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# Mechanical Properties of the Interfacial Transition Zone: A Review

by S. Mindess

**Synopsis**; The mechanical properties of the cement-aggregate bond are reviewed, with particular reference to the inherent difficulties in determining these properties. The properties that are determined experimentally appear to be largely artifacts of the specimen preparation and the test procedures. In particular, bleeding effects, the roughness of the rock surface, and the heterogeneity of the interfacial region make it very difficult to compare experimental results amongst the different investigations that are found in the literature. It is concluded that we are still far from being able to make useful measurements of the properties of the cement-aggregate interfacial zone. We cannot, therefore, yet try to control the properties of concrete by systematically altering the nature of the interfacial region.

Keywords: Aggregates; bleeding (concrete); bonding; cements; fracture properties; hardness; interface; mechanical properties; specimens; strength; toughness

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## INTRODUCTION

It is now commonplace to consider concrete as a material consisting of three phases: the hardened cement paste (hcp), the aggregate, and the interfacial transition zone (ITZ) between the hcp and the aggregate particles. In fact, of course, there are a number of other interfaces within modern concrete, including those between

i) the various phases in the hcp
ii) the hcp and anhydrous cement grains
iii) the hcp and pozzolanic additions or mineral fillers.

All of these interfaces are important in determining the mechanical properties of the concrete. This is particularly the case as we move from normal strength concrete, in which the properties of the hcp largely control the concrete properties, to high strength concrete, in which the composite behaviour of the concrete must be considered.

Clearly, the strength of concrete must depend upon the intrinsic strength of the hcp (and possibly of the aggregate), and upon the strength of the bond between the hcp and the aggregate. Unfortunately, it has so far not been possible to determine, in a meaningful way, the bond strengths between the various phases in concrete, and consequently it has not been possible to quantify the effect of the properties of the ITZ on the properties of concrete.

It is generally assumed that the ITZ is the "weak link" in normal strength concrete. Thus, the focus of this review is on the ITZ, and in particular, on the difficulties that arise when trying to measure its mechanical properties. Unfortunately, there are no test methods specified in any national standards dealing with the properties (or even the extent) of the ITZ, and so one is left with trying to draw conclusions from the disparate collection of experimental studies that have been reported in the literature. Since there has been virtually no work at all on the other interfaces mentioned above, they will not be discussed in this review.

## HOW DO THE PROPERTIES OF THE ITZ AFFECT THE MECHANICAL PROPERTIES OF CONCRETE?

For the purposes of this review, the precise nature of the composition and morphology of the ITZ is not very important; what we know of this zone has, in any event, been reviewed extensively in recent years (e.g. 1-9). It is sufficient to note that the thickness of the ITZ is generally taken to be about 50 μm, with the major differences from the bulk hcp occurring within about the first 20 μm from the physical interface. We must also recognize the extent of the ITZ. While it is only 50 μm thick, Diamond et al. (10) have shown that, in normal concrete, the average minimum spacing between adjacent aggregate particles is only about 75-100 μm. Thus, a relatively large proportion of the hcp lies within the ITZ.

While it is generally accepted that increasing the cement-aggregate bond strength will lead to an increase in the concrete strength, the experimental evidence for this is not consistent. A number of studies have shown that, in going from "no bond" to "perfect bond" (insofar as either case can be simulated experimentally) strength increases have been in the range of 15% to 40%, with increases in tensile or flexural strength being higher than the increases in compressive strength. For instance, Alexander and Toplin (11,12), based on a regression analysis of the data then available to them, developed a relationship of the form

$$\sigma = b_0 + b_1 m_1 + b_2 m_2$$

where $\sigma$ = concrete strength (compression or flexure)
$b_0, b_1, b_2$ = linear regression coefficients
= 480, 2.08, 1.02, respectively, for compression
= 290, 0.318, 0.162, respectively, for flexure
$m_1, m_2$ = flexural strength of the paste and of the cement-aggregate bond, respectively,

From these regression coefficients, it may be seen that a change in the strength of the paste has about twice as much effect in the concrete strength as does a change in the bond strength. Similar results were reported by Darwin and Slate (13).

Other investigations, however, have yielded different results. For instance, Chen and Wang (14) showed that an improvement in cement-aggregate bond strength would significantly increase the tensile strength, and to a lesser extent the compressive strength, of concrete. Similar results were obtained by Wu et al. (15) and Wu and Zhan (16). One can only assume that the differences between these results and those referred to above (11-13) are due to differences in test techniques.

Results of numerical simulations (17) have also shown that changing the bond strength should increase the tensile and flexural strengths, but should have little effect on the compressive strength. On the other hand, a numerical study by Schlangen and van Mier (18) showed that "the specimen strength is mainly governed by the matrix strength". Thus, "numerical" concrete appears to be at least as inconsistent with regard to bond strength as does "real" concrete!

## RELATIONSHIP BETWEEN SPECIMEN PREPARATION AND MEASUREMENT OF INTERFACIAL MECHANICAL PROPERTIES

The inconsistencies in the effects of bond strength on the mechanical properties of concrete appear to be due to inconsistencies in the measurements of the properties of the ITZ or of the cement-aggregate bond. There are a number of reasons for this:

1. It is not possible to make direct tests of the strength of the material in the ITZ, because it is not possible to isolate this material, which is only about 50 μm thick. Moreover, the ITZ is itself variable in its composition, and thus its mechanical properties must also vary from point to point, as shown by the microhardness data that have been reported (19-20). These data indicate that the weakest part of the ITZ lies about 20 μm from the aggregate surface.

2. Because of bleeding effects, water tends to be trapped at the undersides of large aggregate particles. Thus, the ITZ will vary in the general case, from the top to the bottom of a coarse aggregate particle.

3. The bond between the aggregate and the cement must depend upon the roughness of the aggregate surface. Different investigations have prepared the aggregate surface in various ways, ranging from a "mirror-like" finish (21) to the rather rough fracture surface of rock (22). These different surface finishes will clearly lead to very

different measurements of bond, and perhaps to different morphologies of the ITZ.

4. Most studies of the ITZ involve specimens specially prepared by casting cement against a rock surface. However, such interfaces are quite different from those which occur in conventional concrete, where there is relative movement between the cement grains and the aggregate particles during mixing.

5. As has been shown clearly by Odler and Zurz (21), different cement/rock systems exhibit different failure mechanisms, with failure occurring either right at the interface, or at various distances from the interface, depending on the aggregate.

## DISCUSSION AND CONCLUSIONS

From these observations, it is clear that we are still unable to measure the properties of the ITZ, or of the cement-aggregate bond, in a reproducible and unambiguous manner. There is no standard test specimen or test method. Indeed, to the author's knowledge virtually no two studies of the transition zone have been truly comparable, because of differences in the test procedure.

Moreover, it is also still not clear whether it is the actual cement-aggregate bond, or the strength and density of the entire 50 μm thick ITZ, which must be modified in order to improve concrete strength. Since it is apparently not possible to alter one without altering the other, this question is perhaps only of philosophical interest, but it does illustrate the complexity of the problem.

It is, of course, well known that densification of the ITZ, generally by the incorporation of fine mineral fillers such as silica fume, can lead to significant increases in concrete strength. However, it would appear that we are still very far from being able to alter the properties of concrete in a predictable way by modifying the properties of the ITZ.

In order for us to determine, in a systematic way, the effects of the interface on concrete properties, we need to develop a standardized test procedure, which would address the following questions:

1. What sort of specimen geometry and type of test do we use?
2. How is the aggregate surface prepared?

3. How are bleeding effects controlled?
4. How are the experimental results analyzed?

As pointed out above, there is still no agreement on answers to these questions. New specimen geometries and test methods are still being developed; of these, the push-out test recently described by Mitsui et al. (23) looks quite promising, but much further work with this and other test procedures is required before a standard can be developed.

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## REFERENCES

1. Diamond, S., The Microstructure of Cement Paste in Concrete, in 8th International Congress on the Chemistry of Cement, V. I, Finep, Rio de Janeiro, Brazil, 1986, pp. 122-147.

2. Massazza, F. and Costa, U., Bond: Paste-Aggregate, Paste-Reinforcement and Paste-Fibres, in 8th International Congress on the Chemistry of Cement, V. I, Finep, Rio de Janeiro, Brazil, 1986, pp. 158-180.

3. Mehta, P.K. and Monteiro, P.J.M., Effect of the Aggregate, Cement and Mineral Admixtures on the Microstructure of the Transition Zone, in Mindess, S. and Shah, S.P. (eds.), Bonding in Cementitious Composites, Materials Research Society Symposia, Proceedings, V. 114, Materials Research Society, Pittsburgh, 1988, pp. 65-75.

4. Scrivener, K.L., Crumbie, A.K. and Pratt, P.L., A Study of the Interfacial Region Between Cement Paste and Concrete, in Mindess, S. and Shah, S.P. (eds.), Bonding in Cementitious Composites, Materials Research Society Symposia, Proceedings, V. 114, Materials Research Society, Pittsburgh, 1988, pp. 87-89.

5. Bentur, A., Microstructure, Interfacial Effects, and Micromechanics of Cementitious Composites, in Mindess, S. (ed.), Advances in Cementitious Materials, American Ceramic Society, 1991, pp. 523-550.

6. Scrivener, K.L., Bentur, A. and Pratt, P.L., Quantitative Characterization of the Transition Zone in High Strength Concretes, Advances in Cement Research, V. 1, No. 4, 1988, pp. 230-237.

7. Scrivener, K.L. and Gartner, E.M., Microstructural Gradients in Cement Paste Around Aggregate Particles, in Mindess, S. and Shah, S.P. (eds.), Bonding in Cementitious Composites, Materials Research Society Symposia, Proceedings, V. 114, Materials Research Society, Pittsburgh, 1988, pp. 77-85.

8. Zhang, M.H. and Gjorv, O.E., Microstructure of the Interfacial Zone Between Lightweight Aggregate and Cement Paste, Cement and Concrete Research, V. 20, No. 4, 1990, pp. 610-618.

9. Bentz, D.P., Garboczi, J. and Stutzman, P.E., Computer Modelling of the Interfacial Zone in Concrete, in Interfaces in Cementitious Composites, Proceedings of the RILEM International Conference, E & FN SPON, 1992, pp. 107-116.

10. Diamond, S., Mindess, S. and Lovell, J., On the Spacing Between Aggregate Grains and the Dimensions of the Aureole de Transition, in Liaisons Pates de Ciment Materiaux Associes, Proceedings, RILEM Colloquium, Toulouse, France, 1982, pp. C42-C46.

11. Alexander, K.M. and Taplin, J.H., Concrete Strength, Paste Strength, Cement Hydration and Maturity Rule, Australian Journal of Applied Science, V. 13, No. 4, 1962, pp. 277-284.

12. Alexander, K.M. and Taplin, J.H., Analysis of the Strength of Fracture of Concrete Based on Unusual Sensitivity of Cement-Aggregate Bond to Curing Temperature, Australian Journal of Applied Science, V. 15, No. 32, 1964, pp. 160-170.

13. Darwin, D. and Slate, F.O., Effect of Paste-Aggregate Bond Strength on Behaviour of Concrete, ASTM Journal of Materials, V. 5, No. 1, 1970, pp. 86-98.

14. Chen, Z.Y. and Wang, J.G., Effect of Bond Strength Between Aggregate and Cement Paste on the Mechanical Behaviour of Concrete, in Mindess, S. and Shah, S.P. (eds.), Bonding in Cementitious Composites, Materials Research Society Symposia, Proceedings, V. 114, Materials Research Society, Pittsburgh, 1988, pp. 41-47.

15. Wu, X., Li, D., Wu, X. and Tang, M., Modification of the Interfacial Zone Between Aggregate and Cement Paste, in Mindess, S. and Shah, S.P. (eds.), Bonding in Cementitious Composites, Materials Research Society Symposia, Proceedings, V. 114, Materials Research Society, Pittsburgh, 1988, pp. 35-40.

16. Wu, K. and Zhou, J., The Influence of the Matrix-Aggregate Bond on the Strength and Brittleness of Concrete, in Mindess, S. and Shah, S.P. (eds.), Bonding in Cementitious Composites, Materials Research Society Symposia, Proceedings, V. 114, Materials Research Society, Pittsburgh, 1988, pp. 29-34.

17. Schorn, H., Numerical Simulation of Altering Mechanical Properties of Concrete due to Material Behaviour of the Interfaces, in J.C. Maso (ed.), Interfaces in Cementitious Composites, E & FN SPON, 1992, pp. 159-168.

18. Schlangen, E. and van Mier, J.G.M., Numerical Study of the Influence of Interfacial Properties on the Mechanical Behaviour of Cement-Based Composites, in J.C. Maso (ed.), Interfaces in Cementitious Composites, E & FN SPON, 1992, pp. 237-246.

19. Lyubimova, T. Yu. and Pinus, E.R., Crystallization Structure in the Contact Zone Between Aggregate and Cement in Concrete, Kolloidniyi Zhurnal (USSR), V. 24, No. 5, 1962, pp. 578-587.

20. Mehta, P.K. and Monteiro, P.J.M., Effect of the Aggregate, Cement and Mineral Admixtures on the Microstructure of the Transition Zone, in Mindess, S. and Shah, S.P. (eds.), Bonding in Cementitious Composites, Materials Research Society Symposia, Proceedings, V. 114, Materials Research Society, Pittsburgh, 1988, pp. 65-75.

21. Odler, I. and Zurz, A., Structure and Bond Strength of Cement-Aggregate Interfaces, in Mindess, S. and Shah, S.P. (eds.), Bonding in Cementitious Composites, Materials Research Society Symposia, Proceedings, V. 114, Materials Research Society, Pittsburgh, 1988, pp. 21-27.

22. Alexander, M.G., Mindess, S. and Qu, L., The Influence of Rock and Cement Types on the Fracture Properties of the Interfacial Zone, in J.C. Maso (ed.), Interfaces in Cementitious Composites, E & FN SPON, 1992, pp. 129-137.

23. Mitsui, K., Li, Z., Lange, D.A. and Shah, S.P., Relationship Between Microstructural and Mechanical Properties of the Paste-Aggregate Interface, ACI Materials Journal, V. 91, No. 1, 1994, pp. 30-39.

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# Softening Slip and Size Effect in Bond Fracture

by Z. P. Bažant and R. Desmorat

SYNOPSIS: The size effect caused by post-peak softening in the relation of interface shear stress and slip displacement between a fiber or reinforcing bar and the surrounding matrix, is analyzed. The problem is simplified as one-dimensional. It is shown that the post-peak softening leads to localization of slip. The larger the bar or fiber size, the stronger the localization. The size effect in geometrically similar pullout tests of different sizes is found to represent a transition from the case of no size effect for small sizes to the case of a size effect of the same type as in linear elastic fracture mechanics, in which the difference of the pullout stress in the fiber and the residual pullout stress corresponding to the residual interface shear stress is proportional to the inverse square root of bar or fiber size. An analytical expression for the transitional size effect is obtained and is found to approximately agree with the generalized form of the size effect law proposed earlier by Bažant. Measurements of the size effect can be used for identifying the interface properties.

Keywords: Bonding; composite materials; damage; fiber reinforced concretes; fibers (discreet fibers); fracture properties; size effect