# PREDICTION OF THE PUNCHING SHEAR STRENGTH OF REINFORCED CONCRETE SLABS WITH ASR.

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The results are presented of punching shear tests on 84 reinforced concrete slabs with alkali silica reaction (ASR). It is shown that ASR expansion does not have a detrimental effect on punching strength except for free expansion in excess of about 6000 microstrain. At such very high expansions delamination in the reinforcement planes of doubly reinforced slabs caused some reduction in punching strength. It is also shown how existing punching shear theories for prestressed concrete slabs can be applied to the analysis of reinforced concrete slabs with ASR.

## INTRODUCTION

A potential failure mode for reinforced concrete slabs subjected to concentrated loads is that of punching shear. This failure mode has to be considered in the design of flat slabs in buildings and of bridge slabs supported on discreet columns and/or subjected to concentrated wheel loads.

Many slab bridges were designed and built in the United Kingdom prior to 1973 with no, or very little, shear reinforcement, whereas current design codes would require shear reinforcement. Therefore, such bridges have, according to current codes, insufficient shear capacity even if they do not show evidence of material deterioration. Furthermore, a number of pre-1973 slab bridges constructed with alkali silica reactive aggregates are of viaduct form and are supported on small diameter circular columns. The punching shear strength of slabs containing potentially reactive aggregate and without shear reinforcement has been questioned.

Research into the effects of ASR on punching shear capacity is sparse. The only data available are those of Okada et al (1) who tested four slabs which indicated no reduction in punching shear strength due to ASR. Tests were planned by the Danish Ministry of Transport (2), but the results do not appear to have been published. In view of the lack of punching shear data, the slab tests and analytical work described in this paper were undertaken.

## THEORETICAL APPROACH

### General

ASR has two basic effects on reinforced concrete: (i) the mechanical properties of concrete, such as compressive and tensile strength, are reduced as a result of the ASR microcracking; and (ii) the restraint provided to the potential ASR expansion by the reinforcement induces compressive stresses in the concrete and equilibrating tensile stresses in the reinforcement. Whereas the reductions in concrete strength should tend to reduce the load carrying capacity of a structural member, the "prestressing" compressive stresses should tend to increase the load carrying capacity. The actual effect of ASR on load carrying capacity is a combination of the former detrimental and the latter beneficial effects.

Clark (3) has discussed the structural effects of ASR in detail and has proposed a method of calculating load carrying capacity using conventional ultimate strength analytical models.

Essentially, the reduced concrete strengths are allowed for in the same way as conventional prestress.

Punching Shear

A number of theories for predicting the punching shear strength of a prestressed concrete slab were examined, and three selected as being suitable for modification to allow for the effects of ASR. The three methods were: plastic theory (4); the decompression load approach (5); and the two-phase approach (6). Each of these is briefly described and the necessary modifications to allow for ASR explained.

Plastic theory. The plastic theory of Braestrup et al (4) assumes a failure mechanism in which a rigid plug of material moves in a direction which is normal to the plane of the slab and its reinforcement. Rigid-perfectly plastic behaviour of reinforcement and concrete is assumed. The reinforcement is assumed to resist only axial stresses and, because the failure is assumed to take place normal to the reinforcement, it makes no contribution to punching shear strength.

The rigid-perfectly plastic assumption for the concrete implies that prestress, including that due to restraint to ASR expansion, has no effect on punching strength.

The predicted punching strength is a function of slab and load geometry and the effective "yield" stress of the concrete in compression. Tests on slabs without ASR (4) have shown that the "yield" stress is proportional to the square root of uniaxial compressive strength of the concrete. Hence, the effect of ASR on punching strength can be allowed for simply by substituting the uniaxial compressive strength of the ASR-affected concrete in the prediction equation.

Decompression load approach. Regan (5) has proposed that the punching shear strength of a prestressed slab can be calculated by adding the load to decompress the extreme fibre to the punching shear strength calculated assuming the slab to be non-prestressed with zero initial extreme fibre stress. Restraint to ASR expansion induces compressive stresses in the concrete, and the beneficial effect of such stresses can be determined by calculating the decompression load required to reduce the extreme fibre stress to zero.

In order to determine the punching shear strength in the non-prestressed condition Regan (5) used an empirical equation for the punching shear strength of a reinforced concrete slab. In this equation, punching strength is proportional to the cube root of the compressive cube strength of the concrete. This term is really a measure of tensile strength and, because the tensile strength of ASR-affected concrete reduces more than its compressive strength, it was replaced by tensile strength.

Hence, the detrimental effect of the concrete strength reduction could be allowed for using the reduced tensile strength of ASR-affected concrete, and the beneficial effect of the induced compressive stresses could be allowed for by calculating the decompression load.

Two-phase approach. Two basic modes of failure are considered (6): (i) a flexural mode in which the tension reinforcement yields before the concrete fails; and (ii) a shear mode in which the concrete fails before the tension reinforcement yields. In its final form the two-phase approach contains a large number of empirical formulae. However, it is based on logical modes of actual behaviour which can be modified to include the effects of ASR.

The detrimental effects of concrete strength reduction can be allowed for by substituting the appropriate tensile and compressive strengths of the ASR-affected concrete in the empirical formulae.

The beneficial effects of the prestress induced in the concrete by the restraint to ASR expansion can be allowed for as follows. In the flexural mode, the moment of resistance of the section is enhanced by considering the resultant of the induced compression as a membrane force. In the shear mode, the depth of concrete in compression is increased as a result of the induced compressive prestresss.

## TEST DETAILS

### Slab Details

A total of 84 slabs were tested in punching shear to examine the effects of the following variables:

1. Free expansion: 0 to 8000 microstrain.
2. Amount of reinforcement: 0.44% to 1.75%.
3. Location of reinforcement: one face and two faces.
4. Reinforcement type: smooth and ribbed.
5. Reinforcement anchorage: straight and bent.
6. External restraint: with and without surrounding steel restraint.
7. Punch diameter: 0.5 to 3 times the slab thickness.

The slabs were proportioned so that punching failure with little bending would occur. They were 80 mm thick and 406, 430 or 610 mm square. The reinforcement consisted of isotropic meshes of 6 mm ribbed or smooth bars with yield stresses of 534 and 460 N/mm$^2$, respectively. No shear reinforcement was provided.

The reactive concrete mix consisted of ordinary Portland cement with a 0.86% sodium oxide equivalent alkali content, reactive Thames Valley fine aggregate and inert 10 mm limestone coarse aggregate in the ratios 1.00:1.36:3.24 by weight with a water/cement ratio of 0.48. The alkali content of the concrete was increased to either 7 kg/m$^3$ by adding sodium and potassium sulphates or 9 kg/m$^3$ by adding potassium hydroxide.

### Control Specimens

100 mm cubes and 100 x 200 mm cylinders were cast with the slabs. The cubes were tested in compression either in the conventional manner or with friction eliminating pads between a cube and the testing machine platens to enable the uniaxial compressive strength to be determined. The cylinders were monitored for free ASR expansion and ultrasonic pulse velocity, and used to obtain the splitting tensile strength.

### Test Procedures

The slabs and associated control specimens were stored under damp hessian and polythene sheets for 28 days after casting. They were then instrumented and conditioned in a water tank at, generally, 38°C. Expansion measurements were taken on the slabs and cylinders at regular intervals. When the average free expansion of the cylinders cast with a particular slab reached a predetermined value the slab was tested to failure in punching.

In a punching test, a slab was bedded on a support ring of 366 mm internal and 406 mm external diameter. A load was applied at the centre of the slab by means of a hydraulic testing machine through a punch of, generally, 80 mm diameter. However, in one test series, the punch diameter varied from 40 mm to 240 mm. All tests were conducted under displacement control.

## TEST RESULTS

### ASR Cracking

In general, ASR cracks occurred on the top surface of a slab with bottom reinforcement only, and on both surfaces of slabs reinforced in both faces.

### Punching Strengths

Full details of the punching strengths and the effects of the variables studied have been presented by Ng (7). In this paper, only the effect of free expansion on punching strength is considered.

In any experimental study of the effects of ASR it is extremely difficult, if not impossible, to have reliable non-reactive control specimens to compare with reactive specimens at the same age. This is because the strength-time relationship of the concrete is affected by the method adopted to obtain a non-reactive control. In view of this problem, the effect of ASR expansion on punching strength was examined by comparing the strength of ASR-affected slabs at ages in excess of 28 days with the strength of nominally identical slabs at zero expansion at 28 days.

In Figure 1, the ratio of punching load of an expanded slab with ribbed bars to the value for a nominally identical slab at 28 days (zero expansion) is plotted against free expansion, as measured on companion cylinders. In this and subsequent figures, "bottom" refers to bottom reinforced slabs, and "top and bottom" refers to slabs reinforced in both faces.

It can be seen that punching strength initially increased with an increase in free expansion up to about 1000 microstrain and then decreased. However, there was not a significant decrease in strength until the free expansion was of the order of 6000 microstrain. It should also be noted that the decrease was greater for slabs reinforced in both faces than for slabs reinforced in one face only. The reason for this is that at very high free expansions, the restraint provided by the reinforcement in both faces caused delaminations in the planes of the reinforcement.

## THEORETICAL COMPARISONS

### Prestress due to ASR

In order to calculate the theoretical punching strength, the compressive prestress induced by the restraint to ASR expansion had to be determined. The procedure adopted was to measure the restrained expansions on the top and bottom of a slab. The strains at the reinforcement levels were then interpolated by assuming that plane sections remain plane. From the known stress-strain relationship of the reinforcement the reinforcement stresses and forces could be determined. The stress distribution in the concrete required to equilibrate the reinforcement forces was then determined. These stresses were the ASR-induced prestresses.

It is also possible to calculate the stress inducing strain in the concrete, due to restraint to ASR expansion, as the difference between the potential free expansion and the measured restrained expansion. However, one must be careful in the choice of measurement method for the free expansion. This is because free expansion tends to be greater parallel to the direction of casting the concrete (7). Hence, free expansions measured on vertically cast cylinders over-estimate the potential horizontal free expansion of a slab by up to 35%. It is,thus, necessary, to measure free expansions on horizontally cast specimens.

In Figure 2 the ASR-induced prestresses in each slab are plotted against the stress inducing strain calculated using potential free expansions obtained from horizontally cast control specimens. There is considerable scatter of the data, but it can be seen that the elastic modulus in compression due to ASR is of the order of only 1 $kN/mm^2$. The negative (tensile) values in Figure 2 occur on the top face of a slab with only bottom reinforcement.

### Comparisons with Theories

In Figures 3 to 5, ratios of predicted to experimental punching strengths are plotted against modified free expansion (taking into account the effect of casting direction) for the plastic, decompression load, and two-phase theories, respectively.

Figure 3 shows that the plastic theory gives a good lower bound to the test data for all values of free expansion. The decompression load theory (Figure 4) and the two-phase theory (Figure 5) give good lower bounds to the test data up to free expansion of about 6000 microstrain for slabs reinforced with ribbed bars in both faces. The overestimates at high expansions are due to delamination microcracking in the case of ribbed bars in each face. It is significant that the plastic theory prediction, which is independent of reinforcement, does not overestimate strength at high expansion.

## CONCLUSIONS

1. ASR only affects the punching shear strength of reinforced concrete slabs at free expansions in excess of about 6000 microstrain.
2. Existing punching shear theories for prestressed concrete slabs can be used to predict the punching shear strength of reinforced concrete slabs with ASR, provided that the reduced material strengths of the ASR concrete are used and the ASR-induced compressive prestress is included in the analysis.
3. Free ASR expansion is greater in the direction parallel to the direction of casting. This fact has to be taken into account when correlating test data from slabs with data from control specimens.
4. The effective elastic modulus of concrete in compression due to restraint to ASR expansion is an order of magnitude less than the conventional elastic modulus.

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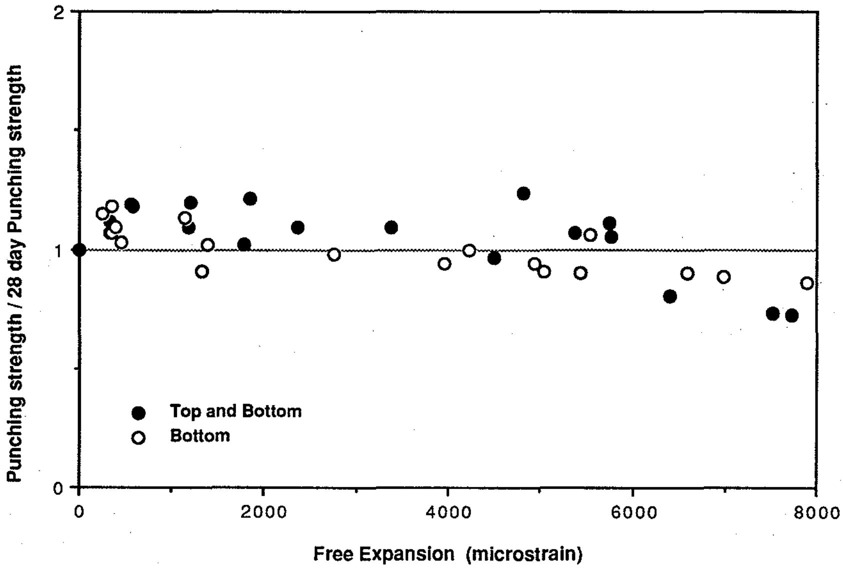


**Figure 1. Effect of expansion on punching strength**

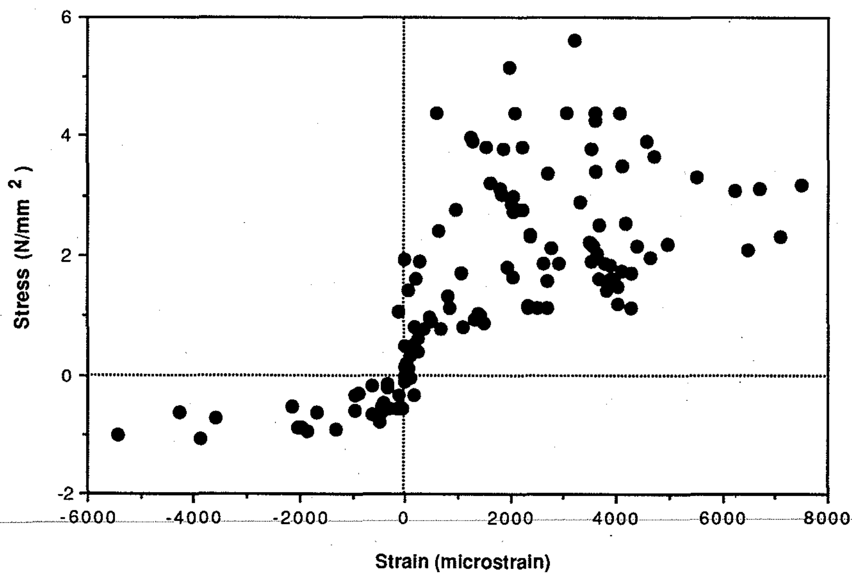


**Figure 2. Slab surface concrete stresses and strains due to ASR**

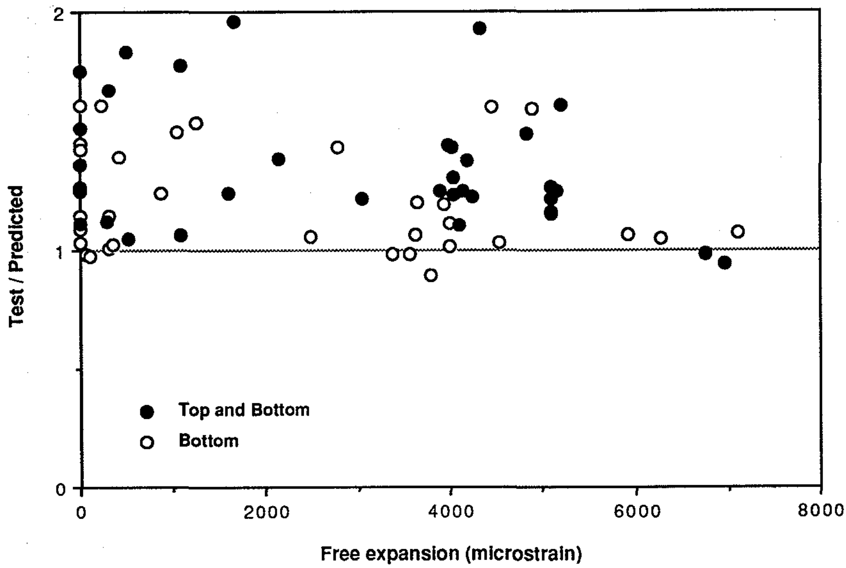


Figure 3. Punching strength ratio: plastic theory.

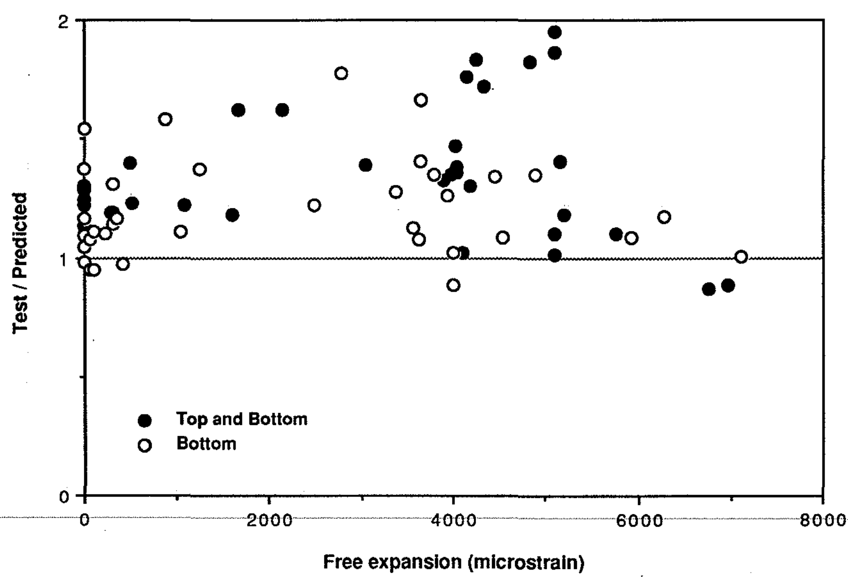


Figure 4. Punching strength ratio: decompression theory.

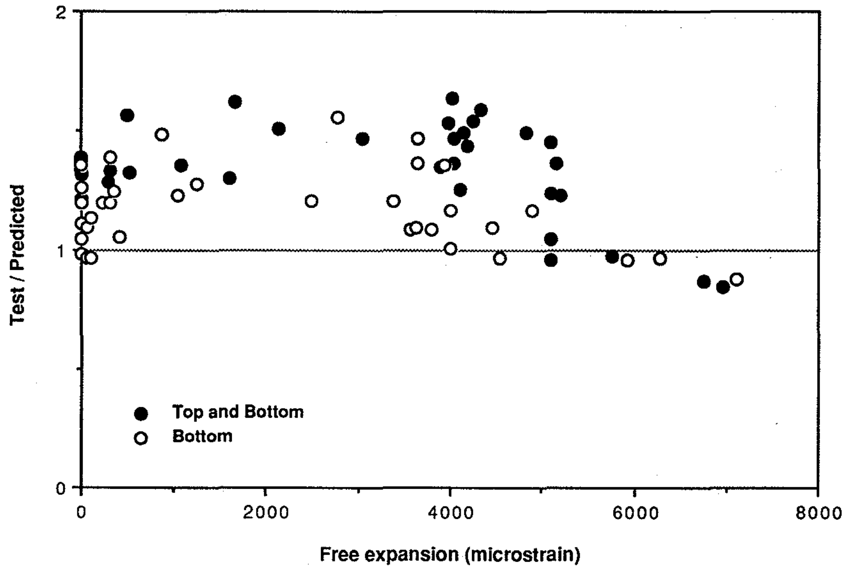


**Figure 5. Punching strength ratio: two-phase theory.**