CONTROL OF ASR EXPANSION BY COATINGS

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ABSTRACT

This paper presents the results of a two-year investigation carried out by the authors, in search of a scientific method in selecting coatings for the control of ASR induced expansion in concrete structures. The effectiveness of the coatings is evaluated and some of the important influencing factors are discussed. It is found that the water resistance of a coating is an important parameter and, by selecting an appropriate coating system and applying it at an early date, it is possible to control ASR induced expansion.

Keywords: concrete, ASR, expansion, coatings

INTRODUCTION

Alkali-silica reaction (ASR) is known to have affected many concrete structures in the UK and many other countries around the world. Even though it does not significantly affect the mechanical performance of a structural element (Clark 1989; Clayton *et al.* 1990; Fujii 1986), it can significantly reduce its durability. For instance, ASR affected concrete is more vulnerable to freeze-thaw attack (Bolton *et al.* 1992) and also to steel corrosion induced by the ingress of chloride ions or carbonation. To preserve the structural integrity of an ASR affected element, it is therefore important not only to arrest the further development of ASR, but also to effectively tackle its secondary effect on concrete durability.

One technique in tackling this problem is to coat the concrete with a proprietary system. If the right material is selected and correctly applied, it could be expected to reduce the further ingress of water and retard the development of ASR. At the same time, it can serve as a shield and protect concrete from taking up deleterious substances from the environment, ie. chloride ions, carbon dioxide and oxygen, hence preserving the durability of the structure.

There are many types of coatings available on the market, which claim to be suitable for the purpose. However, some research workers have demonstrated that the different coatings could deliver highly variable performances (Miyagawa et al. 1991; Blight 1989). Some coating systems have been found to be beneficial in reducing concrete expansion, but others actually appear to enhance this effect.

The main objective of this study is to investigate the physical characteristics of a coating which make it suitable, or unsuitable, for ASR expansion control. Also studied are other factors which could exhibit an influence on the results.

DESIGN OF EXPERIMENT

Theoretical Basis

The prerequisites for ASR are the presence of sufficient alkalis in the concrete, reactive aggregate and also water. In the absence of any one of the factors, reaction between aggregate and alkalis cannot continue. In existing structures, where ASR has been diagnosed, the control of the water content of the concrete (say, by coating), therefore, becomes the only feasible means of controlling the deleterious expansion caused by ASR.

The fundamental physical properties of a coating in connection with ASR control are its water and water vapour resistances. Other properties of a coating also contribute to its effectiveness, eg. adhesion to the substrate and elongation, but these are beyond the scope of this present study. While the water resistance of the coating measures its ability to resist the ingress of water from the environment, water vapour resistance gives an indication of the ease with which water contained in concrete capillary pores can evaporate. Since water plays a crucial role in the reaction of ASR, the less water contained in the concrete, the less the expansion and hence the damage. This, in fact, also applies in the case of reinforcement corrosion. Therefore, an ideal coating should be able to allow the water to escape from concrete freely (ie. water vapour resistance = 0) and, at the same time, to resist any water penetration, ie. water resistance = ∞. These two requirements are contradictory and such a coating may not exist in reality. However, it is useful to investigate the range of these two parameters within which a coating, effective for ASR control, can be found.

Practical Considerations

Under practical conditions, there are other factors which may also influence the effectiveness of a coating. These factors are considered below.

i) Coating coverage. This varies in practice, either by design or by default. In this study, manufacturers' recommended coverage was used as the starting point, and that was compared with the control (no coating), a 50% thinner coating and a 50% thicker (ie. 150%) coating.

ii) Initial expansion. This was to simulate the application of a coating at different stages during the concrete expansion. The coating was applied when concrete cylinder specimens reached an average expansion of e_1= 0.09% (0.035% for prisms) or e_2 =0.155% (0.055% for prisms); in all cases cracks had appeared on the specimens.

iii) Exposure conditions. Both natural outdoor exposure (N) and accelerated (A) laboratory tests were employed. Under the accelerated test conditions, specimens were exposed to a temperature of 38°C and a cyclical wetting for 8 hours and drying for 4 hours.

iv) Volume/surface ratio. The volume/surface ratio of the concrete element is important as it alters the length of the vapour diffusion path to the nearest surface and, hence, affects its drying process. In this study, prism (P) and cylindrical (C) specimens were used and they had volume/surface ratios of 20 and 40mm respectively.

v) Initial moisture state. The initial moisture state of the concrete may affect the performance of coatings through altering the quantity of water contained in the concrete and, thus, the time to dry out. Specimens were coated either in a saturated-surface-dry condition or after a brief period of drying for two hours in the laboratory.

Materials and test specimens

Three different types of coatings were selected for this study. BR1 is an elastomeric paint system of single component products. BR2 is a penetrating water repellent based siloxane and BR3 is a masonry textured coating with vinyl/toluene as active components.

The concrete mix was based on that recommended by the Building Research Establishment, which had a 28 day strength of $53N/mm^2$ and an ultimate expansion of 0.5%. The mix contained, per cubic metre, 400kg cement, 180 l water, 1295kg limestone coarse aggregate and 545kg Thames Valley sand. Additional salts (potassium sulphate at 6.74kg, and sodium sulphate at 2.66 kg) were added to bring the total alkali content of the concrete to 7 kg/m^3.

The concrete was thoroughly mixed and placed in moulds of 150mm diameter by 260mm long cylinder specimens and 76 x 76 x 297mm for prism specimens. The specimens were demoulded at 1 day and were then covered by wet hessian and polythene sheet for a month. Before the test commenced, all the specimens were coated on both ends with a modified bitumen waterproof coating to prevent water ingress or loss. "Demec" studs were then glued to both sides of the prism specimens and the cylinder specimens at angles of 180°.

Experiment Using Partial Factorial Design

In view of the large number of factors considered and their respective variations, it was more feasible and economical to use the partial factorial technique to design the experiment. It allowed the effect of each influencing factor to be evaluated using a minimum number of specimens. In this project, a (4×2^4) design was selected, which could cope with one factor with 4 levels (variations) and 4 factors with 2 levels. The test series which resulted is shown in Table 1. The relative importance of an individual factor is determined by the maximum difference in its experimental results: the greater its value, the more significant this factor is. In addition, the effect of the variations of a particular factor can also be assessed (as shown later in Fig 2).

Table 1. Design of partial factorial experiment

Specimen No	Coating Thickness (0,50,100,150%)	Initial Expansion (e_1, e_2)	Exposure (Accelerated, Natural)	Specimen Type (P,C)	Condition of Coating (Wet/Dry)
1	0	e_1	A	P	W
2	0	e_2	N	C	D
3	50	e_1	A	C	D
4	50	e_2	N	P	W
5	100	e_1	N	P	D
6	100	e_2	A	C	W
7	150	e_1	N	C	W
8	150	e_2	A	P	D

Test methods

The test consisted of two parts, one being the study of the effectiveness of the coating (expansion test), and the other the measurements of its water permeability and water vapour permeability.

Concrete specimens were monitored at regular intervals for dimensional changes via Demec gauges. Before the measurements were taken, all the specimens were brought into the laboratory for a 5-hour conditioning period to stabilise temperature and surface moisture conditions.

The coatings were tested for both water vapour and water permeability. The definition of permeability is the time rate of water or water vapour transmission through a unit area of a flat material of unit thickness induced by a unit pressure difference between two specific surfaces, under specified temperature and humidity conditions. The test method for water-vapour permeability is described by Dhir *et al* (1989) and the specimens after the test were used to measure their water permeability using a water head of 20 metres.

TEST RESULTS AND DISCUSSIONS

Expansion test

The expansion test continued for around 400 days and some typical results are shown in Fig 1. These results relate to specimens, under accelerated test conditions, with coatings applied at the manufacturers' recommended rate at an age of one month after casting.

As the test programme was most concerned about the control of expansion caused by ASR, it can be seen from Fig 1 that the performance of different coatings varied considerably. Whilst BR1 performed better than the control with around 20% reduction in expansion at later age, the performance of BR2 and BR3 is similar or even slightly worse than that of the control.

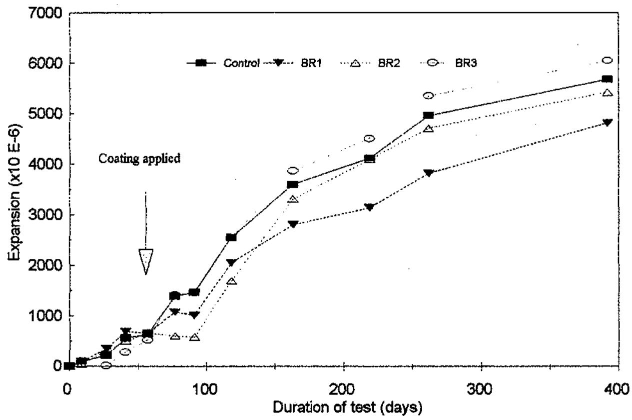

Figure 1. Effect of coating on ASR affected concrete

From the results of continuous monitoring, statistical factorial analysis was carried out, in line with that described previously, to determine the significance of those five chosen factors which influenced the effect of coatings. Some typical outcome of the analysis are shown in Fig 2 (392 days), on which the following discussions are based.

Effect of Coating Coverage

The coverage of coating, or its rate of application, has a significant impact on expansion of concrete, as illustrated in Fig 2(a). At lower coverages, concrete expansion actually increases, rather than reduces, compared with the control. At a high coverage rate, ie. 150% manufacturers' recommended figure, however, all the coatings have shown a beneficial effect, by reducing concrete expansion between 25% and 35%. If this trend persists, it is possible that further reduction may be expected if the coverage rate is further increased.

Initial Expansion

The effect of the initial expansion, or delay in applying the treatment, is shown in Fig 2(b). It is evident that with an earlier application of coating, concrete expansion reduces. This is true of all the three types of coating tested. Translated into practice, this means that, if ASR is diagnosed, early treatment of the concrete element concerned would produce better results in terms of crack control.

Exposure

In the accelerated test, a higher temperature and an alternating wet/dry cycle were employed to speed up the alkali-silica reaction. The effect is apparent as demonstrated clearly in Fig 2(c). The effect of the accelerated test was to speed up ASR expansion by a factor of approximately 4 times, compared with natural outdoor exposure conditions.

Volume/Surface ratio

The effect of volume/surface ratio of the specimens on concrete expansion is shown in Fig 2(d). It is clear that, with an increase in the volume/surface ratio of the concrete element, concrete expansion is increased. This means that, in practice, the task of controlling ASR expansion may become more difficult the greater the cross section of the concrete member.

Specimen condition before coating

The effect of specimen condition at the time of coating is shown in Fig 2(e). It was initially expected that, if the coating was applied to wet concrete, more water would be trapped in and, therefore, concrete expansion would be greater. However, experimental evidence disapproved this hypothesis and, for some of the results shown in the figure, the opposite was true. Within the practical range, the wetness of concrete can therefore be assumed to have no significant effect on concrete expansion in the long term. As a good practice, however, coatings should be applied when concrete is at least surface dry to maximise its adhesion to the substrate.

Relative significance of influencing factors

The relative significance of each factor is judged by the maximum difference in its test results, as discussed previously. From the results presented in Figure 2, the ranking order for different factors can be arranged as follows:

Exposure > Volume/surface ratio > Coating coverage
> Initial expansion > Initial moisture state

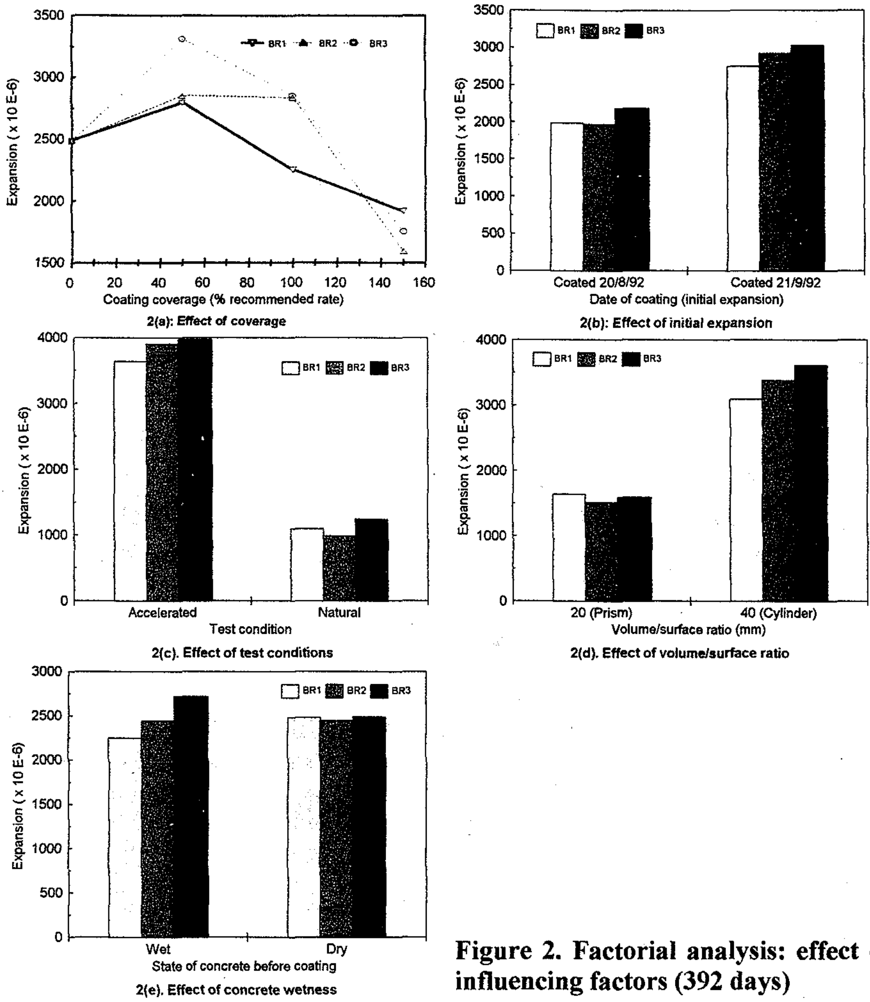

Figure 2. Factorial analysis: effect of influencing factors (392 days)

It is therefore clear that, apart from the exposure conditions, which would be expected to exhibit a significant influence and is, in any case, determined by the location of a structure, the coating coverage rate and the volume/surface ratio of the concrete member are the two most important factors governing the further expansion of the ASR affected concrete. Whilst the second factor is inherent in the design of the concrete structure and, therefore, cannot be modified, the coverage of the coating can be specified to optimise its beneficial effect.

Water permeability and water vapour permeability

The results of water and water vapour permeability (k) tests are shown in Table 2, together with their resistances at manufacturers' recommended coverage rates. The resistance (R) is calculated by dividing film thickness by the coefficient of permeability, k.

Table 2. Results of measured permeability (k) and calculated resistances

	Water Vapour			Water		
	BR1	BR2	BR3	BR1	BR2	BR3
k, $x10^{-12}$ m/s	0.945	n/a	7.65	16.6	n/a	52.1
R, $x10^7$ s	42.3	2.17	7.90	2.40	0.25	1.17

Resistances of coatings and their relation to ASR control

One of the major objectives of this study was to investigate the properties of coating and their effect on ASR expansion. In Fig 3, the water resistance and water vapour resistance of the coatings are plotted against the mean concrete expansion. Despite the scatter of the results, it appears that expansion reduces with an increase either in the water resistance of the coating, as shown in Fig 3(a), or in the water vapour resistance, Fig 3(b). This suggests that, within the range of coatings and their coverages used in this study, the coatings' ability to resist water ingress is more important in controlling ASR than their ability to let water vapour escape. After all, in real structures where the concrete cross sections could be substantial, reduction in water content through vaporization is rather insignificant. Therefore, it may be deduced that a higher rate of coating coverage, in general, would result in better control of concrete expansion due to ASR. The tentative suggestion is that, to control ASR expansion effectively, the minimum requirement for the water resistance of a film-forming coating should be 1.5 x 10^7s.

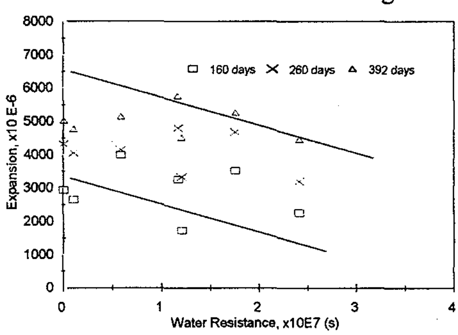

Fig 3(a). Expansion - water resistance

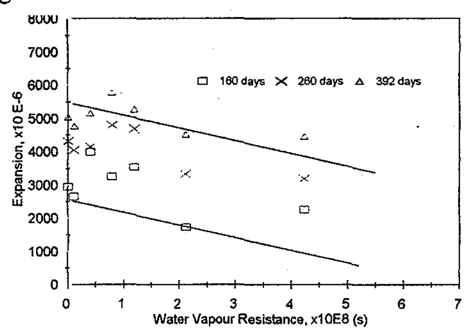

Fig 3(b). Expansion -vapour resistance

Figure 3. Effect of coating properties on concrete expansion

CONCLUSIONS AND RECOMMENDATIONS

Based on the results of this study, the following conclusions can be drawn:

1) The application of coating affects the expansion of concrete caused by ASR.

When the coating coverage is low, it tends to increase concrete expansion. However, at a higher coverage rate, say 50% over manufacturers' recommended figure, all three different coatings have shown to be effective in reducing concrete expansion. It therefore follows that the effective control of ASR expansion is critically dependent upon the water resistance of the coating. This study suggested that, to control ASR expansion effectively, the minimum requirement for the water resistance of a film-forming coating should be 1.5×10^7s.

2) To enable the control of ASR-induced expansion, the coating should be applied earlier rather than later. This requires, in practice, an early treatment of the concrete member once ASR has been diagnosed.

3) The geometry of the concrete element affects the effectiveness of coating treatment. The smaller the concrete volume/surface ratio (ie. the smaller the cross section), the more likely that the ASR expansion can be brought under control using a coating.

4) The initial moisture state of the concrete, prior to the application of the coating, was found to exert little influence on the ultimate expansion.

5) The relative significance of those influencing factors follows the order of volume/surface ratio > coating coverage > initial expansion > initial moisture state.

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