Advanced Topics in Science and Technology of Concrete
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Recycled Concrete Aggregates: Properties and Performance - Part 1

Good day. My name is Professor Mark Alexander from the University of Cape Town in South Africa, and together with my colleague and PhD student at that university, Mr. Ichibaru Amadi, it's my pleasure to present this SPARC lecture. The title of the lecture is the properties of recycled concrete aggregates and performance of concrete with recycled aggregates. So let's get into the lecture as soon as we can. This is what I would like to cover: Some characteristics and properties of recycled concrete aggregate, intrinsic factors influencing the properties of recycled concrete aggregate or RCA, differences between fine and coarse RCA, physical properties of natural aggregates and RCA, mechanical and durability properties of RCA concrete, and then something on the classification of RCA and recommendations for use, and finally, we'll draw a few conclusions.

So let's start off by thinking about what RCA, recycled concrete aggregate is all about. And this diagram as we can see shows us that RCA comprises virgin aggregate, a material that we call adhered mortar, sometimes called adhered paste or AM, and multiple interfacial transition zones. And the multiple interfacial transition zones arise from the fact that the adhered mortar which continues to, as the name implies, adhere to the original aggregate particle, has its own ITZ, and then when this particle is included into a new concrete mix, an additional interface is created, and sometimes this may happen on a few occasions or several occasions, and then you actually even get multiple ITZs. And in many ways it is these ITZs that govern the performance of the recycled concrete aggregate and the concrete made with that aggregate. And it is this adhered mortar that distinguishes the recycled aggregate from virgin aggregates, which obviously don't have that.

The AM is less stiff, and it is more porous than virgin aggregate, and therefore we can immediately begin to understand that the concretes that we make with these materials are also likely to be less stiff and probably more porous as well. And in terms of the way that we produce recycled aggregates, concrete aggregates, one could expect more of this material in the fine RCA than in the coarse RCA because being softer and more abradable it's likely to be abraded off or worked off the original aggregate particle by whatever process we are using and land up more in the fine fraction than in the coarse fraction. And so we will find there are some differences between fine RCA and coarse RCA. Now I'd like to talk about five intrinsic properties of RCA and the influencing factors of these intrinsic properties. The amount of adhered mortar, the type of parent aggregate or the virgin aggregate, contaminants that occur within generally recycled aggregates, processing techniques that can be used, and the grade of the parent concrete itself.

The diagram here shows on this part over here you can see a typical rock quarry from which we get virgin aggregates or fresh aggregates. Here this bottom face has been blasted off. There lies the debris which is going to be crushed to become rock aggregate. And this down here shows us the sort of material. Here is a sample of aggregate where you can see some adhered mortar, there is some adhered mortar there.

This is in fact a piece of probably of original plaster, some old bricks with mortar attached and even some tiles. So in mixed demolition waste we get this almost, one could say, we tend to call it a concrete contaminated recycled aggregate. And ideally what we want to do is to try and separate its source. So we deal only with crushed concrete itself without these other additions, the various contaminants that we have. But I'll deal with that a little bit later as well.

So let's talk about the adhered mortar. And there is some pictures of this adhered mortar which shows it quite clearly. And it's obviously the quantity and quality of this material that influence the RCA properties. It comes in different quantities depending on how we crush and how we process. And it could come from poor quality or high-quality concrete, therefore its quality differs.

And this is this variability in quality and quantity that really distinguishes the AM in terms of its performance. It's not easy to quantify this material either volumetrically or by mass, especially for fine RCA. And so as an indirect measure, we tend to use water absorption and dry density, particle dry density, which provide an indirect assessment of the adhered mortar and the quality of the RCA. And here is just an example in terms of dry density and water absorption, which are these indirect measures. If we compare a typical river gravel, a dolomitic gravel, and then RCA from a 40, 60, or 100 MPa original concrete, you can see quite clearly that the dry density reduces with lower quality.

So, for example, in a 40 MPa recycle from original concrete, you tend to get these kinds of densities here and maybe a little bit there. But you can also see that it has the highest water absorption. So clearly these are indirect indicators but very useful when you're trying to classify and understand these materials. And here we look at the effects of the RCA quality and the quality of the parent concrete. And in this case, what we have in the left-hand diagram here, and let me just get rid of these, is that what we can see here is a ratio of the compressive strength of RCA concrete against conventional concrete.

And we have, in this case also, we have this notation. So we have the recycled concrete, we have the replacement level, and we have the strength of the parent concrete. So for example here, we have a replacement level of 20% up to 100, with 50 in the middle, and we have three different concrete strengths. The original concrete is 100, 60, and 40. And clearly this diagram shows that if we're using high-quality original concrete, 100 MPa for example, in the original crushed variety to make the aggregate, then in terms of the strength at least, there is no penalty that we pay.

We can get concrete of pretty much exactly the same properties, if not even slightly better. And that's also independent, as you can see, of the replacement ratio. So here we can use easily up to 100% of that aggregate if it's of good quality like that. If we start coming down to the lower strengths of the original concrete, and really if you think about it, a 60 MPa concrete is still a very high-strength concrete, and even 40 MPa is a good quality concrete. But you can see that there is some effect.

But in strength terms, the effects are to some extent limited. And you can see that here. It's only really then when we get to the lower strength original concrete and a replacement there of about 100% that we get this lowering of the strengths substantially or significantly. Now, if we look at, on the other hand, if we look at the elastic modulus or stiffness, now all of a sudden there is a very different picture that emerges. And you can see that in all cases there is some effect on the elastic modulus or the stiffness of this material.

And that's very typical of what happens in any concrete, that the stiffness properties, movement or transport movement properties are far more sensitive to the quality of the aggregate under the interfacial transition than say strength is. And you can see it here as well quite clearly. In some cases we may go down to even as little as 70% of the original elastic modulus. Now that in itself may not be a problem. I mean elastic modulus is an important factor, but we may be able to get away with somewhat lower elastic modulus concretes for many, many structural applications and each case must be considered on its own merit.

Let's go on and look at the same sort of diagram but now in terms of durability parameter and electrical resistivity. This is a typical surface resistivity. And here compared to the virgin concrete or the conventional concrete there, you can see that again the values of the resistivity are coming down. Eventually, we get down to a value like this. This is ohm centimetres.

We usually talk about kilo-ohm centimetres. So this is about 10 kilo-ohm centimetres here. And other than this slight improvement here, which is an interesting phenomenon, in general, the addition of recycled coarse aggregate from different concrete strengths and different ratios tends to bring down this value, which may have implications for things like corrosion resistance of that concrete. And once again this is another typical diagram or similar one. This is the total charge passed.

And the same picture emerges. This is the RCPT test, the coulombs, total coulombs passed in this typical test. And again it is quite clear that with the lower quality of the original concrete or strength of the original concrete with higher replacement ratios that the RCPT value goes up in this case by a factor of nearly 2. Again this may or may not be a problem. For example, we are still in most cases within the lower range, having started with of course a very good concrete to start with.

And in many cases, this may be quite acceptable and doesn't necessarily mean that that concrete has to be excluded from possible consideration. And I think that's important to stress as well. We must understand that concrete has to be fit for purpose in all cases. Let's talk a little bit about the contaminants. And here you can see, I've already mentioned actually that the contaminants are all the kinds of things you would find in a typical building, for example.

Metal, wood, plastic, asphalt, glass, soil, masonry, gypsum, etc. The diagram on the right actually shows a little bit of a mixed aggregate. You can see some brick in there, the reddish colour. But actually, this is quite a good aggregate and so it may well do extremely well. But on the other hand, you get these other sorts of things here.

You can see the very angular and jagged particles, the coarse surface in this middle diagram here, which is really not very good material at all. There's even some wood and twigs and other stuff over here, which we certainly don't want in our concrete. And when tiles are broken off the wall, then those tiles can land up as well. So this brings me back to my other point and that is that really we want to try and separate out these other materials right from the start so that what we get into our recycled aggregate is only concrete itself. Because it's these contaminants that can reduce the property of the concrete can also cause problems.

For example, if there's gypsum, this can expand and cause falling and cracking of the new concrete, which is certainly not what we would like to have. So one must understand that as well. So the effect of these contaminants is to bring in extra heterogeneity, variability, variable density, the absorption will change, mechanical durability properties will also be affected by these contaminants and hence we'd rather not have them. And how to mitigate? Well, selective demolition is what I've already spoken of.

Separation at source. There are means like air blows or water separation where different densities can be separated in that way or even possible manual sorting. These days we're even looking at robotic sorting. So if we do have a mixed waste, one can possibly still use it but it will add extra effort and cost to the whole process. So let's talk a little bit about the beneficiation techniques for ROCA. And really there are just two primary techniques.

There's the removal or the partial removal at least of the adhering mortar or the surface modification of the recycled concrete aggregate. And this table helps us to see the picture as a whole. So here for example we have on the left-hand side the removal or partial removal of the adhered mortar. We can do that with mechanical scrubbing, with acid soaking, that's not generally recommended because of the environmental impact of that. Microwave heating is useful for small quantities but probably not big quantities.

Conventional heating can be used for all kinds of quantities and ultrasonic water cleaning likely would only be used for small quantities or small samples. On the other hand, the surface modification route does things like trying to see if we can modify the surface or the internal system by pozzolanic materials, SCMs and so on. The addition of nano silica or lime, bio deposition of calcium carbonate through that sort of a process and then a carbonation of the adhered mortar or CO_2 curing which transforms the fine material into a carbonate and a reactive silica. Very interesting process. So with these in mind, in terms of this program that we were doing, we tended to use, the IITM team were using a semi-mechanical kind of scrubbing, a combination of temperature and abrasion if you like and the team from Cape Town were using the addition of SCMs, typically fly ash or slag and see what could be done in that way.

So we decided to work in these two different streams and see what we got. So the influence of the processing technique is as you would expect, if you do multiple crushing you tend to improve the final product but you of course lose or you have the penalty of losing yield because the more you crush or the more cycles of crushing through which you go, the more fine aggregate is produced and less coarse aggregate. So depending on what your final intent is, you would sort of match your crushing and grinding techniques to the final product required and the yield that you would like from that. Multiple crushing is certainly done and then generally it would be passed initially through a jaw crusher and after that maybe through an impact crusher or a cone crusher to improve the particle shape and then you can go all the way down as I have said, although that is not always done in terms of the yield of the material. So that is how that works and this is just a nice example of a typical mechanical scrubbing or abrasion rubbing process, just an ordinary Los Angeles abrasion machine with the initial recycled concrete in those chunks in the left there put through this machine and you can see that there is a very dramatic improvement in the quality of that recycled aggregate in the right-hand picture there where effectively one has almost brought that back to a virgin aggregate condition.

In this case, of course, it takes quite a lot of effort of that scrubbing or rubbing technique, abrasion, and the addition of temperature to this process can speed that up quite considerably. In this case, in fact, just to read the numbers that I have here, there was a reduction of nearly 70% in the adhered mortar and an increase in the density of about 20%, so it was very substantial. Now, density and water absorption, as we have said, are proxies if you like for the amount of adhered mortar, and compared to normal aggregates and owing to the presence of that mortar RCA has first of all lower density. Quite clear here if you look at the diagram on the right, natural aggregate, fine and coarse, have densities typically within the range given there and those whisker diagrams on the right, the fine and the coarse RCA you can see the densities are substantially reduced and usually the variability is reduced, the variability is increased actually and the differential between the fine and the coarse goes up because you are in a sense preferentially selecting materials that go into the fine fraction as compared to the coarse fraction. That would be expected to be reflected in the higher water absorptions and exactly that is what happens.

On the right there the fine and coarse RCA have got substantially higher water absorptions whereas in normal concrete we would have water absorptions typically in coarse not more than about 1 or 2% and in fine maybe up to 3 or 4% like there by the time we go to the recycled materials it can go up to 10% or higher on the fines and around about 5% if it is a reasonably good quality material on the coarse. So there is a big difference and that is simply as I have said a reflection of the amount of adhered mortar and the nature of that adhered mortar. And here is a very interesting correlation between water absorption on the one hand and oven dry density on the other and it is a scattered diagram so there are probably several hundred points here at least and you can see there is a very clear correlation between those two parameters as you would expect. Generally the natural aggregates would land up down in this corner over here and some of the really good quality recycled aggregates mainly coarse of course would end up in that area as well whereas the fine aggregates would tend to land up here together with some of the poorer natural aggregates maybe where you do get occasionally high absorptions and then clearly right up here we are up to the sort of the extremes where 20 or 25% absorption is probably not something that we really want to work with because it becomes very difficult to work with that kind of material. Now, if we look again at the correlation between recycled aggregate size and water absorption exactly the same picture emerges as you would expect although the spread or scatter here is also again quite wide but in general the larger the maximum aggregate size the lower is the water absorption so up here at about a 35 to 40 aggregate size you can expect this low water absorption and that generally carries right through even to generally the sort of 19 or 20 mm aggregate over here although there are some higher values and in general as the aggregate size or maximum aggregate size reduces so the water absorption increases and that is to be expected because of this finer material it has got more adhered mortar in it, it is more porous, it is more absorptive and it has this preferential material characterization.

So, just to summarize what we have said so far the difference between coarse and fine RCA. In coarse RCA we have less adhered mortar, in fine higher adhered mortar content. Coarse RCA high density, fine lower density. Coarse RCA we have a lower water consumption and a higher water consumption and water demand in terms of the fine material. The coarse RCA tends to contain less contaminants and usually they are not a problem whereas in the fine we could have contaminant content which may be a problem and again in the coarse RCA this can be used for structural concrete in most standards and most applications whereas in the fine aggregate fine RCA presently structural concrete application is restricted if not completely excluded in most standards although with the work that is going on there is no reason why that can't change.

Here are just some physical properties of natural versus recycled aggregates, examples from India and South Africa and this is a busy diagram, I am not going to go through it in detail but you can in general see that in terms of the natural aggregates we get dry densities up in the region of 2700 here in India or 2690 there and water absorption is down in the very nice low range of 0.4 but when you get up to the coarse RCA you can see the difference immediately as you would expect and the bulk densities reflect the same thing. In the fine aggregates you also see of course that the densities come down and we go from around maybe 2400 to 2600 all the way down to 2200 that's in the Indian case and even in the case of a fine aggregate that we were working with down at 2148 or so and absorptions up to over 10%. So exactly what we saw before, so all we are saying is that the aggregates that we worked with are very typical of what you generally get and we need to bear that in mind that we have these aggregates in terms of the way that they worked in concrete. Now let's then go on to the mechanical and durability properties of concrete with recycled concrete aggregate, both coarse and fine and we will consider three aspects.

Compressive strength, that's what most engineers are interested in as the first question they would have. Secondly carbonation resistance and thirdly chloride resistance, the last two particularly because we are now very concerned about issues like durability in concrete. So let's have a look at each of these in turn and see what we can learn from what we will see. Now this is a graph which shows compressive strength ratio again, in other words, it's a compressive strength of the recycled versus the normal or the natural aggregates as a function of coarse aggregate replacement. So this is only coarse RCA and what is immediately apparent is what we find here is that there is a huge variability.

This is a range of about seven or eight different references including one actually this is one from the local product. You can see again that up to about let's say 50% or so, in fact in this range there is quite a lot that only brings the strength down by a fairly nominal amount. Of course, there are the outliers that have a huge influence and in that case you are dealing with a different material altogether. So even up at 100% here you can see that it is still quite possible to have full replacement and we saw that in an earlier slide and still get very good strength values. So it is quite possible to have recycled coarse aggregates that can give us concrete properties that are really quite acceptable.

On the other hand, there are others that even independent of the water cement ratio and you can see here the water cement ratios are all over the place that may not give us what we want but on the other hand may still be fit for purpose for low-grade applications. So for example, concrete bricks or blocks there may be no problem with using them in those lower-grade applications. It depends entirely on what we want to use the material for. With a fine RCA interestingly enough the similar picture emerges even though it has the higher water content and in the rather more limited set of results that we have here you can see also much the same picture emerges it is quite possible to have

even up to 100% recycled fine aggregates giving us strengths that are not terribly much reduced but on the other hand some of them may. So the same picture but what it gives us the idea of is that if we treat these materials properly and understand them well it is quite possible to use them in our concretes without great penalties in the properties that we measure.

This is an example from the IITM studies looking at compressive strength with over 3, 7 and 8 days and what you can see here is of course that depending on the age you get the higher strength at the higher ages but what you really see here is that it doesn't matter how much coarse RCA replacement has been done there is very little effect on the concrete. The concrete is still doing extremely well and the strengths are maybe modestly but hardly reduced at all maybe a little bit more at 28 days than at the earlier ages so there is virtually no penalty in this case. This is a bit high quality recycled aggregates. On the other hand if we look at the route that we took in our studies where we used in this case fly ash, fly ash treated concrete and by the way what we did here was we didn't increase the water content of these concretes to account for the moisture absorption we just dealt with it as it was but we did use a modified mixing procedure which other work will illustrate. And here you can see again that overall if we look at the different ages we got 3, 28 and 180 days here.

180 days because fly ash takes some time to develop its properties and we have plain and fly ash concretes. The general picture here is that there again is something of a penalty. We have these replacement ratios of 25 and 50% and at the 50% replacement ratio if you compare the plain concrete with the plain concrete with just zero replacement there is a slight reduction but it's not huge and it's quite manageable within much of our concrete design and the same occurs with the fly ash comparing the natural aggregates with the recycled aggregates. So the picture that emerges is that the reductions are generally not large and can usually be accommodated within our designs and in this case we can do other things with the SCM that we are using. Talking about carbonation resistance a little bit of a mixed picture emerges and here we have on the left coarse RCA and on the right fine RCA and you can see that with the use of fine RCA there is immediately apparently anyway a much greater increase in the relative carbonation depth with a substantial increase and a very substantial variability that comes through in this case.

And I guess that's to be expected because the fine RCA does have these properties of higher porosity, more penetrable and maybe in this case the carbon dioxide can penetrate more readily. But one must realize that in all these cases very much depends on the nature of the material that was used and indeed how it was prepared, whether additional water was used to compensate for the higher absorption or not. These are important issues. For example, if we look at this one here, this is from another set of investigators, what we find here is that almost conversely to the previous, with in this case fly ash treated concrete and fine recycled replacements, we see that it is apparently up to even 100% the carbonation resistance is very modest.

There is a little bit of a difference here. So this sort of sets you thinking why would this be the case. And unfortunately in this case the authors of this article from which we got this didn't really explain or offer an explanation for this which was a bit disappointing, we would have liked them to have told us why. But some possibilities here are that first of all because there was no extra water added that one could have to some extent got a slightly lower water binder ratio due to the absorption initially. And then with the higher contents of fine recycled aggregates you really got additional calcium species in the system to act as buffering agents against the carbonation. Because you got this recycled aggregate which has got quite a lot of calcium residual in it in form of hydroxide, in the form of CSA and so on.

Calcium silicate hydrate. So a little bit of a question mark here but it seems to indicate that depending again on how you handle your material and treat it, it's possible to get away and not necessarily have a penalty. And here is another example of moving to chloride resistance and again with the work done at IITM where in effect if you use a high quality thermo mechanically treated aggregate even up to 100% you can see here with a coarse or fine the chloride resistance is very low and the chloride migration coefficient from the Nord test is effectively the same. There is no penalty at all in this case. So the aggregate is having no ill effect. On the other hand if you simply use an untreated aggregate there is an effect and it goes up quite substantially and this may or may not be critical.

I mean for example if you are not working in a chloride environment then it doesn't matter at all. But in a chloride environment that may be a factor. And then if we look at the fly ash side of things, here you can see of course that the benefit of fly ash is that with age and with replacement level we have clearly an advantage here. So the first diagram is at 21 days and the second diagram here B is at 56 days and immediately you can see that at 56 days everything is remarkably changed because of this ongoing hydration of the fly ash.

A great benefit to be obtained. But even in the early stages with fly ash contents between 0 and 30% you can see here that for example indeed when you replace with fly ash there is an increase, this is the total coulombs again so it's the RCPT test does go up and so that may be an issue. But as I said by the time you get to the later ages it's quite clear that there is a great benefit by extended curing. And so that's another important thing just to bear in mind. Okay so this is another look at chloride ingress, this is the chloride conductivity test. So this now the measure here is a conductivity measure of the concrete so like an inverse of a resistivity and the unit is a milli siemens per centimetre which is exactly the inverse of a kilo centimetre if it was a resistivity.

And here we have two concretes at two ages, again 28 days and to give the fly ash the possibility to, in fact in this case the 180 days here, and you can see that we have two water binders ratios, one at about 0.55, one at about 0.45 and two replacement ratios 25 and 50. And in this case again with the longer period of curing with the fine RCA the result looks a whole lot better because those fine RCA materials can in fact in the long term there is a degree of additional interaction with the cement, if you want to call it additional hydration I'm not sure, but there seems to be some benefit and improvement in that material with time which tends to improve the situation. So we can't always go on the very short term results, we sometimes have to look indeed at the long term results to see what's going on.

That's quite a bit on the properties of these recycled aggregates and what we can expect, the picture that emerges at this point in time is simply this, that every source of recycled aggregate where the coarse will fine is to some extent unique, each needs to be understood, needs to be measured, properties need to be obtained in order for intelligent decisions to be made about its use, which always has to be linked to the purpose in mind. Now here is a recycled aggregate classification system suggested by Silver et al. where the aggregate classes are suggested to be put into four different classes, A, B, C, D. Within A, B and C there are three subclasses in each and the basis of classification is the oven dry density here, which would obviously be linked with the water absorption because of their inverse relationship and a further measure here which is the Los Angeles abrasion loss, which could be added to the classification if you wish.

And so we go from the high quality A1, this would in fact be typical of natural aggregates, but also of really good quality recycled aggregates, through to B1 in which you can see the density has come down by 300 kg/m^3. And by the time we get to the C1 category by a further 300 kg/m^3 and the absorption has gone from 1.5 to 5 to 10.5. And then the subcategories 2 and 3 then extend those basic categories further. And so this is quite a useful way maybe of classifying because it is always useful to classify.

This helps engineers in selection of the material and to know more or less what kind of properties the concrete will have from this selected material. And this classification is plotted here in a diagram with the colors there to sort of differentiate and again from the bottom right hand corner we get the A category with its three subcategories, then the B category likewise and then the C category and the D category which would tend to be only for very low grade applications but which in many cases are the things that we are looking for when we are just looking for fairly low strength block and brick production it may well be quite acceptable to use those materials. So here is a way of looking at it. This diagram tends to be dominated by results from course aggregates, recycled course aggregates data simply because that is predominantly in the literature at this stage but as more data become available from fine aggregates this could possibly be refined.

But quite a useful way forward in terms of classification. Okay, now with that in mind what sort of recommendations can we have for our CA selection? And in addition to what we have just looked at which is the classification approach, I think the important point to stress here is that we must link the aggregate quality with the application. So that is extremely important over here. So for example if we have an excellent quality aggregate which we would have for most natural aggregates, particularly if they are crushed from fresh rock, then of course we can apply those aggregates across a whole range of applications from high grade to low grade. And in fact sometimes we would rather not put them into the low grade because then we are using high grade materials for low grade applications which is a little bit of a mismatch.

Maybe there are other ways of doing that more intelligently. On the other hand if we have a poorer quality which we may get from recycled aggregates then we would tend to use those in the lower grade applications. And there would not be a great deal of sense in trying to do that. In other words spending a huge amount of money and effort to try and turn a poor quality material into a high quality material where its application may well be much more applicable here. So it depends on the application, it depends on the starting material and the quality thereof and each case again to be considered on merit as to how we are going to use these materials. But once we begin to understand them better, then of course we are able to use them more intelligently and to make our selections in a better way.

So that would be the suggestion of how we should be using these materials. So we have come to the end of our lecture and thank you very much for your attention. I presume that you have been attending even though I cannot see you. But thank you very much and let me draw some conclusions here. And that is that the presence of the adhered mortar in recycled concrete aggregate distinguishes it from the virgin aggregate. Secondly, due to that adhered mortar, RCA aggregate may be more porous, less stiff and less dense and therefore exhibit higher water absorption and indeed higher water demand in concrete mixes when compared to virgin aggregate, which in turn may impact concrete properties.

I think a point I have made along the lecture is that this additional water absorption can be accommodated by additional water addition or by revision of the mixing regime, you can sometimes get away with that or use of modern admixtures. The RCA density and water absorption can be influenced by the amount of the adhered mortar, the presence of the contaminants, quality of the parent concrete and the processing technique. Water absorption and density can be considered as key quality parameters to assess the quality of RCA and therefore to classify it. Due to the high surface area of the fine RCA and the inclusion of those broken mortar pieces, the quantity of AM is higher in fine RCA than in coarse RCA. And lastly, incorporating up to 50% fine RCA may not adversely impact the concrete properties and we could possibly go even higher in the fine and certainly higher in the case of RCA. So with that, thank you for your attention and I wish you a good day.