Discussion on two related papers published in the

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The bearing strength of concrete loaded through rigid plates*

The bearing strength of concrete loaded through flexible plates†

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The object of the tests described by Dr Hawkins in his two papers is similar in many respects to that of a series of tests that the writer has completed at Imperial College, London.⁽¹⁾ The purpose of the latter tests was to establish a criterion for the failure of concrete at tendon anchorages of post-tensioned concrete members. The investigation included tests on the effects of rigid and flexible plates as well as some in which the friction properties of the interface between the steel bearing plate and the concrete, and the internal friction properties of the concrete (particle shape and surface texture of the aggregate), were varied.

The most significant conclusion from these tests in the context of the papers under discussion is that the failure mode observed was the wedging action of a cone of concrete under the bearing plate. It would appear that shears at the bearing interface, arising from the stiffness incompatibility between the concrete 'end-block' and the steel bearing plate, induce tri-axial compressive stresses in the concrete immediately below the bearing plate, thus giving rise to a cone of stiffer concrete,^(2,3) i.e. concrete with a higher Young's modulus.

The writer's tests were all on saturated concrete model end-blocks, either 6 in. square $\times$ 18 in. long with a central $\frac{5}{8}$ in. diameter hole or 8 in. square $\times$ 24 in. long with a central $1\frac{1}{2}$ in. diameter hole. Transverse 'bursting' strains were measured by electrical-resistance strain gauges on the faces of the end-blocks.

The strains measured showed that the maximum splitting tension occurs, as predicted by 'classical' theories (see, for example, references 4 and 10 of the paper), remote from the loaded face, and not adjacent to the bearing plate, as assumed by Dr Hawkins's failure model. In fact, strain measurements show the concrete adjacent to the loaded face to be in compression.

The writer's tests indicated that the maximum tension coincides approximately with the apex of the cone. It would therefore appear that a more accurate failure model would be one in which failure was initiated in the 'slice' coincident with the apex of the cone rather than in the uppermost slice adjacent to the bearing plate.

The geometry of the failure cone was unaffected by the surface texture or particle shape of the aggregate. For rigid bearing plates, the height of the cone was approximately equal to the width of the bearing plate—that is an apex angle of 53° . This is in line with the results of work on shear bond characteristics of concrete reported by Alexander et al.⁽⁴⁾ and others. It may be, though, that the intrinsic friction properties

*Page 31 to 40 of *Magazine* No. 62.

†Pages 95 to 102 of *Magazine* No. 63.

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of the mortar matrix have a greater influence, this being kept constant in the writer's tests. (Mix proportions were 1:2.4:3.6/0.55, the aggregates being $\frac{3}{4}$ in. maximum size angular granite, irregular river gravel and rounded sea gravel—descriptions in accordance with BS 812:1967).

In contrast, varying the friction properties of the bearing interface had a marked effect upon the geometry of the cone. A very rough surface, formed by machining grooves in the bearing plate, produced a cone with a larger apex angle, whereas the cone was eliminated by making the interface 'frictionless' (a polished bearing plate with anti-friction coating on the concrete). Failure in this latter case was due to a cleavage splitting crack extending right under the bearing plate.

The writer's tests on flexible plates were mainly concerned with varying the thickness of the plate and the stiffness of the steel, the 'punch' size being kept constant. Figure I shows the results of some of these tests compared with Dr Hawkins's series A, B and C. The yield stress of the steel in the Imperial College tests was 40,000 lb/in² and the concrete strength 5,500 lb/in² (true uniaxial strength). Figure I is plotted in general rather than particular parameters, Dr Hawkins's results for a plate thickness of 0.06 in. being taken as equivalent to loading directly via the punch; the error arising from this is very small.

It can be seen that the plate behaves as a rigid plate when $tc/ab > 0.15$, i.e. in Dr Hawkins's tests, a plate thickness of 0.85 in. for series A and a plate thickness of 0.80 in. for series B and C. This is 50% more than given by equation 10 of the paper.

It is apparent from Figure I that the yield stress of the steel has only a minor effect upon the strength of the bearing block, as was found in a separate series of tests made by the writer. It would therefore seem that, apart from the requirements of serviceability, there is little advantage to be gained from using plates manufactured from high-grade steels. The failure mode observed in both Dr Hawkins's papers, and those referred to in this discussion, raise the fundamental problem of the mechanics of failure of concrete, i.e. whether an apparent shear failure such as that described for the faces of the cone of concrete occurs before or after the cleavage splitting in the body of the concrete.

Recent research⁽⁵⁾ shows that, for plain concrete models in uniaxial compression, vertical splitting precedes shear-bond cracking. However, both the research reported by Dr Hawkins and that outlined in this discussion indicate that the shear failure is dominant. Perhaps the final answer will come from the students of crack mechanics, who will be able to say whether a shear failure has a lower surface energy and/or higher stress concentration requirement than does a cleavage splitting fracture.

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Figure I: Effect of flexibility of bearing-plate upon load-carrying capacity of bearing block.

t = thickness of bearing plate
 $2a$ = width of bearing plate
 $2b$ = width of bearing block
 $2c$ = width of punch

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Contributions discussing the above paper should be in the hands of the Editor not later than 30 June 1970.