Advanced Topics in Science and Technology of Concrete
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Week - 01
Lecture - 02
Aggregates and their effects on concrete properties-2

Okay, I would now like to turn to the matter of the effect of aggregate on the hardened properties of concrete. So we've had a conversation about the effects of aggregates on the fresh properties of concrete. We've now mixed that concrete, we've placed it in its form, we've compacted it, we've finished the surface to a suitable surface by floating or whatever preparation was necessary, and the concrete is now, the cement is hydrated, we've ensured that sufficient curing is available, and we're now interested in the hardened properties of concrete. And the best place to start this conversation is at what is referred to as the Interfacial Transition Zone, or ITZ. This is a zone about 50 microns thick, and it is the zone that is the interface that represents the interface between aggregate particles and the bulk cement paste. And I've shown a diagram here, which is taken from Mehta and Monteiro, which shows an aggregate surface, an aggregate particle, and the transition zone between the aggregate particle and the intact concrete cement paste and bulk cement paste in the concrete.

And what we see is a transition zone where there is a reduced amount of calcium silicate hydrate, which is the hydration product that cements all the material together. There's also a preponderance of calcium silicate hydrate crystals; that's CH. I'm sorry, that is calcium hydroxide crystals (CH). And then a preponderance of these needle-like ettringite crystals, which sit at this interfacial transition zone.

What I want to emphasise here is that the interfacial transition zone is generally more porous and generally slightly weaker than the bulk cement paste. And that's an interfacial effect. This ITZ does affect, as a result, the bond strength of the cement paste with the aggregate. And of course, it strongly influences the cracking characteristics in the zone between the aggregate and the bulk cement paste. For low-strength concretes, the inherent strength of the aggregate has only a small influence on concrete strength.

But the aggregate strength is more important in high-strength concrete. I will talk to this issue a little later. Let me also say that the mechanical bonding between the cement paste and the aggregate is equally important as the chemical bonding. And here, the influence of surface texture, surface irregularity, and surface intactness of the aggregate has an influence on the quality of the bond between the bulk cement paste and the aggregate itself. Let's just explore the nature of this interfacial transition zone a little further.

And here I am relying on work that was done by Alexander and Menders in a very thorough book that they published in 2005. The bond between the hardened cement paste and the aggregate is neither perfect nor continuous around the entire aggregate particle. The state of stress within the transition zone will vary depending on the location on the aggregate surface and also with age, because with age, the interfacial transition zone develops its properties and becomes more and more refined as hydration proceeds. Different surface finishes of the aggregate, ranging from very smooth poly surfaces to rough fractured surfaces, will provide different bond properties. This is a point I made a little bit earlier about the effect of surface quality on the aggregate nature and quality.

But importantly, there is no agreement on the method of surface preparation that could be used in experimental work when considering the bond strength between aggregate and cement paste. The interfacial zone itself is variable in composition, and its mechanical properties vary spatially. Therefore, there are no unambiguous values that can be regarded as constants. Even the thickness of the ITZ around the individual aggregate particle will vary as one traverses around the aggregate particle. Bleeding, which we spoke of before, is the ability for the aggregate particles to hold water.

When there is more water than can be held, this will lead to bleeding. But bleeding because of this preferentially upward movement of water will lead to an uneven distribution of water around the aggregate particles, usually more water on the underside. And this then exacerbates the variability in the ITZ character. Some examples of the point I am making. If one thinks of an aggregate particle in a body of cement paste,.

If a crack arrives in the cement paste, whether the crack passes through the aggregate, as in this case on the right, or around the aggregate, as in the case in my diagram on the left, will depend on the quality of the interfacial transition zone and the strength of the bond between cement paste and aggregate. And here I am showing you an example where almost all the cracks—this is a freshly broken surface of concrete—have gone around the aggregate particles. You can see the imprint of aggregate particles here. There's a broken aggregate particle there. On the top, there's a broken aggregate particle on the right-hand side here.

There's some small broken aggregate, but mostly the cracks have gone around the large aggregate particles. Here on the right-hand side, most of the cracks have gone through the aggregate particles, and you can see fractured, broken aggregates in almost all of them. Here's one aggregate particle that has been pulled out, but mostly the cracks have gone through the aggregate particles. And simply looking at a surface like this, when your eyes get used to it, you can get a reasonably good estimate of the strength of this concrete by looking at where the aggregates went around, whether the cracks went around the aggregate particles or through the aggregate particles. Here's an example of some research work that we did where we looked at two types of aggregates: quartzite and an andesite.

Andesite, being a highly later-developed sort of sandstone to metamorphic rock, would sort of grade between sedimentary and metamorphic. Andesite, being a primary igneous rock deposited by lava, cooled fairly close to the surface of the lava deposit, so it would be very fine-grained. And we looked at the effects of these aggregates on compressive strength of concrete. We made three concretes with exactly the same mixture proportions but simply with different aggregate types. We also matched the grading of the sands—the quartzite and andesite sands—so that workability was similar.

And then we made three strength grades. And what was interesting is the fact that simply by changing the aggregate particles, we were able to get significantly different concrete strengths. But what I want you to notice is that the concrete strength increase or improvement with andesite aggregate was larger for high-strength concrete than it was for low-strength concrete. And this gave an indication that the mechanism or the reason for the strength increase was less likely to be a chemical effect than it was a mechanical effect. And the reason for that is if it was a chemical effect, low-strength concretes, which have more sand and therefore more finer particles, would have probably shown a higher strength increase than the high-strength concretes, which have less sand.

And since this is a reverse trend we are seeing, it made us think that the effect was probably more largely a mechanical effect rather than a chemical effect. And that would be about issues associated with bond strength, adhesion properties, nature and quality of the aggregate surface itself. Further work, which was based on the earlier slide that I showed you and was done by Alexander and Davis, showed that, in fact, we could group South African aggregates into their strength-enhancing properties. And there were clearly distinct groups which were placed into three categories, with group one being the andesite, dolerite, quartzite, felsite, and siltstone that are commonly used as aggregates in South Africa. Group two were the dolomites and the greywackeys.

And group three, which at the high end of the cement-water ratio gave the lowest strengths, were the vatvartasone quartzites, iron-based quartzites, and granites. And so clearly, there is a pattern emerging here with the sort of origin, geological origin of aggregates showing a strong influence on compressive strength that goes beyond the water-to-cement ratio. Here we look a little further at the effects of aggregate characteristics on concrete strength, and again, at the same water-cement ratio, rougher surface textures, angular shapes, and flaky to elongated particles tend to increase the tensile strength of concrete. For higher-strength concrete, the compressive strength of the concrete correlates positively with the 10% factor value of the aggregate, which is an indirect measure of the strength of the aggregate. In the range of 40 to 80% by volume of concrete mixture, increasing the volume of aggregate increases the compressive strength.

But it may cause a decrease in tensile strength, depending on the particle shape of the aggregates. The table I am showing you here gives an illustration of the effects of the premiums that can be obtained from andesite over quartzite concrete in cube compressive strength, tensile strength, and the modulus of rupture, which is an indirect tensile measurement of tensile strength. You can see that the andesite has benefits throughout this range and, of course, for all three water cement ratios that we used in that test program. Thinking about aggregates and elastic modulus, aggregate characteristics have a much stronger effect on elastic modulus than on the strength of concrete. And here's an important point to bear in mind, and I will make this point in relation to normal approaches to specification.

For the same compressive strength, different aggregates can cause up to 100% variation in elastic modulus. Most specifications will rely only on compressive strength to allow you to predict the elastic modulus. And what the statement is saying is that one must be careful of those kinds of prediction models that rely only on compressive strength because our experience is that aggregate type can have an influence as well. The effect of aggregate characteristics on elastic modulus is stronger at early ages than at later ages, and this we think is because of the increasing refinement of the interfacial transition zone as hydration proceeds between 28 days and 6 months. But this has started us to think about concrete as a three-phase material rather than a two-phase material, which is cement paste plus aggregate plus the interfacial transition zone.

The ITZ is clearly having a fairly significant effect on the properties of hardened concrete, and as we start modelling the behaviour, it's important that we start thinking of the interfacial transition zone as an important added component. Just to illustrate the points in this slide, here are some examples of the relationship between static elastic modulus and cube strength, and it is clear you can see that depending on the aggregate type, you can have very very significant variation in elastic modulus. For example a granite aggregate at about 65 MPa strength will give about 30 GPa, 32 GPa elastic modulus. The same strength of concrete made with dolomite will give elastic modulus closer to 55 GPa. So, ACI, we've plotted on this curve the American Concrete Institute 3-1-8 relationship, which clearly shows how inadequate a reliance on cube strength is if one is trying to predict elastic modulus.

This curve on the right, or set of curves, shows the decreasing sensitivity of elastic modulus to cube strength as the concrete gets older. The dotted line relates to the relationship at 28 days, while the solid line relates to relationship at 6 months. And here you can see a decreasing sensitivity of elastic modulus to cube strength as the ITZ becomes more and more refined with hydration. Just to consider now time-dependent deformations and here for creep and shrinkage deformations, aggregate volume concentration has a much larger effect than the nearing characteristics of the aggregate. And this is simply because the source of creep and shrinkage commonly is in the cement paste.

And so higher volume of aggregates means less volume of cement paste and, therefore, reduced shrinkage and deformation. The sand fraction of the aggregate has an indirect effect in influencing the water content, and that's because of workability, which we've spoken before. And if water content is increased, it means the cement content must be increased to maintain strength expectations, and that means a higher volume of cement paste, and that then means increased creep and shrinkage deformation. It's important to consider the water absorption capacity of the aggregate because this appears to influence the extent of shrinkage, and the relationship appears to be that higher water absorption of the aggregate results in higher shrinkage. Some sandstone aggregates with higher water absorption capacity will themselves cause shrinkage as they dry out.

And if these aggregates are used in concrete, they will have the effect of increasing drying shrinkage over time. Where you may be considering using these quite porous sandstone aggregates, do be careful with shrinking aggregates. They can cause quite serious problems with significant deflections, for example, in British structures. Just some illustration of the relative effects. This is from Power's work that he did in 1971.

Note that, interestingly, he's thinking of the unhydrated cement as part of the aggregate volume fraction. So he's treating unhydrated cement as effectively a well-bonded aggregate. And he have a fairly good relationship. Here's a cement paste. This is relative shrinkage in relation to the volume of aggregate.

And of course, normal concrete would be around 70 to 80 percent, so this would probably be the range of normal concrete in relation to plain cement paste, which is around here. Remember, unhydrated aggregate is also cement paste, which is also being considered as aggregate. So this is paste. But by the time you get to normal concrete, you're getting to about 20 percent of the shrinkage. These curves, and really, I'm not going to go through them, are really for your records.

It gives an illustration of the relative shrinkage of different of concretes made with different aggregates. Same in the sense of strength and mixture design. And here you see if we're in this case taking what would that be an andesite dollarite andesite as 100 percent or reference reference aggregate. The truth is that the dolomites give you lower shrinkage while the sandstones and saltstones give you higher shrinkage. And similarly on this side for creep effects.

Let's consider just an illustration of the effect of water absorption capacity of the aggregate. And I should just explain here. This is we made a series of concretes; in fact, we made two strength grades of 30 and 50 MP concrete. But in each of the aggregates, we replaced or we blended the sand and stone with mixtures of quartzite and shale aggregate. You remember I showed you the dark-coloured and the light-coloured aggregates in quartzite?

And we found that as we increased the proportion of shale in the total aggregate sand and stone, the shrinkage increased. And when we looked at the two aggregates, in fact, the shale has a higher elastic modulus than the quartzite. Both parallel and normal to the bedding planes. Shale is, of course, a very layered material. It has a slightly higher relative density than the quartzite.

But the significant difference was in the water absorption. And in fact, it correlated quite well when we looked at the effect of water absorption. Our conclusion was that it was the increased water absorption of the aggregate. And remember, we started with dry aggregates. That resulted in this increased shrinkage behaviour when shale was added into the total aggregate.

This, of course, is a feature that is going to be important when you consider recycled aggregates because the adhering cement paste in construction rubble that is used as aggregate will, of course, absorb more water as well. And so it is an issue to keep in mind. So to conclude, here are some of the important points to emerge from this lecture. Aggregate size, shape, and grading distribution have a very large effect on the fresh properties of concrete. They influence workability, water requirements, cement content, and the cost of the concrete as a result.

The quality of the aggregate-to-cement paste interface, or what we refer to as the interfacial transition zone, influences the hardened properties of concrete quite significantly. And then lastly, the geological type of aggregate, its surface texture, its density, strength, dimensional stability, and water absorption capacity will all have an effect on the strength and deformation properties of concrete, which, of course, structural engineers are very interested in. Thank you very much for your attention. Thank you.