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Cube tests and the uniaxial compressive strength of concrete*

by B. P. Hughes, B.Sc., Ph.D., A.M.I.C.E. and B. Bahramian, B.Sc.

Contribution by Roger M. Zimmerman, Ph.D.
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The authors are to be congratulated for their timely contribution. I have been conducting research on the biaxial and triaxial strengths of plain concrete by loading 2 in. cube specimens and the problem of surface friction has been very evident. Morrison and Serata[1] have studied various materials that could be used to eliminate friction and have found a 'friction reducer' with a coefficient of friction as low as 0·00246 for normal stresses up to 13,000 lb/in^2. I have used[2] a friction-reducing pad composed of two layers of p.t.f.e. film 0·003 in. thick combined with a layer of a grease-graphite mixture, and it has been found to have an average coefficient of friction of 0·014 for normal stresses up to 50,000 lb/in^2. This same type of pad has been used in a study under my direction by Shepard[3] to determine the effects of surface friction on the biaxial strength of a single mix of concrete. Figure 1 shows the results of these tests. The quantities σ_1 and σ_2 refer to the normal stresses applied to the specimens and the quantity σ_c refers to the control strength for the mix. The effects of surface friction are clearly shown to be even more significant for the biaxial tests than for the uniaxial tests mentioned by the authors. The concrete used by Shepard had a water/cement ratio of 0·6 by weight and a ⅜ in. maximum size aggregate was used. Currently this study is being extended to a triaxial study on various mixes of concrete.

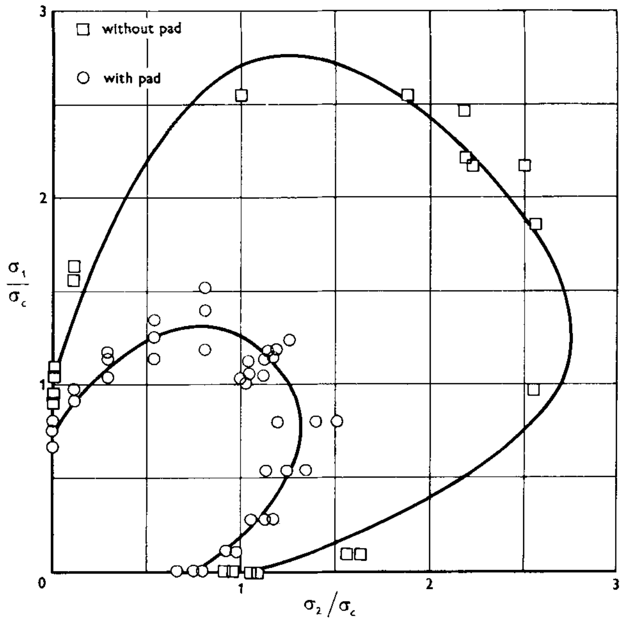

Figure 1: Comparison of biaxial strengths of concrete with and without friction-reducing pad.

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Contribution by D. H. Trollope, M.Sc., Ph.D., M.I.E.Aust., M.A.S.C.E.
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It is with some concern that we note the comments in the paper by Hughes and Bahramian about the relationship between cube test results and the uniaxial compressive strengths of materials such as concrete.

As a result of a recent investigation into the uniaxial strength of cubes and cylinders of gypsum plaster, one of us (E.T.B.) has demonstrated that, with smooth ends, longitudinal splitting will occur. It would appear that the authors have had a similar experience as shown by their photographs in Figure 5 which are to be compared with the form of failure noted in their Figure 1 where ill-defined modes are shown which are neither fully tensile nor fully shear. Furthermore, Gramberg[4] has indicated similar behaviour in tests on glass and a number of dense rocks.

There is thus a considerable body of experimental evidence available to support our recent contention[5] that, in uniaxial compression, longitudinal splitting is a primary mode of failure occurring under effective tensile stresses and is distinct from the more usually recognized compressive or shear failure. In our view the application of a uniaxial compressive load induces changes in the internal inter-molecular stress regime which are reflected as effective tensile stresses in directions at right-angles to the direction of load application. If the ends of the element under test are completely smooth, i.e. under pure uniaxial compression, then it would appear that for many non-metallic brittle materials the load required to generate the effective tensile (splitting) failure is less than that which would be required to induce shear or compression failure.

Where there is adequate frictional restraint at the ends, the tensile failure may be suppressed and end cones with associated shear failures as indicated by Figure 2 will be developed. Under these conditions, however, the effective lateral restraint is indeterminate. In the standard cube or cylindrical compression control test, it is tacitly assumed that under shear failure the material behaves as a Tresca solid with a constant yield strength so that introduction of the relatively small confining effect is not significant.

When, however, the testing mode is one which generates tensile failure, such an assumption is no longer valid and it would appear highly undesirable to continue to equate indiscriminately those values of axial load which are required to induce splitting with those which are required to develop shear, as the authors imply when they say that the cube test with smooth ends (in which splitting failures occur) is a satisfactory means of measuring the uniaxial *compressive* strength of concrete.

It is clear that if the compressive (shear) strength properties of materials such as concrete are to be studied, then triaxial compression testing is essential and the confining pressures must be adequate to ensure uninhibited development of shear failure rather than the complex modes shown in Figure 1.

Contribution by A. B. Lingam, B.Sc., B.E.
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It is realized by concrete engineers and research workers that the crushing strength of concrete, determined from the crushing strength of a cube or cylinder, is affected by factors which are not intrinsic to concrete and whose influence is not so obvious and direct. Important among these are the shape and size of test specimens, surface friction between the ends of the specimen and machine platen, and distribution of contact stresses during the test. These factors were investigated in 1959 with the object of making a quantitative, experimental and analytical study of the above factors.[6-8]

From the analysis of test values, it was observed that pitch-capped specimens showed a marked increase in reproducibility with 5 to 6% coefficient of variation in all cases. Considerable scatter was noted for wax-capped specimens, with cement cap occupying an intermediate position.

It was concluded that:

the cube is not a suitable shape, as it suffers from a rather high sensitivity to variation in end conditions and surface friction between the ends of the specimen and the testing machine platen;

the cylinder, on the other hand, is not affected to such a degree by secondary influences;

the interposing capping material must be suitable and plastic enough to ensure that the distribution of contact stresses under that load will be even and also to reduce to a considerable extent the scatter and improve the reproducibility of the crushing strength—hard pitch has given encouraging results in achieving this.

In judging the suitability of a capping or packing material, the important criteria are convenience, cost and reproducibility of test results for different grades of concrete. The data presented in the paper are too few to say how far M.G.A. pads satisfied these requirements when used for the cube test.

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Reply by the authors

We thank Professor Zimmerman for his interesting contribution concerning biaxial and triaxial tests on 2 in. cube specimens. The values quoted for the coefficients of friction are so low that presumably some difficulty must have been experienced with specimens gently sliding out of the machine at the start of the test. Although the effects of surface friction on the biaxial strength of concrete may be even more significant than for the uniaxial tests, as suggested by Professor Zimmerman, the results given in Figure I must be treated with caution. This is because the p.t.f.e. film, 0·003 in. thick, immediately adjacent to the concrete would tend to expand too much under load and has almost certainly given strength values which are low. This is illustrated by considering some uniaxial tests carried out by the authors during their preliminary investigations.

Figure II shows the results of tests carried out on concrete containing crushed limestone coarse aggregate and Ham River sand. The lubricated pads in this case consisted of two layers of 0·005 in. thick p.t.f.e. with Molyslip grease in between. The aggregates and age of testing of 91 days are the same as the limestone Ham River concretes and in Figures 2 and 3. Notice that for these p.t.f.e. pads the cube results are much lower than the normal prism strength values. The p.t.f.e. layer between the grease and the concrete is clearly expanding too much and is causing premature failure of the concrete. The error in these results is also seen to increase at the higher crushing strengths. Figure III shows the results for the same limestone and Ham River mixes when the M.G.A. pads, which are recommended in the paper, are used. Notice that the crushing strength of cubes with M.G.A. pads, and prisms with or without M.G.A. pads, are very similar. In addition, notice that the onset of microcracking for prisms without M.G.A. pads is virtually the same as for cubes with M.G.A. pads. This was not so for the tests using p.t.f.e. pads included in Figure II.

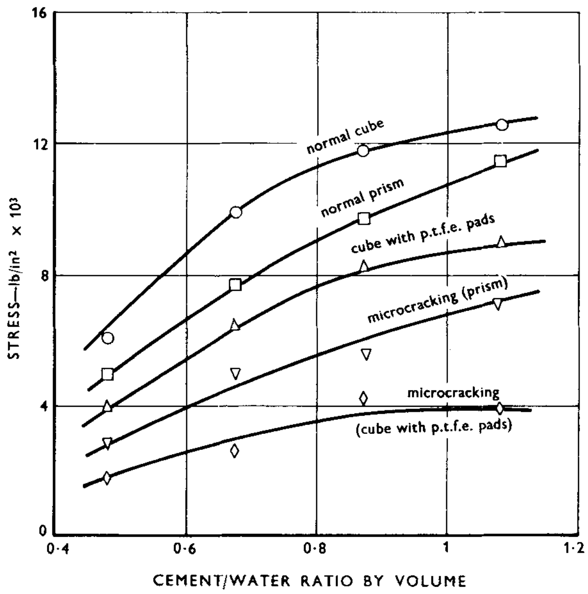

Figure II: Results of micro-cracking and crushing tests with and without p.t.f.e. pads.

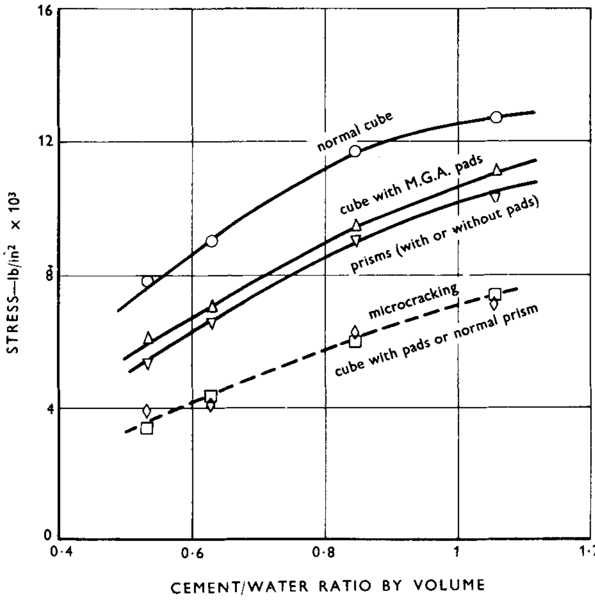

Figure III: Results of micro-cracking and crushing tests with and without M.G.A. pads.

We thank Dr Trollope and Mr Brown for drawing our attention to Gramberg's recent paper(4). Having read this paper, however, we find it difficult to appreciate why Dr Trollope and Mr Brown state that "It is with some concern that we note the comments in the paper . . ." since Gramberg's views support the views in the paper. Gramberg states that axial cleavage fracture (i.e. fracture in the direction of the load axis when subjected to uniaxial compression) of brittle materials is caused by indirect or induced tensile stresses. These induced tensile stresses are assumed to be dispersed microstresses, since the measurable and calculable loads and continuous tensile macrostresses in a truly uniaxial compression test are, of course, zero. The present paper enables satisfactory uniaxial compression tests to be carried out on concrete and other materials. This facilitates, rather than conflicts with, Gramberg's work since he relies on a less satisfactory form of uniaxial compression test pad. (From Figure 11 of reference 4 it is clear that Gramberg's pad is only satisfactory for materials of a particular, and constant, lateral stiffness.)

Perhaps it is simply the different terminology which is the main reason for the concern of Dr Trollope and Mr Brown. They agree that, in uniaxial compression, longitudinal splitting is the primary mode of failure in concrete and is distinct from the so-called 'shear' (or ill-defined triaxial stress) failure which occurs in the normal cube crushing test. It is also clear that for concrete and similar brittle materials the introduction of *any* lateral compression increases the apparent compressive strength of the material.

If a general failure criterion for concrete in all states of triaxial stress is to be determined then this is likely to be related to the following three factors:

(a) uniaxial compressive strength;
(b) uniaxial tensile strength;
(c) strength in pure shear.

The paper, of course, was concerned with item (a) only. It would be fortuitous if some form of arbitrary compression test, as suggested by Dr Trollope and Mr Brown, gave a perfectly satisfactory estimate of item (c).

Mr Lingam's contribution suggests the use of hard pitch as a capping material on the basis that the reproducibility (5 to 6% coefficient of variation) is very good. This suggestion, however, suffers from two disadvantages.

First, the main object of the paper was to show that M.G.A. pads enable any specimen (long or short) to expand under load, in the test machine, in exactly the same way as it would if placed between platens made from exactly the same concrete, and of the same cross-sectional area, as the specimen. In other words, M.G.A. pads enable artificial effects due to machine-platen restraint to be eliminated in what are intended to be uniaxial compression tests. Since the deformation characteristics of specimens vary, not only with different concretes but also with different loads, it is clear that a single capping material such as pitch (which according to Mr Lingam[6] had an average coefficient of friction against a steel surface of 0·37) cannot be satisfactory for all, if any, concretes.

Secondly, a coefficient of variation of 5 to 6% is the order of magnitude that one could expect for normal cube crushing tests carried out on laboratory specimens. For example, for the series of tests which enabled the curves given in the paper to be drawn, the closest and widest variations (for four individual cubes) in standard deviation (and corresponding coefficient of variation) were 67 lb/in^2 (0·5%) and 835 lb/in^2 (6·4%) respectively for the normal cube crushing strength. The standard deviation for cube tests with M.G.A. pads is at least as good as the normal cube tests; the above mixes gave 288 lb/in^2 (3·0%) and 387 lb/in^2 (3·6%) respectively. When convenience, cost and reproducibility of a standard test (rather than a more fundamental basic test of concrete) are the main considerations, then the normal cube test is clearly the most suitable. Any marginal advantages, obtained in improved reproducibility, would be more than offset by the inconvenience and cost of capping with hard pitch.

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