# BOND STRESS FAILURE IN ALKALI SILICA REACTIVE REINFORCED CONCRETE BEAMS

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*A number of 1/3 scale beams made with alkali silica reactive mixes were tested to induce bond failure in lapped reinforcing bars. Substantial reductions in the ultimate load carrying capacity of the beams occurred. From these results the authors have concluded that very significant reductions in the ultimate average bond stress can occur with plain mild steel bars when such bars are used in certain alkali silica reactive mixes that induce high levels of expansion.*

## INTRODUCTION

Alkali Silica Reactive (ASR) concrete members have been considered by many engineers to be likely to exhibit reduced load carrying capacity due to reductions in concrete crushing strength, shear capacity and bond stress. The authors of this paper have developed a wide variety of ASR mixes that can be used to produce a great range of reactive properties in model concrete elements. Variations in both the rate and total amount of expansion can be modelled as can cycles of expansion, damage and autogeneous healing.

The purpose of the investigation reported here was to investigate, using lapped bars in beams, variations in the ultimate average bond stress of mild steel bars that might occur in alkali silica reactive concrete. The subsequent publications of the results of a similar investigation by Chana and Korobokis of British Cement Association (BCA) [1] allowed a comparison to be made between the results obtained at BCA and at QMW.

The QMW Concrete Research Group will shortly publish the result of a more extensive investigation which has considered various lap lengths and also used high tensile steel in the test programme.

## DETAILS OF TEST

Concrete. In this test programme 6 different mixes were used. Three of the mixes included fused silica and additional alkali to promote ASR. Two mixes were controls with varying cement contents and one mix had additional alkali but no fused silica. Details of the mixes used are given in Table 1. The fused silica was graded to pass through a 1 mm sieve and was included, at a rate of 15% of the total aggregate, to replace nearly half the sand fraction.

The percentage of fine aggregate passing 0.6 mm was 55%, and the coarse aggregate was a combination of angular and rounded particles of medium sphericity. The particle sizes of the two aggregates were in the range of 4.75 - 20.00 mm and 4.75 - 10.00 mm. Ordinary Portland cement was used in this test programme and a sodium oxide equivalent level of 7.0 and 12.0 $Kg/m^3$ was achieved by adding potassium hydroxide in the free water just prior to the mixing of the ingredients of the concrete.

Table 1 - The proportion of various mixes used in the experimental work.

| Mix No | 20 mm Aggregate (Kg) | 10 mm Aggregate (Kg) | Sand (Kg) | Fused silica (Kg) | Cement (Kg) | Water/ cement ratio | $Na_2O$ equivalent ($Kg/m^3$) |
|---|---|---|---|---|---|---|---|
| 1 | - | 1060 | 300 | 240 | 550 | 0.41 | 12.0 |
| 2 | - | 1060 | 300 | 240 | 550 | 0.41 | 7.0 |
| 3 | 1060 | - | 300 | 240 | 550 | 0.37 | 7.0 |
| 4 | - | 1060 | 540 | - | 550 | 0.41 | 7.0 |
| 5 | - | 1060 | 540 | - | 550 | 0.41 | - |
| 6 | - | 1060 | 540 | - | 200 | 0.74 | - |

The two levels of alkali were used to investigate the effect of different levels of expansion and the direct effect of additional alkali on bond stress. The fresh concrete from the high alkali mixes are noted to be less workable and more viscous than the standard mixes and it may be that some additional chemical adhesion occurs as a result, on the surface of the reinforcement.

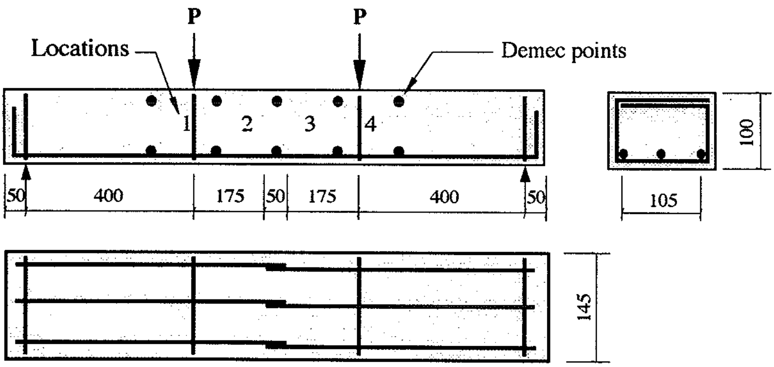
A minimum of three cubes were crushed for each mix prior to beam testing, and these results are reported in Table 3.

Casting and curing. The specimens were cast and cured in the concrete laboratory at QMW. Curing took place in two stages. First the concrete was cured for 4 weeks at 20°C and then transferred to the conditioning curing tank which was heated to 38°C. The relative humidity in both cases being 100%.

Reinforcement. The main reinforcement in all the beams was 6 mm plain mild steel bars located only in the bottom of the beams. Laboratory tests showed that the actual characteristic strength of the reinforcement ($f_y$) was 375 ± 5 $N/mm^2$. The transverse reinforcement used in the beams consisted of 6 mm diameter mild steel stirrups.

Beams. Fifteen beams 1300 x 145 x 100 mm were tested in this experimental programme. Each beam had 3 longitudinal reinforcing bars with 50 mm overlaps in the middle of the span. 4 stirrups were used in each beam and the details of the specimens are given in Figure 1. According to British Standard Code of Practice 8110 the minimum lap length should have been approximately 300 mm.

In order to monitor the expansions, a number of Demec points were attached in two rows near the top and bottom of the beam sides. (See Fig. 1). This arrangement enabled the expansions due to ASR, to be measured in both the vertical and the horizontal directions, at different positions along the beam, and the horizontal expansions to be measured at both the top and bottom of the beam.




All dimensions in mm.

Figure 1 - Typical loading arrangement of beams for investigation of bond failure.

Bond mechanisms. Bond stresses allow a force to pass from a reinforcing bar into the surrounding concrete and vice versa. When bars are lapped to provide continuity in a reinforced concrete beam the bond forces between the bars and the concrete must be sufficient to allow the force in one bar to pass into the lapping bar via the surrounding concrete. The bond forces that can develop are a function of the bond stresses that can develop and the lap length over which these stresses can act. If the bond forces cannot equal the force in the reinforcing bar then slippage will occur, leading eventually to failure of the beam.

The bond between concrete and a reinforcing bar can be considered to consist of three components: (I) - Mechanical interlock between irregularities on the surface of the bar and the concrete cast around it. (II) - Friction, which is micro interlock similar to (I) above and (III) - Chemical adhesion between the bar and the concrete.

In this test programme mechanical interaction has been limited by the use of plain bars. Hence the bond is principally a function of chemical adhesion and surface friction.

Table 2 shows the expansive behaviour of beams 11, 21 and 31. It can be seen that the greatest expansions are in the vertical direction, closely followed by horizontal expansions near the top of the beam. This behaviour seems similar to other work which shows expansion being related to member size and shape [2, 3] but modified by the presence of reinforcing in the bottom of the beam only. The lowest expansions are at the bottom of the beam where the reinforcement provides the greatest restraint. Figure 2 shows clearly that greater horizontal expansion has occurred close to the lap zone than in the regions where the reinforcement is well anchored, pointing to slippage occurring between the reinforcement and concrete in the central region.

Table 2 - Average expansion of the beams in different direction.

| Beam No | Average horizontal expansion top edge (mm/m) | Average horizontal expansion bottom edge (mm/m) | vertical expansion (mm/m) | Radius of curvature (m) | Mix No |
|---|---|---|---|---|---|
| 11 | 14.4 | 7.45 | 18.0 | 10.2 | 1 |
| 21 | 11.8 | 6.71 | 13.2 | 13.9 | 2 |
| 31 | 12.5 | 7.72 | 14.2 | 14.8 | 3 |

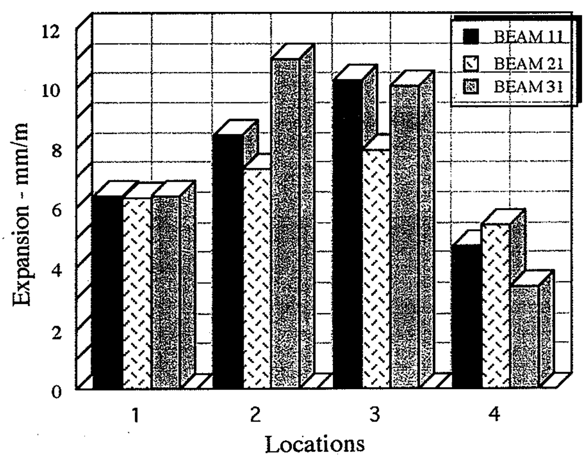



Figure 2 - Bar chart illustrating reinforcement slippage.

The restraint from the bottom reinforcement induces a curve within the beam as the expansion takes place. The greatest expansion and the smallest radius of curvature is seen to occur with beam 11. It is also seen that though the expansion in beam 31 is greater than in beam 21, the radius of curvature of beam 31 is the greater. This would support the findings from Figure 2 which indicate that slippage is more extensive in beam 31 than in beam 21.

## TEST RESULTS

Table 3 shows the cube crushing strength, ultimate failure load, ultimate tensile stress, and average ultimate load stress for the test beams. The value of the average ultimate bond stress determined according to $f_{bu} = 1.4\beta\sqrt{f_{cu}}$ (Ref. BS 8110) is also given.

Table 3 - Mechanical properties of the beams.

| Beam No | Mix No | Cube crushing strength ($N/mm^2$) ($f_{cm}$) | Failure load = 2P (KN) | Ultimate average tensile stress ($N/mm^2$) ($f_s$) | Ultimate average bond stress ($N/mm^2$) ($f_b$) | $(f_s)/(f_y)$ $f_y = 375$ % | $f_{bu} = 1.4\beta\sqrt{f_{cu}}$ $\beta = 0.28$ $f_{cu} = f_{cm}$ ($N/mm^2$) |
|---|---|---|---|---|---|---|---|
| 11<br>12 | 1 | 32.7 | 4.92<br>4.23 | 147.5 | 4.4 | 39.3 | 2.2 |
| 21<br>22<br>23 | 2 | 37.7 | 2.58<br>2.57<br>2.54 | 82.6 | 2.5 | 22.0 | 2.4 |
| 31<br>32<br>33 | 3 | 35.2 | 2.29<br>2.54<br>2.41 | 77.8 | 2.3 | 20.7 | 2.3 |
| 41<br>42 | 4 | 57.2 | 8.54<br>7.00 | 250.5 | 7.5 | 66.8 | 3.0 |
| 51<br>52 | 5 | 69.4 | 9.48<br>10.2 | 317.3 | 9.5 | 84.6 | 3.3 |
| 61<br>62<br>63 | 6 | 35.9 | 9.21<br>7.81<br>8.64 | 275.8 | 8.3 | 73.5 | 2.3 |

It is seen that reactive mixes 2 and 3 have resulted in beams whose bond stress is similar to the values given in BS 8110. However reactive mix 1 which had the 12 $Kg/m^3$ of alkali and the greatest expansions resulted in a bond stress value nearly double than that given by mixes 2 and 3 and therefore more than twice the BS 8110 value. It is suggested that this might be due to the additional alkali resulting in increased adhesion between the bars and the concrete and that the positive effect of the increased adhesion compensated for the negative effects induced by the increased expansion that occurred. The possibility that differences in the rate of reaction between the various reactive mixes has resulted in a period of autogeneous healing occurring before testing in the case of mix 1 beams could also have influenced the results [2]. The two non reactive mixes have produced beams where the bond stress is about three times the values quoted in BS 8110, and nearly four times larger than the values recorded for the reactive mixes.

When comparing mixes 5 and 4 it is noted that the additional alkali of (to 7 $Kg/m^3$) has resulted in the ultimate average bond stress being reduced by 21%. Considering only the differences in cube strength between these two mixes a reduction in ultimate average bond stress of only 6% might have been expected. When comparing mixes 5 and 6 it is seen that based on the cube strength, a reduction in ultimate average bond stress of 25% might have been expected whereas in practice a reduction of only 13% has occurred.

BCA TEST RESULTS. Chana and Korobokis of the British Cement Association carried out similar tests to the above [1]. They used 16 mm reinforcement and had stirrups throughout the beam. The BRE mix was used with 7.0 Kg equivalent alkali and the beams were loaded with a single point load. The BCA tests recorded only a 32% reduction in ultimate average bond stress due to ASR when using plain mild steel bars.

## DISCUSSION

The differences between the results obtained at BCA and at QMW are likely to be a function of:

a - The different mixes used.
b - The higher expansions obtained using the QMW mixes and as a result of the lower percentage of steel in the QMW beams to restrain the expansion. (0.6% at QMW, 2% at BCA.).
c - The use of full links at BCA.
d - The fact that the BCA beams were subjected to bending and shear in the lap zone where as the QMW beams had pure bending in this area.

It is also suggested that slippage of the steel occurred in the lap zones prior to load testing the QMW beams. This is likely to have resulted in a reduction in ultimate average bond stress on testing.

## CONCLUSION

It is suggested that in certain circumstances very significant reductions in the ultimate average bond strength might occur with plain mild steel bars in alkali silica reactive concrete. Such reductions are most likely to occur where substantial ASR expansions are experienced.

The BRE model mix should allow the behaviour of most real life ASR structures to be accurately modelled in the laboratory. It is suggested though that reliance on one basic experimental mix to predict behaviour in the field could lead to inaccurate conclusions being reached in certain circumstances.

## REFERENCES

[1] Chana P.S., Korobokis G.A. Bond Strength of reinforcement in concrete affected by alkali silica reaction: Phase II (British Cement Association). Contract Report 233 Transport and Road Research Laboratory.

[2] Rigden S.R., Majlesi Y., Burley E. An investigation into factors influencing the expansive behaviour, compressive strength, and modulus of rupture of Alkali Silica Reactive concrete using laboratory concrete mixes. (Paper in the course of preparation).

[3] Walton C., Clayton N. Alkali silica reaction expansion measurements on a variety of test specimens. Building Research Establishment Note.