in this typical example that it takes much more deformation and substantial energy to fail a lower strength mixture when compared to a higher strength mixture. A lower ultimate modulus is associated with more deformation before cracking. In a cracking analysis, it is the ultimate condition that should be studied, not just the elastic condition. As the mix becomes stronger, the elastic modulus and ultimate modulus approach the same value, so it is not as important with those types of concrete. With low strength mixtures, use of the elastic modulus alone in a cracking analysis can be extraordinarily overconservative, by many orders of magnitude. Initial work has indicated that the ultimate modulus from compression testing is a reasonable indicator of the modulus value that can be used for tensile cracking analyses. Additional work to verify this is underway.

Figures 6 and 7 indicate the overall relationship between compressive strength and elastic modulus for a multitude of different mixtures at the San Rafael and Big Haynes projects respectively. They include results at ages ranging from 3 days to 1 year. The San Rafael project used a range of cementitious content from 60 to 200 kg/m^3 with a constant pozzolan content of 20%. The Big Haynes mixtures used different cement, pozzolan, and aggregates. They also included pozzolan contents ranging from 0% to 50%, and total cementitious contents ranging from 59 to 133 kg/m^3, and some mixtures with different admixtures.

It is clear from these graphs that the elastic modulus decreases dramatically at compressive strengths below about 10 MPa, and that it is fairly constant above that level of strength.

Figures 8 and 9 show the relationship between the ultimate modulus and compressive strength for the same respective projects and broad range of mixtures. The San Rafael data for ultimate modulus includes data from two different labs. The mixtures and tests were supervised by the same person, but the work was done by totally different people who were new to the ultimate modulus. It is clear from the results that the test can be done with confidence as a standard.

The difference in scale between the graphs showing elastic modulus and those showing ultimate modulus should be pointed out. At lower strengths, on the order of 5 MPa, the ultimate modulus is generally about one tenth of the value of the elastic modulus. As the strength increases, the ultimate modulus gets closer to the elastic modulus. Data not included in this paper indicates that the values are essentially the same for very high strength concrete. A large difference between elastic and ultimate modulus indicates an inherent toughness and improvement in ultimate strain capacity. The test provides a method of evaluating this very desirable property when selecting a mix for a project where toughness and ultimate crack resistance are important.

Another useful tool to help better understand how the elastic and ultimate modulus are effected by strength is to look at the ratio of modulus to compressive strength as a function of strength. This is shown in Figures 10 and 11 for the San Rafael mixtures. The scatter of data in the elastic modulus for the strength level from about 2 to 10 MPa has been observed at other projects. The peculiar higher average ratio of elastic modulus to compressive strength within this stress level as compared to higher strength concretes is also typical. Figure 11 shows that the large scatter of data is not present for the ultimate modulus test. It is easier to determine and reproduce than the elastic modulus.

CREEP

A dramatic increase in stress relief due to creep is also associated with low strength concretes. Creep essentially has the effect of further reducing the sustained modulus over time. In addition to the benefits from decreased initial elastic and ultimate moduli, creep has the effect of further reducing the modulus, referred to as a sustained modulus. In low strength mixtures it can significantly reduce the long term potential for cracking. Figures 12 and 13 demonstrate the radical increase in creep when the strength at the time of loading is below about 15 MPa. As shown on the Figures, this relationship appears to be independent of pozzolan content, whether the mixture is conventional or roller compacted, or the age at the time of loading. Data for these figures comes from mixtures with a wide range of cementitious contents, pozzolans ranging from 0% to 70% of the cementitious content, and ages of loading from 7 to 180 days.

INDIRECT TENSION TESTING

Direct tension testing is difficult and expensive. An indirect way to get an indication of the direct tensile strength of concrete is through the splitting tension test (ASTM C 496), sometimes referred to as the Brazilian test. A core or standard cylinder is laid on its side in a compression machine and loaded until it breaks. Failure occurs by splitting down the middle of the specimen due to indirect tensile stresses.

The splitting tensile strength increase with age similar to what can be expected with compressive strength. Figure 14 shows the relationship between age and splitting tensile strength for relatively low strength mixtures having a cementitious content of 89 kg/m^3, with pozzolan contents ranging from 0% to 50%. Figure 15 shows the relationship for the same aggregates but with mixtures having no pozzolan and a range of cement contents from 59 to 133 kg/m^3.

Figures 16 shows the relationship between splitting tensile strength and compressive strength for these particular materials. Figures 17 and 18 show the ratio of the splitting tensile strength to compressive strength as a function of the compressive strength for the San Rafael and Big Haynes projects respectively. The shape of the curve, or relationship of the ratio to compressive strength has been similar for the many projects that the author has investigated. For practical purposes the ratio is fairly constant within the normal range of strengths that are typically experienced during the service life for any particular mixture. However, when the broad spectrum is investigated, the relationship varies as indicated in Figures 17 and 18.

More importantly, the ratio can be very different from project to project. The tendency is for higher strength mixtures to have splitting tensile strengths that are a lower percentage of the compressive strength. However, a trend is not being shown here because of exceptions. To demonstrate how much the ratio of split tension to compressive strength can vary from project to project, the following examples are offered for some typical RCC projects: Upper Stillwater 4%-7%, Willow Creek 7%-12%, Monksville 9%-13%, San Rafael 10%-16%, Urugua-I 10%-18%, Concepcion 12%-17%, Big Haynes 12%-18%, and Middle Fork 13%-18%.

Probably the most important aspect of using splitting cylinder strengths to determine probable direct tensile strengths is the generally unknown fact that the ratio of split tensile strength to direct tensile strength decreases significantly for low strength mixtures. At the normal strength level of about 25 to 50 MPa, the conversion factor is close to 1, or unity, so it is noticed in those situations. Figure 19 has been developed by the author based on an accumulation of test data from different projects. The ratio of splitting tensile/direct tensile strength is a logarithmic function of the compressive strength. The author has found a similar relationship between the flexural strength or modulus of rupture and direct tensile strength. Figure 19 also indicates this relationship as a function of compressive strength.

When the adjusting factor is applied to split cylinder strengths, and the resulting direct tensile strength calculated from appropriate factors, it typically plots as a straight line function of compressive strength as indicated Figure 20. This agrees with results from direct tensile tests, at least within the range of about 0 to 20 MPa.

CONCLUSIONS

Low strength concretes can have significantly more crack resistance than indicated by using the elastic modulus as determined in compression tests. An indication of how resistant the concrete will be to cracking, and its ultimate tensile strain capacity can be obtained by continuing the stress-strain test to failure, and calculating the "ultimate modulus."

Low strength RCC mixtures can be designed to have extremely low ultimate modulus values, as well as low elastic modulus values.

The crack resistance of low strength concretes is also improved by dramatic increases in creep, which further reduce the effective sustained modulus and relax internal stresses.

The split cylinder indirect tensile test is a useful tool for easily obtaining an indication of direct tensile strength. Special care and adjustment factors are needed when converting the split tensile strength to direct tensile strength. This is particularly important at lower strengths.

ACKNOWLEDGEMENTS

The data used in this article was developed from a variety of projects, involving a number of organizations. Among those who should be recognized are the Federal Electric Commission of Mexico, Jordan Jones and Goulding, ATEC, Bechtel, CONCIL, and the North Pacific Division Lab of the U. S. Army Corps of Engineers.

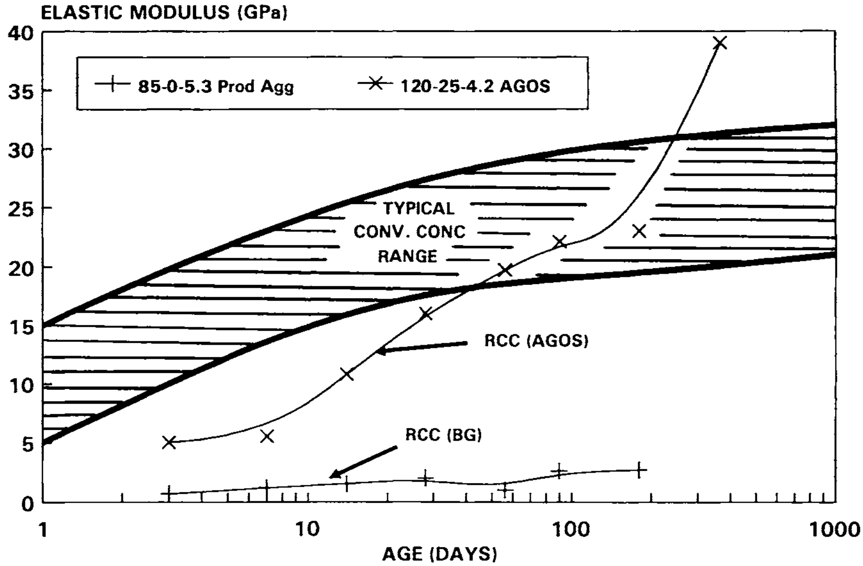

Fig. 1—Sample modulus of elasticity for different concrete mixes

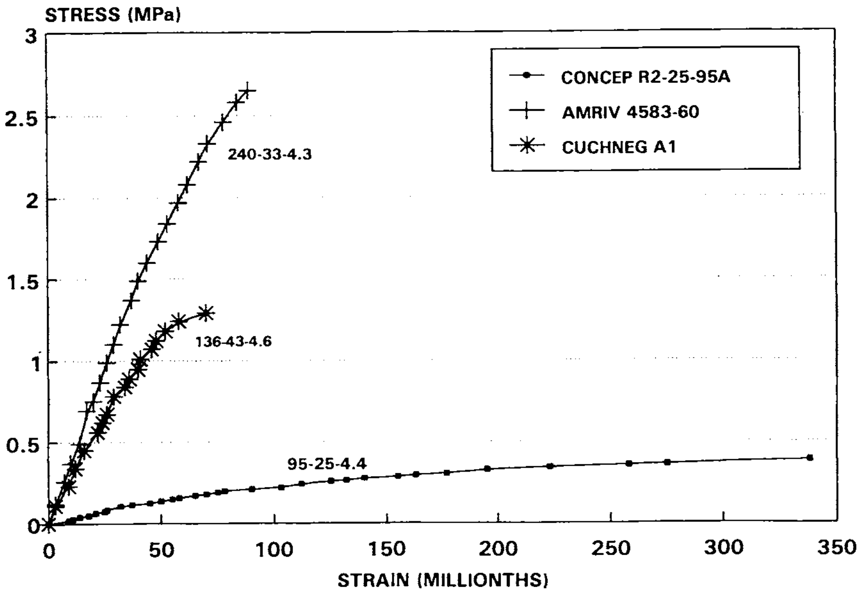

Fig. 2—RCC tensile strain capacities

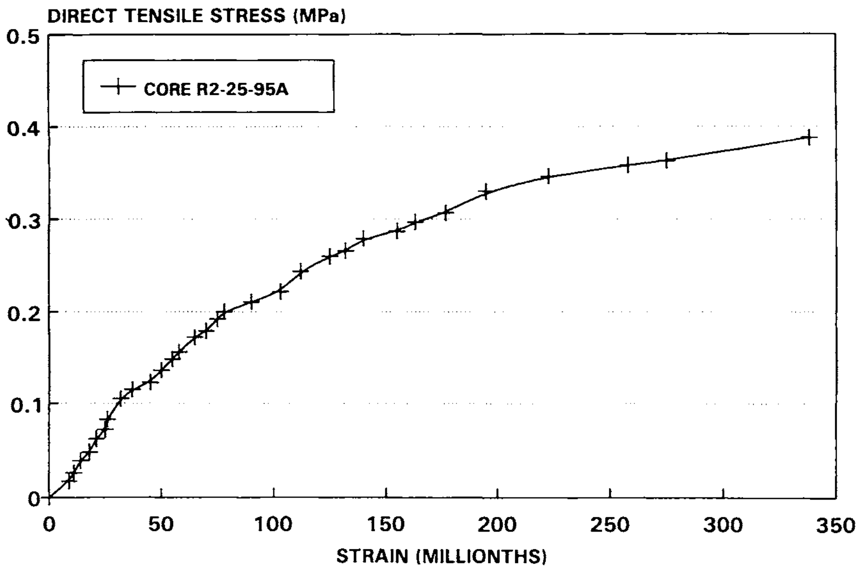

Fig. 3—Tensile strain capacity of low-strength RCC

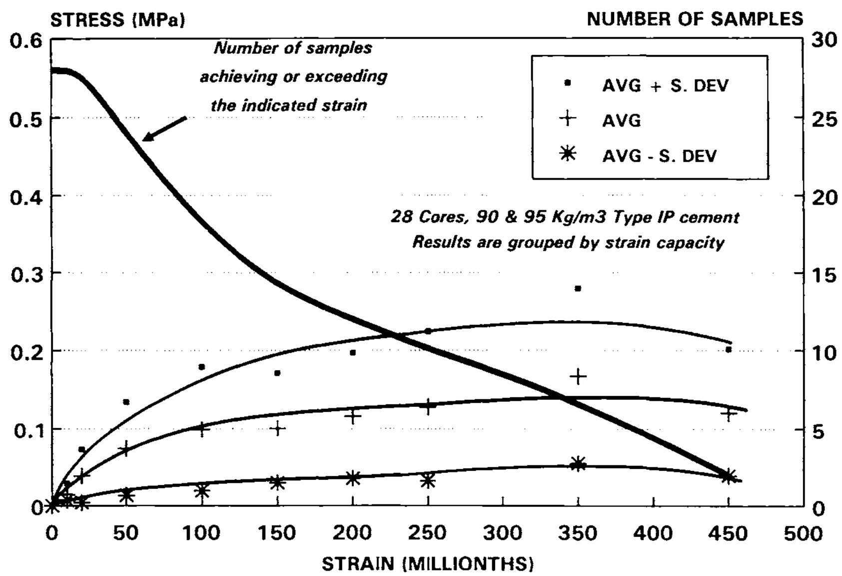

Fig. 4—Summary of Concepcion Dam tensile stress-strain cores

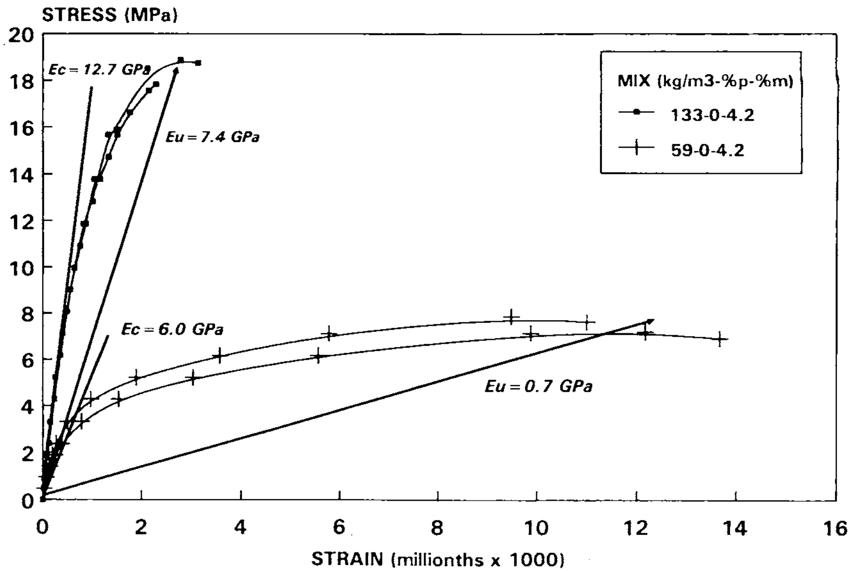

Fig. 5—Compressive stress-strain curves with elastic and ultimate moduli

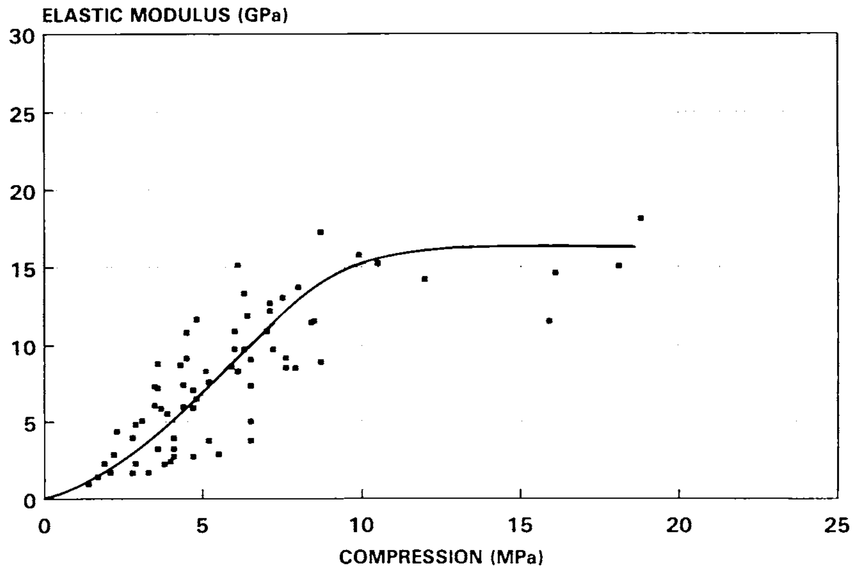

Fig. 6—Elastic modulus versus compression, San Rafael Project

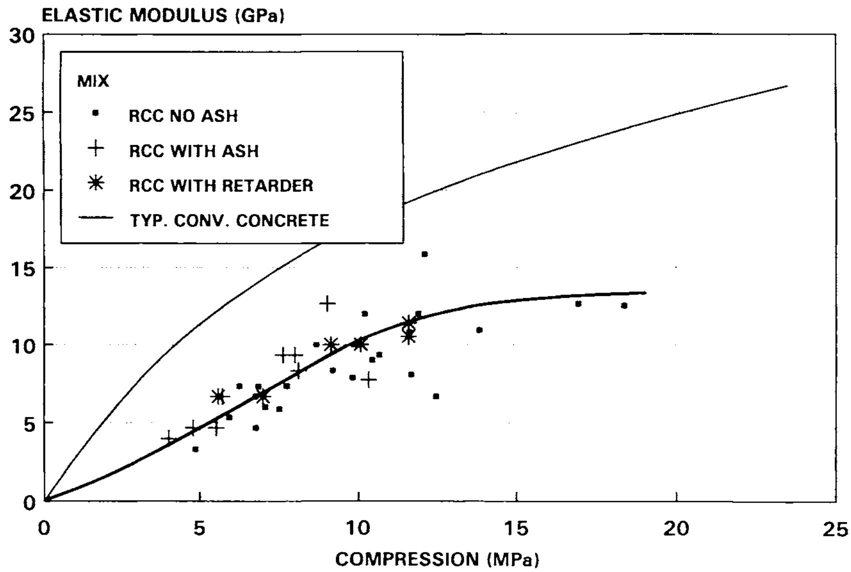

Fig. 7—Elastic modulus versus compression, Big Haynes Project

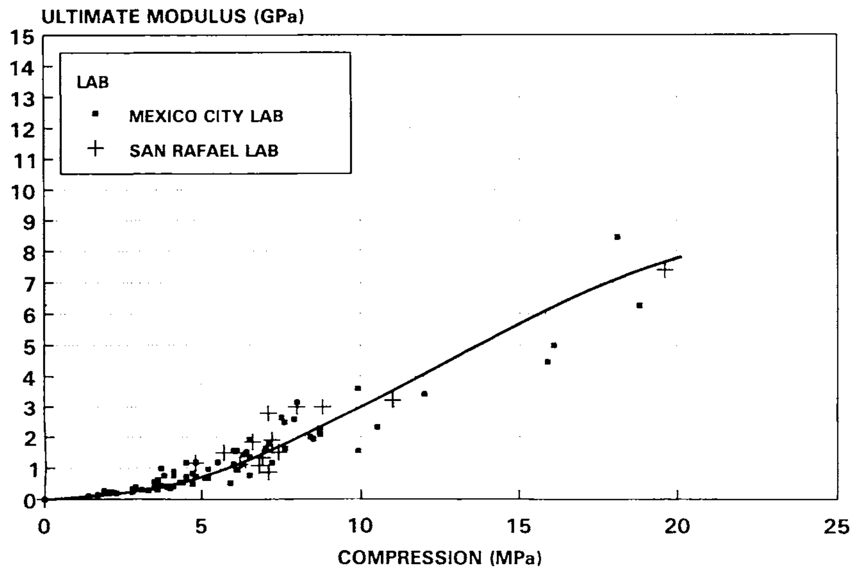

Fig. 8—Ultimate modulus versus compression, San Rafael Project

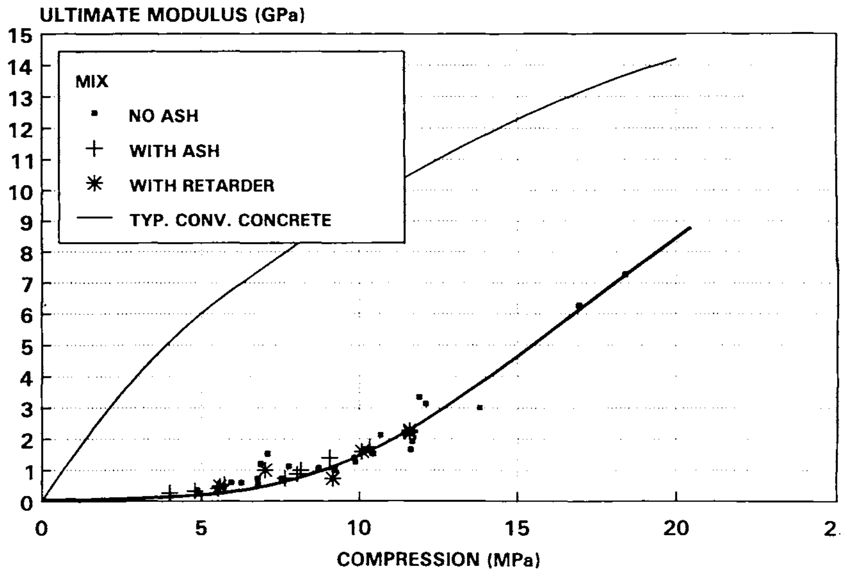

Fig. 9—Ultimate modulus versus compression, Big Haynes Project

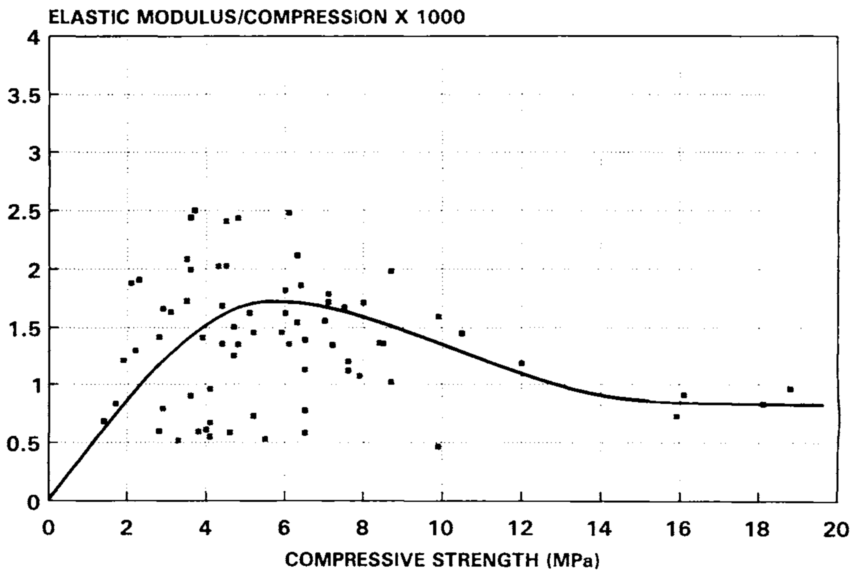

Fig. 10—San Rafael, compression versus ratio of elastic modulus/compression

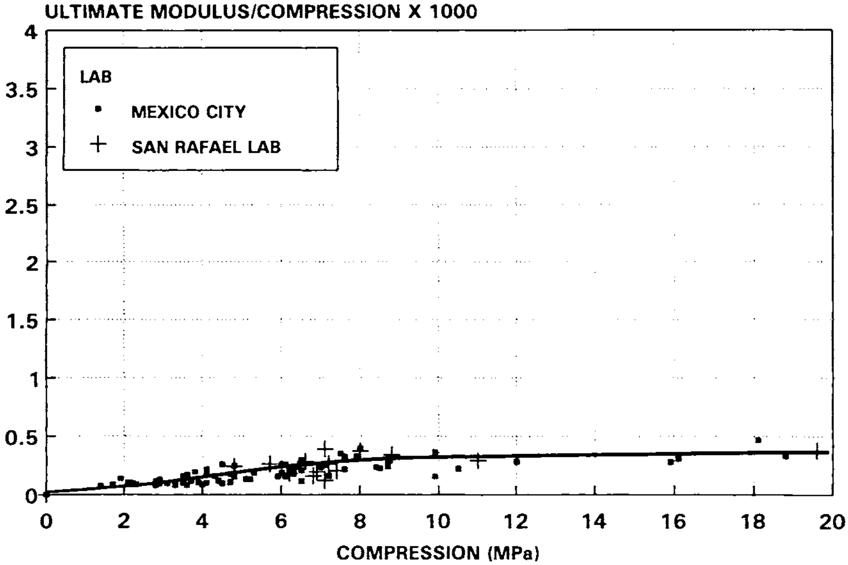

Fig. 11—San Rafael, compression versus ratio of ultimate modulus/compression

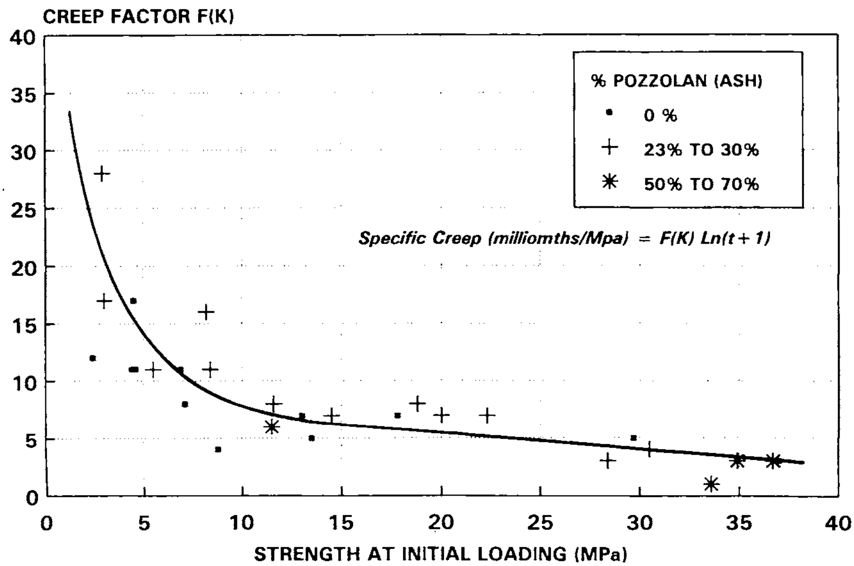

Fig. 12—Specific creep versus compressive strength when loaded