coming from you need to be very careful about adjusting your mixed water.

Imagine if you make concrete with this aggregate, you have 8.6 percent water absorption for your 10 mm. But if your aggregate source now changes to a higher strength aggregate, higher strength parent concrete then your water absorption is dropping. Now if you continue to add so much extra water to your system that means you are then adding let us say about 3.5 percent extra water when your aggregate source is changing to the higher strength concrete. That means you have excess water in your concrete and your strengths will come out to be lower. So compensation for moisture absorption of the aggregate, understanding the characteristics of the parent concrete is very important to really justify the design of concrete for new workability.

Now the issue is in many instances when you get recycled concrete aggregate you do not know where it is coming from. In many instances it comes from a let us say a concrete recycling plant where many different grades of concrete may get crushed together. So you do not really effectively know this. That is why it is very important to sample the aggregate well enough to understand the net water absorption that you get because it will be a mixture of different grades of concrete. You cannot obviously get the same grade of concrete every time.

I mean unless you know that you are demolishing a structure which had a perfectly uniform grade most cases you will actually get mixed grades of concrete. So when you do an assessment or when you do the mix design with mixed grades of recycled concrete aggregate in such cases make sure that you sample well enough from multiple locations in the stockpile to get a true estimate of the water absorption characteristics.

Now in some instances to avoid this issue that comes from the adhered mortar people also attempt like you may have seen in the lecture on processing people also attempt the slurry impregnation technique. So what they intend to do is when you have the adhered mortar along with its pores and fissures inside we attempt a methodology called slurry impregnation in which we put a fine cementitious slurry along with some mineral additives or maybe sometimes non-cementitious slurry also to get absorbed into the porosity and give a solid structure to the pores so that the aggregate characteristic increases.

So the RCA which is typically crushed from concrete has pores and micro cracks. Many instances when you store it in the open atmosphere it tends to absorb CO_2 and mineralize. If there are calcium bearing phases in your aggregate they will tend to convert to calcium carbonate. So that is another way of actually somewhat to some extent sequestering CO_2 from the environment but it is not going to be extremely successful because there is only a limited quantity of CO_2 that can be absorbed.

Now this aggregate is then subjected to the slurry impregnation process where you have a slurry prepared with either silica fume, fly ash or colloidal silica etc. and water which is mixed properly and then the aggregates can be dumped into the slurry. You properly mix the slurry into the aggregate to ensure that each and every aggregate particles get nicely covered with the slurry. Because the aggregate has adhered mortar which is porous it will tend to absorb the slurry into the pores and fissures. And after drying you will actually get the strengthened RCA or Recycled Concrete Aggregate where the pores and fissures are now filled with the slurry material which has been hardened because of the curing process. And now you have an aggregate that forms as a singular entity. The adhered mortar and the parent coarse aggregate are no longer much different.

They have become lot more uniform. In other words you may not actually see the effect of the ITZ which was originally present because of the slurry impregnation. So in other words you are making the aggregate more homogeneous. Now what happens when you do this? For instance in one of the studies conducted at IIT Madras slurry impregnation was done for Recycled Concrete Aggregate and we produced concrete or we produced Recycled Concrete Aggregate that was now more uniform with respect to its overall distribution of porosity because most of the surface porosity was completely filled up by the impregnated material.

So now using this we prepared concrete and tried to assess the compaction factor of this concrete for untreated Recycled Concrete Aggregate, for Recycled Concrete Aggregate where silica fume was used as the impregnation in the slurry, colloidal silica and fly ash. And we did the replacement for 10 mm aggregate separately, 20 mm aggregate separately and in one more set of mixes we did both 10 and 20 mm aggregates which were impregnated with the slurry.

So in this case what you clearly see is the compaction factor achieved from the concrete with the natural or normal aggregate is close to 0.9 whereas when we do with the untreated Recycled Concrete Aggregate untreated without any treatment you are getting less than 0.8. Now 0.8 is the standard value that is required for pavement quality concrete.

This is just a, this is an application that was attempted for pavement quality concrete. That is why that particular limit has been shown here and what we could see is that because of slurry impregnation the compaction factor now could now be enhanced. We could take it to a level much beyond 0.8 and make the aggregate suitable for use in pavement construction. So clearly this goes to show that the compaction factor which is again a measure of workability increases when we do slurry impregnation instead of using the Recycled Coarse Aggregates as they have been obtained.

So slurry impregnation can prove to be quite useful. Of course, you need to check the efficiency with respect to the overall energy and the cost of the process that leads to this aggregate production using slurry impregnation. Again crushing techniques, crushing techniques we talked briefly about this previously also. So here different types of crushers can produce different textures in your aggregate. For instance, we have talked earlier in one of the lectures that when you do jaw crushing of the aggregate and cone crushing you may actually end up with getting a lot of flaky and elongated pieces. But when you do a vertical shaft or a horizontal shaft impact crushing your aggregates will tend to be more and more equidimensional.

So the properties in terms of workability that you get out of the concrete prepared with such aggregate could also be quite different depending upon the number of stages you have in your crushing process. So if you look at the some data on what happens to the extent of what happens to the extent of adhered mortar and the water absorption as a result of adopting different crushing processes here two examples are given. One is a two-stage jaw crusher and one is a horizontal impact crusher. What you tend to see here is that the extent of adhered mortar is lower for the systems with the HSI crusher. The extent of adhered mortar is lower and because you see that for each one of these data points basically the extent of the adhered mortar is much lower for the aggregate that is prepared with the horizontal shaft impact crushing.

And since adhered mortar directly affects water absorption the net water absorption for such aggregate is also lower. Now when you put this in concrete what is going to happen the water absorption obviously is going to determine the extent of water that you need to add additionally on top of the mixed water. So when you are getting aggregates from different crushing techniques you need to compensate carefully. If you have a mixed crushing once again the main strategy is obviously to go into determining the actual net water absorption of your system.