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Effects of thaumasite on bond strength of reinforcement in concrete

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Abstract

The conditions necessary for the formation of thaumasite are well known and much work is in progress to identify concrete mixes resistant to thaumasite form of sulfate attack (TSA). However, there have been no data to indicate how TSA affects the nature and strength of the bond between reinforcement steel and concrete and hence the load capacity of reinforced concrete elements.

During works to repair and strengthen the thaumasite-affected Tredington–Ashchurch Overbridge in Gloucestershire, sections of column were removed and placed in storage. These column sections presented an opportunity to perform pullout tests on full size TSA-affected structural elements and unaffected control specimens from the same structure. In total 63 pullout tests were performed on plain round reinforcement bars embedded in two unaffected and four TSA-affected reinforced concrete elements. The sections were also characterised in terms of estimated in situ cube strength and depth of softened zone.

A statistical analysis of the experimental results indicates that the bond of the plain round reinforcement bars in the unaffected concrete exceeded that of the plain round reinforcement bars in the TSA-affected concrete. TSA reduced the mean experimental bond coefficient by 24% for corner bars and 10% for other bars, representing an average reduction in mean experimental bond coefficient of 15% for all bars.

Keywords: Sulfate attack; Thaumasite; Structural effects; Bond

1. Introduction

The conditions necessary for the formation of thaumasite are well known and much work is in progress to identify concrete mixes resistant to the thaumasite form of sulfate attack (TSA). However, there have been no data to indicate how TSA affects the nature and strength of the bond between reinforcement steel and concrete and hence the load capacity of reinforced concrete elements. This lack of data was recognised by the Thaumasite Expert Group and in its report [1] the Group recommended that future research should include residual bond tests on reinforced concrete sections affected by TSA.

During works to repair and strengthen the TSA-affected Tredington–Ashchurch Overbridge on the M5 motorway, sections of column were removed and stored for future investigative works. As part of an ongoing programme of study of TSA for the Highways Agency, the University of Birmingham was commissioned to perform reinforcement pullout tests on six of the column sections extracted from Tredington–Ashchurch Overbridge. The column sections comprised four TSA-affected structural elements and two unaffected control specimens from the same structure.

The principal objective of the research presented in this paper was to establish the effect of TSA on the bond between reinforcement steel and concrete.

2. Experimental details

To achieve the objective described in Section 1 an experimental programme was undertaken to measure the following properties:

- bond strength of each reinforcement bar in all test specimens,
- depth of softened zone in TSA-affected test specimens, and
- estimated in situ cube strength in all test specimens.

The bond between reinforcement steel and concrete was determined by pullout tests. Before reinforcement pullout tests could be performed on the column sections

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it was necessary to expose the plain round reinforcement bars and reduce their embedment lengths so that when tested the reinforcement bars would not yield but would pull out of the surrounding concrete. The concrete was broken out using hydro-demolition techniques in order to minimise micro-cracking and associated damage within the residual column sections. Fig. 1 shows two column sections following completion of the hydro-demolition works. Prior to testing of the reinforcement bars in a column section the embedment length, diameter and cover(s) of each bar were recorded.

The bond strength of each reinforcement bar was measured using the test arrangement shown schematically in Fig. 2. A test specimen was held in position at three locations to resist uplift and rotation of the concrete block and a tensile force was then applied to a single reinforcement bar in increments of 5 kN. Corresponding measurements of displacement were taken using a dial gauge. Since the displacement readings included the response of the test arrangement in addition to the slip of the reinforcement, the primary purpose of the displacement readings was to indicate when failure had occurred. The bond strength of a reinforcement bar was defined as the maximum bond stress developed during a pullout test. In total 63 pullout tests were performed.

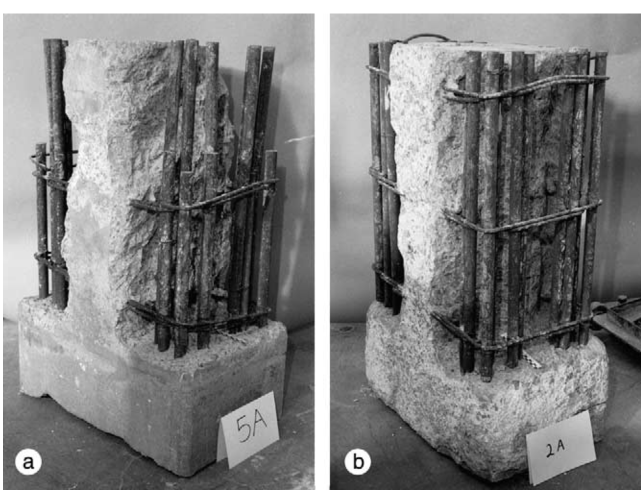

Fig. 1. Specimens prepared for testing: (a) unaffected specimen, (b) TSA-affected specimen.

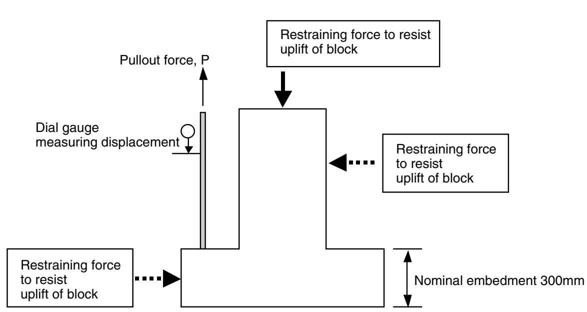

Fig. 2. Schematic illustration of test arrangement.

Upon completion of the pullout tests the depth of the softened zone was determined at two locations along the embedded length of each reinforcement bar in the TSA-affected specimens. The depth was determined by hand held drilling, the softened zone being identified as that concrete which offered little resistance to the ingress of the masonry drill bit compared to unaffected concrete, as recommended in the Thaumasite Expert Group Report [1].

Finally 100 mm diameter cores were taken from each test specimen. These cores were tested in accordance with BS 1881-4:1970 [2] and the results converted into estimated in situ cube strengths in accordance with BS 6089:1981 [3].

3. Results and discussion

3.1. Theory used in analysis of results

Experimental bond strengths may be obtained from maximum experimental pullout forces using the following equation:

$$f_{b,max} = \frac{P}{\pi d l}$$

where $f_{b,max}$ = experimental bond strength, P = maximum experimental pullout force, d = diameter of reinforcement bar, l = embedment length of reinforcement bar.

BS 8110-1:1997 [4] states that the design ultimate anchorage bond stress may be obtained from the following equation:

$$f_{bu} = \beta\sqrt{f_{cu}}$$

where f_{bu} = design ultimate anchorage bond stress, f_{cu} = characteristic concrete cube strength, β = a coefficient dependent on the bar type.

Since BS 8110-1:1997 [4] indicates that design ultimate anchorage bond stress is directly proportional to the square root of characteristic concrete cube strength, it is necessary to take the compressive strength of the concrete into account when comparing the results of the pullout tests. This may be achieved by calculating an "experimental bond coefficient" using the following equation:

$$\text{Experimental bond coefficient of bar} = \frac{\text{Experimental bond strength of bar}}{\sqrt{\text{Estimated in situ cube strength of block}}}$$

It should be noted that the Highways Agency Concrete Bridge Assessment Code [5] adopts the BS 8110 values and the Thaumasite Expert Group Report [1] recommends that code values of bond strength should be used for plain bars.

3.2. General effect of TSA on bond

The experimental results of the pullout tests and core tests are contained in Tables 1 and 2. The four TSA-affected column sections are designated 1–4 whilst the two unaffected column sections are designated 5 and 6. In tabulating the experimental results the data are grouped according to bar location for each column section. This was done in response to an observation made during the test phase that the maximum experimental pullout forces for corner bars tended to be lower than those for non-corner bars. Inspection of the

Table 1
Core test and pullout test data for TSA-affected blocks

Block	Estimated in situ cube strength (N/mm^2)	Bar location	Experimental bond strength (N/mm^2)	Experimental bond coefficient
1	66.9	Corner	1.0	0.12
			4.6	0.56
			1.3	0.16
			2.6	0.32
		Non-corner	2.5	0.31
			4.4	0.54
			4.7	0.57
			4.8	0.59
			5.4	0.66
			4.9	0.60
			6.5	0.79
			4.7	0.57
2	72.5	Corner	4.6	0.54
			5.2	0.61
			4.0	0.47
		Non-corner	3.4	0.40
			3.8	0.45
			4.6	0.54
			4.5	0.53
			4.9	0.58
			2.7	0.32
			2.5	0.29
3	56.1	Corner	6.0	0.80
			3.8	0.51
			5.8	0.77
		Non-corner	4.8	0.64
			5.9	0.79
			6.5	0.87
			5.2	0.69
			5.3	0.71
			4.0	0.53
			5.5	0.73
4	76.5	Corner	2.8	0.32
			4.5	0.51
			2.4	0.27
			2.6	0.30
		Non-corner	3.6	0.41
			5.4	0.62
			6.0	0.69
			5.3	0.61
			5.0	0.57
			4.4	0.50
			4.7	0.54
			4.2	0.48

Table 2
Core test and pullout test data for unaffected blocks

Block	Estimated in situ cube strength (N/mm^2)	Bar location	Experimental bond strength (N/mm^2)	Experimental bond coefficient
5	73.3	Corner	5.3	0.62
			6.4	0.75
			4.9	0.57
		Non-corner	5.6	0.65
			5.9	0.69
			7.3	0.85
			5.5	0.64
			5.6	0.65
			5.3	0.62
6	73.6	Corner	5.1	0.59
			3.8	0.44
		Non-corner	5.7	0.66
			5.0	0.58
			4.9	0.57
			5.8	0.68
			3.9	0.45
			5.2	0.61
			5.3	0.62
			5.3	0.62

experimental bond coefficients in Tables 1 and 2 indicates that there is some merit in this observation in the case of TSA-affected column sections and so the subsequent statistical analysis of the data includes a consideration of bar location.

Table 3 contains a summary and statistical analysis of the experimental results. The statistical analysis of the experimental results uses a one-tailed Student t-test for two samples with unequal variance. The null hypothesis is that the mean experimental bond coefficient in the unaffected concrete is equal to that in the TSA-affected concrete, whilst the alternative hypothesis is that the mean experimental bond coefficient in the unaffected concrete is greater than that in the TSA-affected concrete. The chosen level of significance, ρ, is 5% and the test results are significant at the 5% level, indicating that the null hypothesis is untrue, i.e., the mean experimental bond coefficient in the unaffected concrete exceeds that in the TSA-affected concrete. TSA reduced the mean experimental bond coefficient by 24% for corner bars and 10% for other bars, representing an average reduction in mean experimental bond coefficient of 15% for all bars.

In addition, it should be noted that the coefficients of variation of the measured values of bond coefficient for corner bars and other bars in the TSA-affected concrete are 46.4% and 24.7% respectively, whilst the corresponding coefficients of variation for the bars embedded in unaffected concrete are 18.3% and 13.4%. A further consequence of TSA would therefore seem to be increased scatter in the experimental results, particularly in the case of the corner bars.

3.3. Effect of softened zone on bond

The bond between reinforcement steel and concrete is affected by the degree of cover. Figs. 3 and 4 show plots of experimental bond coefficient against the cover to bar diameter ratio for non-corner bars and corner bars, respectively. Cover is measured from the surface of a concrete element irrespective of the presence of thaumasite. The correlation coefficients for the trend lines are 0.71 and 0.62, respectively, and are statistically significant at the 5% level. It can be seen that TSA resulted in increased scatter in the measured values of bond coefficient and had a far greater detrimental effect on the bond strength of corner bars than on non-corner bars. The corner bars were tested after the tests on non-corner bars and, hence, it appears that more internal micro-cracking occurred in the TSA-affected concrete as the sequence of tests on a block proceeded. Whether or not this observation is relevant in practice depends on the order in which bars at a section would be predicted to slip.

Table 3
Summary statistics of core test and pullout test data

			Corner bars	Non-corner bars	All bars
Experimental bond coefficient results	Affected concrete	Mean	0.448	0.570	0.531
		Standard deviation	0.208	0.141	0.173
		Coefficient of variation (%)	46.4	24.7	32.6
	Unaffected concrete	Mean	0.595	0.636	0.625
		Standard deviation	0.109	0.085	0.091
		Coefficient of variation (%)	18.3	13.4	14.6
Student t-test (one-tailed and two samples with unequal variance)		Critical value, $\rho = 5\%$	1.761	1.685	1.672
		Test statistic	1.992	1.901	2.810
		Conclusion	Unaffected mean > SA-affected mean	Unaffected mean > TSA-affected mean	Unaffected mean > TSA-affected mean

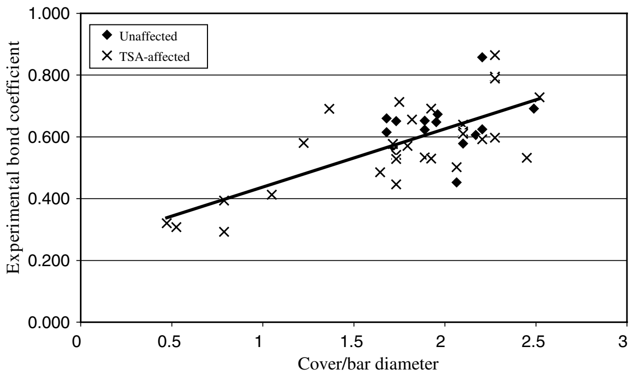

Fig. 3. Test results of non-corner bars: experimental bond coefficient against cover/bar diameter.

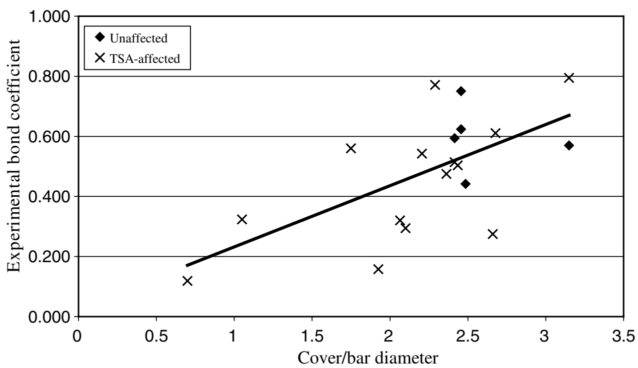

Fig. 4. Test results of corner bars: experimental bond coefficient against cover/bar diameter.

Figs. 5 and 6 show plots of experimental bond coefficient against the nett cover to bar diameter ratio for non-corner bars and corner bars, respectively. Nett cover is defined as cover less the depth of any softened zone. The correlation coefficients for the trend lines are 0.75 and 0.55, respectively, and are also statistically significant at the 5% level.

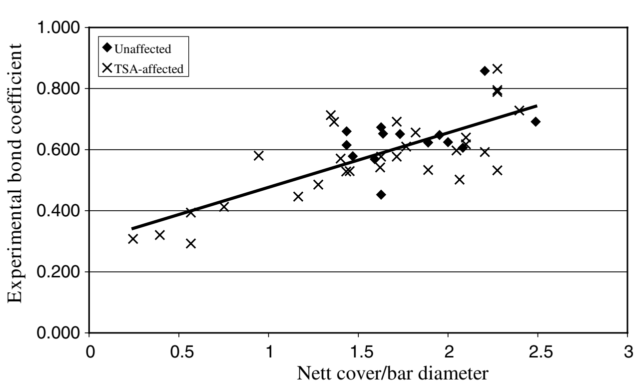

Fig. 5. Test results of non-corner bars: experimental bond coefficient against nett cover/bar diameter.

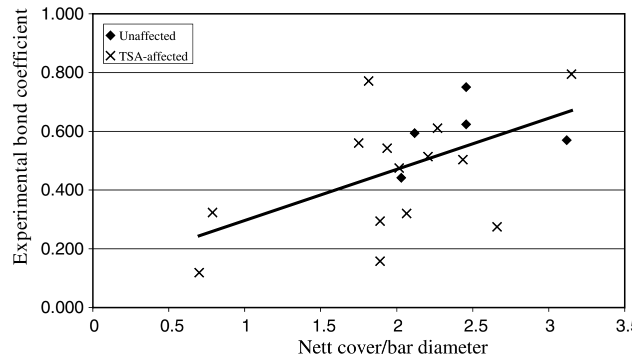

Fig. 6. Test results of corner bars: experimental bond coefficient against nett cover/bar diameter.

Figs. 5 and 6 indicate that bond is affected by nett cover and hence as the depth of softened zone increases one would expect the bond between reinforcement steel and concrete to reduce.

The Thaumasite Expert Group Report [1] implies a characteristic bond coefficient of 0.39 irrespective of cover and bar location. However, it is apparent that the nett cover does affect the bond strength. It should also be noted that the recommendation of the Thaumasite Expert Group Report [1], although generally conservative for non-corner bars, overestimates the bond strength when the nett cover is less than about 0.5 times the bar diameter. Hence, caution should be exercised for such small covers.

As discussed above the effect of TSA on the bond strength of corner bars in practical situations is not clear. However, in the absence of further data it would be prudent to take only 50% of the bond strength recommended in the Thaumasite Expert Group Report [1].

4. Conclusions

Based on the test results and discussions presented in this paper the following conclusions can be made:

- A statistical analysis of the experimental results indicates that the mean experimental bond coefficient of the plain round reinforcement bars in the unaffected concrete exceeded that of the plain round reinforcement bars in the TSA-affected concrete. These results are significant at the 5% level. TSA reduced the mean experimental bond coefficient by 24% for corner bars and 10% for other bars, representing an average reduction in mean experimental bond coefficient of 15% for all bars.
- Experimental data indicate that bond is affected by nett cover, and, as a consequence the bond between reinforcement steel and concrete decreases as the depth of softened zone increases.

- The Thaumasite Expert Group recommendation is conservative for non-corner plain bars except for nett covers less than 0.5 times the bar diameter.
- In the case of corner bars, until further data are available, it is recommended that the Thaumasite Expert Group values should be reduced by 50%.

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