Concrete in Compression

by David Darwin

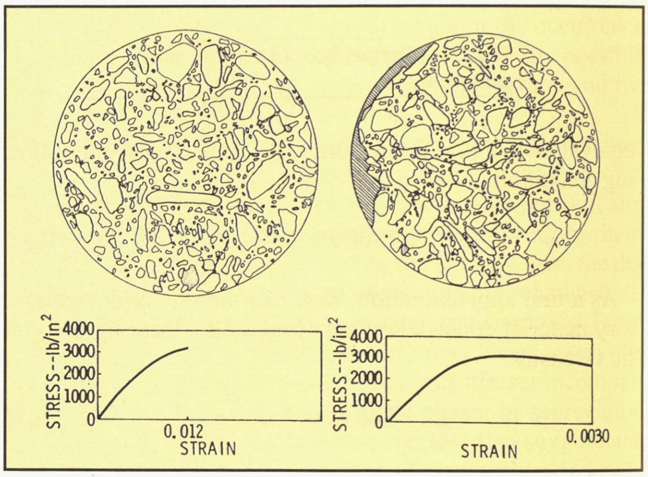

Fig. 1 — Cracking maps and stress-strain curves for concrete in loaded uniaxial compression.[5]

One hundred years ago, engineers were debating whether density, aggregate gradation, or water-cement ratio controls the strength of concrete. Today, those debates have been settled, but the factors that control the behavior of concrete in compression remain controversial. The debate has now shifted to the roles played by cement paste, the interfacial transition zone between paste and aggregate, and the relative stiffness of the components. While all three ingredients play significant roles, the properties of cement paste and the heterogeneous nature of the material appear to be the key factors in the response of concrete in compression.

This article highlights some of the research that demonstrates the roles played by the various constituents, with emphasis on microcracking, interfacial bond strength, and models of concrete. The reader is directed to Reference 1 for a more complete discussion of the subject.

Microcracking

Prior to the pioneering microcracking studies at Cornell University in the early 1960s, the reasons why concrete responds in a nonlinear fashion in compression were not clear.[2-5] The material consists of cement paste and aggregate, both of which, it was believed, behave as linear elastic brittle materials in compression. As illustrated in Fig. 1, the studies showed that microcracks (observable with a light microscope) exist around coarse aggregate particles prior to loading. With the application of compressive stress, these bond microcracks remain stable until the compressive stress reaches about 30 percent of the ultimate value. At higher stresses, bond microcracking increases until about 70 percent of ultimate, at which point microcracks move into the mortar, connecting the coarse aggregate particles, while bond cracks continue to increase. The rate of microcracking progresses at an increasing rate up to and past the strain corresponding to the peak stress. The early studies demonstrated that a nearly linear relationship exists between the applied compressive strain and the total amount of microcracking.

Interfacial bond strength

During these early studies, microcracking appeared to provide a clear answer as to why concrete has a nonlinear stress-strain curve. With the preponderance of bond cracking, it seemed clear that interfacial bond strength between cement paste and aggregate must play an important role in concrete behavior. This conclusion led to the development of a number of tests in which the bond strength between coarse aggregate and cement paste was modified, with the goal of observing the effects on concrete strength. First, coarse aggregate particles were coated with soft coating materials to produce a reduction in bond strength. As expected, the resulting concrete strength was reduced significantly.[6,7] Unfortunately, the soft materials had the undesired effect of isolating the coarse aggregate from the surrounding cement paste — causing the coarse aggregate to look more like holes than a solid constituent. Thus, the use of soft coatings proved to be inadequate as an experimental tool for measuring the effects of interfacial bond strength.

The soft coatings were then replaced by hard coatings that significantly reduced interfacial bond strength but did not substantially reduce the effective stiffness of the aggregate particles.[8] When these coatings were used, substantial differences in concrete behavior were also expected. However, as shown in Fig. 2, the initial stiffness of the concrete was unaffected and compressive strength was reduced only about 10 percent, indicating that interfacial bond strength plays a measurable but not dominant role in the behavior of concrete in compression.

Models for concrete

If interfacial bond strength does not play the dominant role in the nonlinear behavior of concrete, the question arises — what aspect of concrete response causes the nonlinear stress-strain relationship that is so well known for this material? This question can be partially answered by observing the extent to which the constituents of concrete behave in a manner that is similar to that of the full composite. Fig. 3 compares the stress-strain curves of concrete, mortar, and cement paste with a water-cementitious material ratio *(w/cm)* of 0.5.[9] The sand-cement ratios of the concrete and mortar are identical. As demonstrated in Fig. 3, when mortar is loaded in compression, it has a somewhat higher compressive strength and a little more ductility than concrete but, otherwise, possesses a similar stress-strain curve. Thus, mortar can be considered a good model for concrete. The differences in the behavior of the two materials, however, provide useful information.

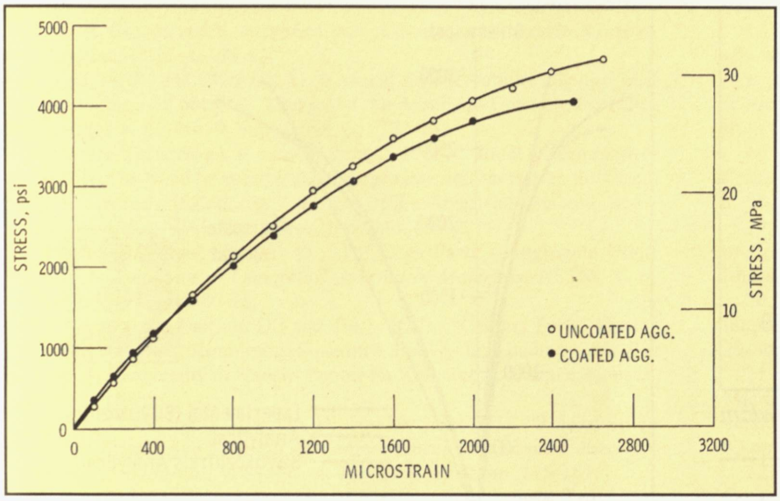

Fig. 2 — Stress-strain curves for concrete as influenced by coating aggregates.[8]

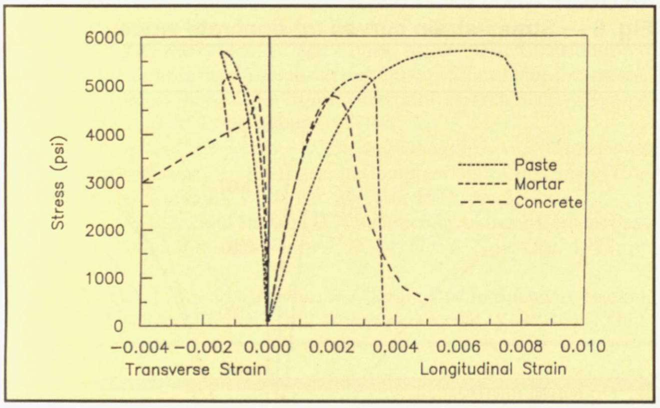

Fig. 3 — Stress-strain curves for concrete, mortar, and cement paste with a *w/cm* of 0.5.[9]

If mortars and matching concretes are tested in compression, the combined effects of interfacial bond strength and the heterogeneity caused by the coarse aggregate can be measured. Fig. 4 shows the results for a series of mortars and concretes cast using two different *w/cm* and tested at ages of three, seven, and 28 days.[10] The materials differ in that one-third of the test specimens contain no admixtures, one-third contain superplasticizer, and one-third contain both superplasticizer and silica fume. It is well known that silica fume increases the strength and density of the interfacial transition zone, as well as the bond strength between cement paste and aggregate.[11-13] Fig. 4 compares ratios of concrete strength to mortar strength as a function of mortar strength. The ratios range from 74 to 61 percent, dropping as mortar strength increases. At three days, the mortars containing silica fume exhibit lower strengths than the corresponding mortars without silica fume, while at seven and 28 days, the mortars containing silica fume exhibit the highest strengths. The key observation, however, is that the results fall in a relatively narrow band, independent of the use of silica fume or superplasticizer, indicating that any increase in interfacial bond strength provided by silica fume has little measurable effect on the compressive strength of the concrete. In fact, for tests at seven and 28 days, the materials containing silica fume exhibit the lowest ratio of concrete to mortar strength.

Going back to Fig. 3, it can be concluded that most of the nonlinear behavior of concrete can be ascribed to its mortar constituent. But now the question arises as to what causes mortar to be nonlinear. The answer lies in the cement paste, a material that exhibits neither bond nor mortar microcracking. As shown in Fig. 3 and even more clearly in Fig. 5, cement paste is not a linear-elastic material, but a highly nonlinear material in its own right.[9,14] It is a material that, at the same *w/cm,* is generally stronger in compression than either mortar or concrete and has a significantly greater strain capacity than either of the materials containing aggregate. The lower strength of mortar and concrete results from stress concentrations induced in the cement paste constituent of these materials due to differences in elastic properties of aggregate and paste. Failure of the paste-aggregate interface also contributes, but to a lesser degree.

As with concrete, the nonlinear behavior of cement paste can be tied to microcracking, but microcracking that requires a scanning electron microscope, rather than a light microscope, to be observed. As demonstrated in several studies, the density of these microcracks is two orders of magnitude greater than that of the bond and mortar microcracks observed in concrete.[15-18]

Qualitatively, however, the microcracks in cement paste are much like the microcracks in concrete. In cement paste, microcracks form principally in the lower density phases (calcium silicate hydrate) adjacent to or between the harder phases (unhydrated cement particles and calcium hydroxide), behavior on the microscopic level that matches the larger microcracks in concrete.[17-18]

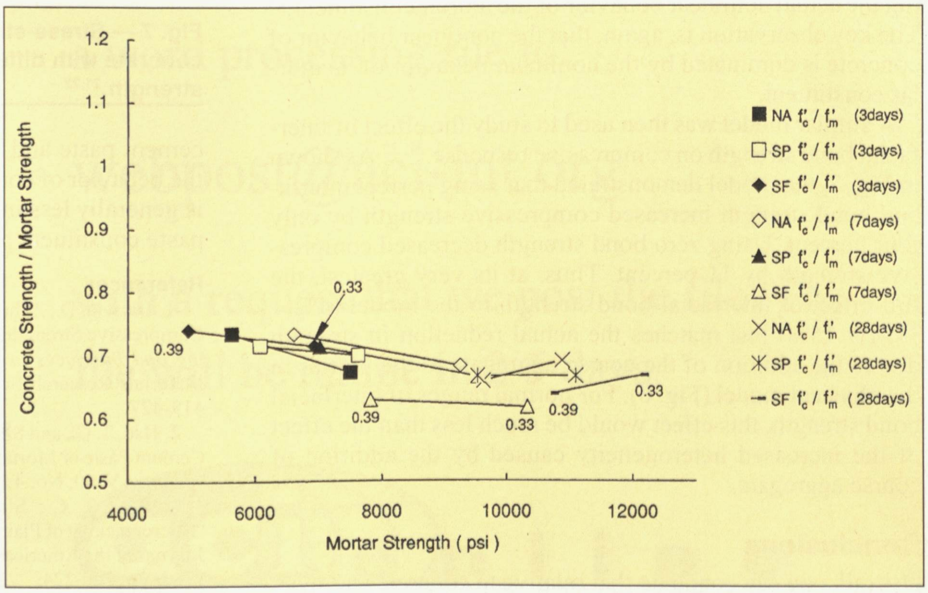

Fig. 4 — Ratios of concrete strength *(f_c')* to mortar strength *(f_m')* as a function of mortar strength (NA = no admixtures; SP = superplasticizer; SF = superplasticizer and silica fume).[10]

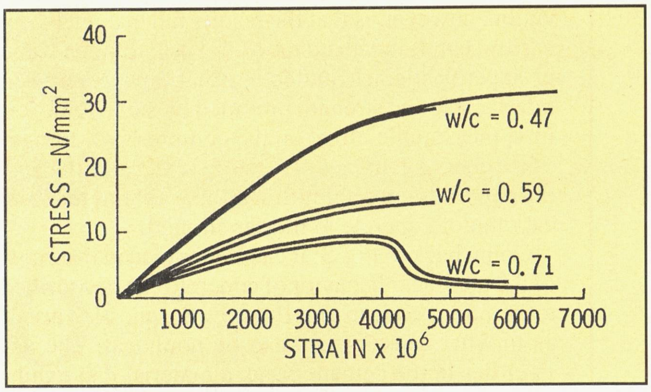

Fig. 5 — Stress-strain curves for cement pastes with *w/cm* of 0.47 to 0.71.[14]

Finite element studies

Experimental studies to evaluate the contributions made by interfacial bond strength and paste strength suffer from the disadvantage that it is rarely possible to change only one property of concrete. For example, the addition of silica fume increases both interfacial and paste strength. One of the principal advantages of finite element analysis lies in the fact that one property can be changed at a time. An excellent example of the application of the procedure involves a physical model of concrete.[19] The two-dimensional model consisted of nine cored aggregate cylinders imbedded in a mortar matrix (Fig. 6). The compressive strength of the physical model was about 85 percent of the compressive strength of its mortar constituent. The physical model behaved in a nonlinear fashion (solid curve in Fig. 6) and exhibited microcracking (observed using x-rays) at the interface and through the mortar constituent. In the initial finite element studies of the model, an attempt was made to match the nonlinear stress-strain curve using bond and mortar microcracking as the only nonlinear behavior.[19] As shown in Fig. 6, a match could not be obtained, and the resulting stress-strain curve exhibited little deviation from a linear response. Also as shown in Fig. 6, a later finite element study successfully matched the experimental behavior by modeling the actual nonlinear behavior of the mortar constituent.[20] The key observation is, again, that the nonlinear behavior of concrete is dominated by the nonlinear behavior of its mortar constituent.

A similar model was then used to study the effect of interfacial bond strength on compressive response.[21,22] As shown in Fig. 7, the model demonstrated that using perfect interfacial bond strength increased compressive strength by only four percent. Using zero bond strength decreased compressive strength by 11 percent. Thus, at its very greatest, the full effect of interfacial bond strength in the model (4% + 11% = 15%) just matches the actual reduction in strength due to the addition of the coarse aggregate to the mortar in the physical model (Fig. 6). For normal ranges of interfacial bond strength, this effect would be much less than the effect of the increased heterogeneity caused by the addition of coarse aggregate.

Conclusions

Overall, one can conclude that relative to concrete and mortar, cement paste is a stronger, more ductile material in compression, and that the addition of aggregate tends to reduce both strength and strain capacity. The bond strength between cement paste and aggregate also plays a significant role in the behavior of concrete in compression. However, its effect is generally less important than the properties of the cement paste constituent and heterogeneous nature of the material.

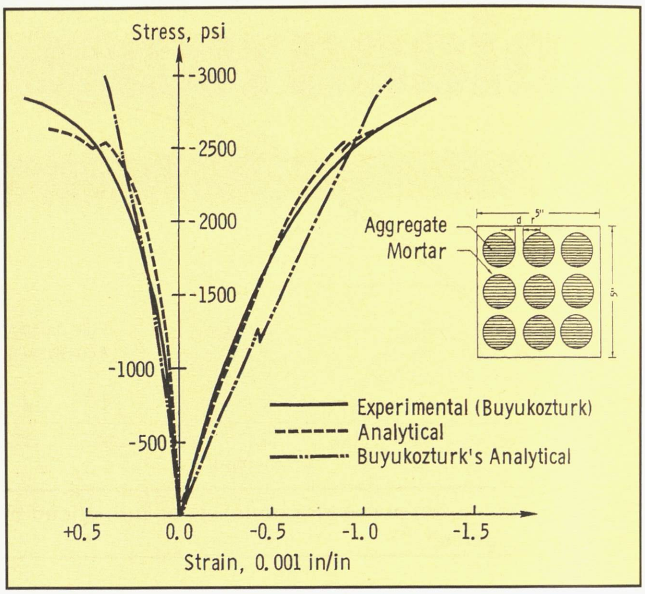

Fig. 6 — Stress-strain curves for concrete model.[20]

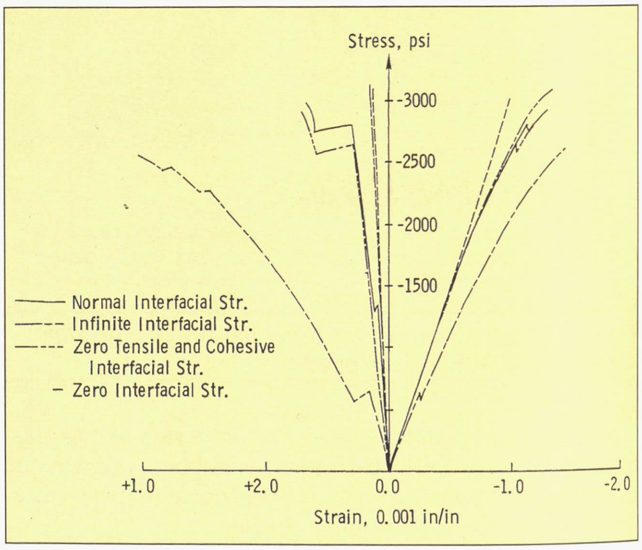

Fig. 7 — Stress-strain curves for finite element models of concrete with different values of mortar-aggregate bond strength.[21,22]

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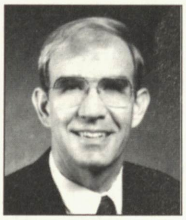

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