Advanced Topics in Science and Technology of Concrete
Prof. Alexandar S. Brand
Department of Civil & Environmental Engineering
Virginia Tech, Blacksburg
Week - 03
Lecture - 13
Effect of moisture condition on the microstructure and design of RCA concrete - Part 2

Another thing that we're going to talk about a little bit today is something known as the two-stage mixing approach. So we're going to talk about one study where we combined this concept with the moisture condition of the arrogance. But this was an idea developed by Tam and colleagues where you basically try to improve some of the negative aspects we consider the RCA by basically allowing it to absorb a cement slurry. So knowing that the area is going to absorb some material as it's an SSD condition, we first just mix the RCA in a cementitious slurry, so just cement and water maybe if you have you know fly ash or whatever else you're going to add. Mix that initially. The idea is to let the slurry sort of fill the pores and surface structure of the RCA before you then mix your concrete entirely.

There's different variations on this. So the slide I'm showing here, this process, this procedure is what we adopted for our study, but if you look in the literature you'll find some additional modifications of this as well. So why am I talking about this? So the first study I want to showcase and talk about today is where we took a higher quality course RCA. We knew where it was from, so it was part of an airport that was pretty much laying out, relaying out all of its runways.

So it was demolishing its existing runway directions and paving new ones and longer ones. So the concrete there in that case was not necessarily damaged. It was still a high quality, right, so it had to meet strict regulations for the FAA. So we know this was a fairly high quality RCA, didn't have durability issues, so as we expected it should perform well. So what did we do in this study? Well we did a factorial of 12 different mixes.

So we of course look at the RCA, only coarse RCA, compared that to a natural aggregate, in this case a dolomite. We compared that two-stage mixing to conventional mixing by the ASTM standard, and then we looked at three moisture conditions, and we used those moisture conditions for the natural aggregate and for the RCA. We also did a matched gradation here so that there weren't any gradation effects, all right, and we did adjust the mixing water accordingly to account for that moisture condition of the aggregate. Now what we'll find here is this is just the RCA results. So these are mixes where 100% of the coarse aggregate was either RCA or dolomite.

The fine aggregate in both cases was the same, it was just a natural sand. So all we're showing here are just the solid lines use that two-stage mixing approach, dash lines use the ASTM mixing method, and you can see for all cases, for all three moisture conditions, that two-stage mixing approach increases the strength. Okay, that's telling us that it is fairly beneficial. We'll also see in this case here that the sub-SSD, or roughly it was 80% of the SSD condition, performed the best, with oven dry performing the worst in this case. So what we did next is basically did a statistical treatment of all of our data, right, so again we did these 12 different mixes.

Of course we had replicates, right, so that we could do the statistical testing. Here we use something known as Tukey's significant difference test. It's just another method to basically compare multiple means amongst each other. And so what we're looking at here are specific groupings. So any grouping of the same letter, right, so A and A here, right, we basically show that these two mixes did not have statistically different means with 95% confidence.

Right, but the next one down, A and B, right, these ones were different, that's not the same letter. Okay, but I want you to note is as we can see that the natural aggregate had higher strengths across the board, but what's important to note, right, is that we can start to have RCA mixes that have statistically the same performance as certain natural aggregate mixes, right, and that's an important consideration here is that we can start to see some type of equivalent performance. It's not across the board, it's not for all mixes, but at least in this case we can see that the two-stage and the sub-SSD condition were both advantageous for the compressive strength. All right, you can see these strength differences, right, relative to let's say oven dry, right, fairly large order of magnitude difference there. And then here we're looking at split tensile strengths and flexural strengths.

So we can now see flexural strength not as much variability, right, so if we look at all the ones labelled on M here, these are all the ones that had statistically similar means, and you can see it's a mix of natural aggregate and RCA, and again that is the critical consideration here, and again it's that 80 SSD that seems to be performing the best, right. So tensile strength here again, so these top four appear to just be natural aggregates, but here again if we look at the J, right, we start to see some of the RCA can have equivalent strength to virgin areas, right, the dolomite, right, and that's the important finding here, right, is that for not all mixes are we meeting the same performance with RCA, but with careful design, so in this case using an 80 SSD and using that two-stage mixing approach, it would seem that we can achieve much better performance than let's say if we did oven dry RCA with conventional mixing, right, so there right there is just one important consideration that is worth exploring further. So the next question to examine is, okay, so we know that the moisture condition has a big impact here, as does the mixing approach, okay, but how does that affect the microstructure, right, so how is that changing the microstructure of the concrete, which then is, you know, directly related to sort of the, you know, the macroscopic mechanical performance of the concrete, okay, and especially if we're thinking about something like oven dry, we know that there can be this effective water cement ratio, at least locally, right at the interface, so in this next study we're going to be talking something known as the interfacial transition zone, all right, that is the zone that forms near the arrogance surface, it's usually about, you know, maybe less than 50 microns thick, it tends to be higher porosity, less CSH, it's a lower density, and it forms due to the wall effect, right, cement grains can only pack so efficiently against an aggregate, right, so the size of the aggregate appears as a wall relative to the small particle size of your cement grains, so since there's an inefficient packing of the cement grains, that's how we end up with the ITZ, okay, and so why is this an important consideration, all right, the ITZ is fairly well known as the weak link of

the concrete, right, so your concrete's only as strong as your weakest link, right, because once that weak link breaks, your concrete fails, okay, and that tends to be the ITZ, not in all cases, but it tends to be, okay, and so why is that, right, so number one, it's that larger porosity, right, larger porosity, less CSH, there's also an argument of theirs larger calcium hydroxide crystals in the ITZ, which is argued to allow for easier crack propagation, and then the last one is actually just the physio-chemical interface between the aggregate and the ITZ, right, so that now we're only looking at maybe a few nanometres or less than a micron, where it's really just how are we chemically, let's say, bonding, right, between the ITZ and the aggregates, so that can be weak as well, okay, so in our case we're going to use microstructural analysis to do this ITZ study, all right, we're going to be talking about how we did that in just a few minutes here, so what did we do here, all right, so I took RCA, I used only a small range of particle sizes, because we do know that there are gradation effects, particle size effects on the ITZ properties, so to sort of remove gradation effects, we just sort of looked at a narrow particle size range, this was a fairly high absorptive RCA at 9%, okay, I looked at three different moisture conditions, oven dry SSD, and again this 80% SSD or sub SSD, and what I did is non-traditional, so I took those RCA aggregates at those conditions and immediately mixed them into a fixed water cement ratio paste, I did not adjust for moisture condition, okay, so the idea here was to only have one variable, right, and that is the moisture condition of the aggregate, how is that immediately affecting the ITZ, if I adjusted for moisture condition, now we are going to have these effective water cement ratio distributions in the paste, and I didn't want to see that effect, all right, so that's probably a future study that we would have to look at, so after one day and 28 days of curing, we cut samples vacuum dried them to remove moisture, backfilled the pores of the epoxy, and polished them in preparation for microstructural analysis, and we're going to see what that looks like in just a moment, so just to see what the strength looked like here, okay, again remember that this did not adjust the mixing water, okay, so it's interesting here that SSD actually performed worse, this is in contrast to the previous study of ours that I talked about where we did adjust for the moisture condition of the area by changing the mixing water, right, but in either case, in both, yeah, I guess in both cases we found that that 80 SSD condition still performed the best, so once we have those cut and polished surfaces, we use backscatter electron imaging, all right, so that's an imaging mode in an electron microscope, we're now looking at electrons that interact with the atoms in your surface, and they come out with different energies based on how they interact with those atoms, so unhydrated cement tends to turn up white as we adjust the contrast and brightness settings, okay, so we can see of course we have, let me put the laser pointer on, right, so of course we can see we have our arrogance, unhydrated cement appears as white, calcium hydroxide is sort of this light gray epoxy with mainly composed of hydrocarbons, very light elements, shows up as black, and all the other grayscale in between are things like CSH and other hydration products, all right, and so what we can do is we can start to do grayscale thresholding, right, and this has been a common methodology in the literature for a number of years, so we used the grayscale thresholding method by Wong in order to pull out the porosity, and then additional thresholding to pull out the hydration products from the calcium hydroxide from the unhydrated cement, so what we can then do, right, is once we remove our aggregates, so here there was an aggregate here, we digitally removed that already, we basically do grayscale thresholding, and then just some morphological filters just to sort of clean up the image, all right, from there we can do something known as Euclidean distance mapping, where now that's a nearest neighbour algorithm, so we can now account for the tortuosity of this surface, all right, so we can see the aggregate surface here is fairly rough, if we did just a 1D offset method, we wouldn't account for that tortuosity, so now doing this Euclidean distance mapping, we can convert, right, so we have our grayscale thresholded image, here we pulled out all of the porosity in this one, so everything that was black in this image is now white in this image, so this is only porosity in this binary image, couple that with the distance mapping, and now we have sort of the mean distribution of porosity as a function of distance from that aggregate interface, right, so as the mean distance of, again, this sort of tortuous surface, that's the porosity as a function of distance, so now doing that over multiple images, we can start to collect sort of the mean performance of the ITZ, here we're just looking at just some microstructures real quick before we look at the ITZ distributions, right, so again here we can see our RCA, our aggregate, and you can already see just the oven dry in this image at least tends a much larger porosity than let's say this one here at the sub SSD or the SSD condition, right, but again we're going to collate data from many, many images, tends to be usually 50 to 60 if not more images that we'll collect data from and sort of collate all of the findings, so here we have the ITZ distributions at one day, and what we can see, let's pull on the laser pointer again, what we can see is we tend to apparently have a higher porosity for the oven dry RCA, we'll also see a higher unhydrated cement UH, which is perhaps not surprising, again we're going to have this effective water cement ratio due to the oven dry aggregate absorbing more water from your paste, right, so since there's less water now in the ITZ, there's less cement that can react with that water, right, so that explains we would have a higher unhydrated cement, right, since we have less hydration of cement we of course also have less CSH as well, so as we get to 28 days, what you will note here is that the SSD and the sub SSD conditions both seem to be fairly similar and fairly consistent in terms of their performance, so not much microstructural difference here, but we still see differences then with with the oven dry, all right, so we tend to see maybe a slightly higher porosity very close to the interface, but then we also have a lower porosity, we're going to call this the bulk porosity further out from the interface, right, again since we're absorbing more water into the oven dry RCA, we're changing that local effective water cement ratio, right, so since we have less water

we're actually going to sort of densify that microstructure a bit and end up with less porosity, this is what we will see, right, if we were to do the same study just looking at different water cement ratios, all right, lower water cement ratio we would find less porosity in the ITZ as has been shown in a number of studies, all right, using a statistical method you can look at the paper in terms of how we did that, we tried to figure out what is the size of the ITZ based on porosity, so basically we started looking up here and said okay at what point as we move along this distance from the interface do we have statistically the same porosity as further out which is what we're calling the bulk, all right, and so when we do that statistical analysis we find that the size of the ITZ for SSD and sub SSD is about 24 microns, so right about here, whereas for oven dry it ends up being 49 microns, so right about here, okay, so we actually appear to have a larger ITZ when we have oven dry aggregates, okay, so what were the results we found here, right, again we did not adjust for mixing water here, but we still did see that the 80 SSD yielded the greatest compressive strength, we did not really find a difference microstructurally for the SSD in the sub SSD conditions, which is interesting then because we still have to explain how the strength is different, which we haven't quite explained yet, since we're changing that effective water spent ratio we do see differences in the performance when we do have oven dry RCA, all right, particularly we do see a higher porosity near the interface and then sort of a lower bulk porosity when we have oven dry relative to SSD and sub SSD. Just to sort of, you know, corroborate what we found, this was a study from from Ontario's group where they use synchrotron microtomography to look at RCA concretes, or maybe it was mortars, I don't recall, so they had a control with natural aggregates, that's the reference one, REF, and then they had an 80 MPa concrete that was used to make the RCA, and then looked at an oven dry and then SSD conditions, and what they showed is the oven dry RCA also found higher porosities and also found a larger percentage of larger pores, okay, so there again, you know, some sort of very similar findings to what we found with the electron microscopy analysis. And just sort of as a last discussion that this is some of the latest data that we've been looking at, we're doing a machine learning meta-analysis of the literature because no one has quite looked at this effective moisture condition, no one's factored in moisture condition when doing these machine learning analyses, so we wanted to see how big of an impact does that have, and so we're able to collect 774 unique data sets from the literature. This is unpublished data as of now, you know, hopefully we'll have it published soon, but just this is kind of showing a ranking of what are the most important variables after doing an analysis on all 774, well actually it was a subset of that and then we used a training set as well, and some of the results are not surprising, right, so this is now what are the effects of these variables on the compressive strength is what we're trying to predict here, right, so things like water cement ratio, of course water cement ratio and age, no surprise, we know that for certain that those have big impacts, right, same thing, what's your percentage of fine aggregate, percent of coarse aggregate, again no surprise, we already know those all affect your compressive strength, but as we start to see, same thing with cement content, of course cement content affects your compressive strength, right, but what percentage of coarse RCA you have, how much coarse RCA relative to how much natural coarse aggregate you have, that's of course a big effect, and of course here moisture condition of the RCA we do see does have an effect, right, and you know we're still kind of doing some of the analysis to understand, you know, how big that impact actually is, but it's good to see that, you know, sort of a meta-analysis of the literature also agrees with our results. You'll see fly ash here apparently shows no effect, of course we know that fly ash will have an effect, but this is just due to too small of data sets, right, so of the 774 unique data sets we looked at, only a small percentage of it also factored in fly ash content, right, and so it's just not enough data to really see what that impact is, but stay tuned we hope to have the study out. So what are sort of the key takeaways here that are important to remember, you know, and it's really that I want everyone to remember that moisture condition is sort of the biggest critical parameter here, okay, at least from what we find we need some type of partial saturation, right, you know, it appears from our results that a partial saturation, some percent of SSD, in our case we kept looking at 80%, we don't really know, you know, what is the effect of different percentages, but at least 80% SSD seems to have the greatest impact on at least mechanical performance. Microstructurally we did not see differences in the ITZ between that 80% SSD and true SSD, all right, but regardless we do know from these data that oven dry causes some difficulty, right, so we do know that there is slump loss in the literature, we do know that it's affecting this effective water cement ratio, there's likely to be a gradient of effective water cement ratio in the ITZ, maybe that's why we're seeing, you know, such this larger ITZ based on porosity when we look at the data, but in the end the findings from our data here suggests that, you know, sort of the sub SSD condition is optimal. Further studies are needed to understand more about this two-stage mixing approach, particularly with regard to the ITZ, but certainly there's data in the literature to suggest that it does improve mechanical properties, so that might be just an easy change in your mixing process to already improve some of your performance. So with that I will end the presentation. I thank you all for your attention. If you're interested to know more or wish to discuss anything, here's my contact details. Feel free to email me. Thank you very much for your attention. Thank you.