THE 9TH INTERNATIONAL CONFERENCE ON ALKALI – AGGREGATE REACTION IN CONCRETE 1992

SUPPRESSION OF DAMAGE FROM ALKALI SILICA REACTION BY FLY ASH IN CONCRETE DAMS

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This paper reports the findings from an investigation of two mass concrete hydraulic dams forming part of a hydro-electric scheme. One of these dams was severly cracked and laboratory examination of cores taken from the structure diagnosed alkali silica reaction of greywacke aggregate to be the primary cause of damage, although evidence of frost damage was also found close to the surface (100mm). The second dam was in excellent service condition despite the use of the same reactive greywacke aggregate. Construction records and later examination showed that fly ash had been used in this structure.

INTRODUCTION

Although the use of fly ash as a partial replacement for Portland cement is generally accepted as a means of reducing the risk of damaging alkali silica reaction (1,2), there is still conflicting evidence concerning the effectiveness of fly ash in this rôle. Much of this conflict originates from laboratory studies using reactive aggregates, alkali levels, cement contents or storage conditions that accelerate the reaction and do not represent conditions that exist in practice.

Fly ash has been widely used in concrete construction in the U.K. for over thirty years and to date there has not been a single reported case of damage due to alkali silica reaction in a fly ash concrete structure in the U.K. However, although the evidence from the case histories suggests that fly ash has a beneficial effect of suppressing damaging alkali silica reaction in the field,little credence will be given to the evidence unless the precise rôle of the fly ash can be evaluated independently of other variables. In order to achieve this, reference to comparable cases without fly ash are desirable; i.e. cases where variables such as aggregate type, cement content, alkali level, exposure, type and age of structure are similar.

This paper reports on two mass concrete dams within a single hydro-electric scheme in the U.K. that together provided an opportunity to compare the condition of concrete structures with and without fly ash and with a reactive aggregate after thirty years service.

RHEIDOL SCHEME

The Rheidol Hydro-electric Scheme was constructed between 1957 and 1962 and consists of three mass concrete dams, Nant-y-Moch, Dinas and Cwm Rheidol, and two main generating stations at Dinas and Cwm Rheidol. Only the Nant-y-Moch and Dinas dams are of interest here and a brief description of their construction is given below, more comprehensive details having been reported elsewhere (3,4)

The Nant-y-Moch dam is a buttress dam and was constructed using a crushed greywacke aggregate from the nearby Carn Owen quarry (3). The concrete to the upstream face (1.25m thick) is reported to have a total cement content of 380 kg/m^3 whereas the hearting concrete has 252 kg/m^3 of cement (3). In both concretes 25% of the cement was replaced with fly ash.

TABLE 1 - Typical Composition of Cements

Oxide	Nant-y-Moch		Dinas
	Fly ash[1]	Cement[2]	Cement[3]
SiO_2	46.4	23.4	21.2
Al_2O_3	27.7	5.1	6.5
Fe_2O_3	14.1	2.4	1.9
CaO	2.1	62.7	64.5
MgO	1.8	2.2	1.3
K_2O	4.4	0.7	0.75
Na_2O	1.0	0.2	0.13
SO_3	0.7	1.4	2.6
LOI	6.4	2.2	1.4
Na_2O_e	**3.88**	**0.66**	**0.62**

[1]average analysis for 1977-1987 (source CEGB)
[2]analysis for 1959 OPC sample (source BRE)
[3]analysis for 1962 RHPC (source cement works)

The Dinas dam is an arch dam which was constructed using the same source of greywacke aggregate as the Nant-y-Moch dam and the concrete used was generally of the same specification (4) although no fly ash was used.

Site records show that different sources of Portland cement were used for Nant-y-Moch and Dinas dams. The source of fly ash used in Nant-y-Moch was Bold Power Station. Chemical analyses for these materials have not been reported, but typical analyses of materials from these sources are given in Table 1.

EXPERIMENTAL

Visual Examination

A visual examination of the dams was carried out by the authors in 1991. The Nant-y-Moch dam showed no external indication of distress and all parts of the structure appeared to be in satisfactory condition.

The Dinas dam was severely cracked in many places and most parts of the structure that were visible showed some degree of cracking. The downstream face showed a series of horizontally orientated cracks approximately 200mm apart and often spanning the width of the lift. Lime leaching was associated with many of these cracks and moisture appeared to be exuding from some of the wider cracks. The abutments also showed extensive cracking with a more random pattern and crack widths in excess of 5mm were observed. Lime deposits and exudation activity were also associated with many of these cracks.

Sampling

A number of concrete cores (Φ100x500mm) were taken from both dams. For the Nant-y-Moch dam, cores were taken from the upstream face (facing concrete), about 2m below the level of the spillway (this location would periodically be submerged by the reservoir), and from the buttresses at downstream ground level (hearting concrete). Most parts of the Dinas dam were inaccessible and the location of coring was restricted to the western abutment, about 2m above the level of the spillway. This area was characterized by extensive randomly orientated cracks at the surface.

The cores from the abutment of the Dinas dam generally showed cracking parallel to the surface in the outer 100mm. Cracking of a more random nature was observed at greater depths. Damp patches were observed around many of the coarse aggregate particles and on fracture surfaces and white reaction rims were in evidence around the perimeter of the coarse aggregate. Gel deposits were located in some of the pores and within cracks in the fracture and cut surfaces of the cores.

None of these features were observed for the cores from the Nant-y-Moch dam.

A sample of material (approximately 500kg) was taken from a stockpile at the Carn Owen quarry.

Petrographic Examination

Petrographic sections (100x100mm) were prepared both from the surface region of cores and at depth (>300mm). The results from petrographic examination are summarized in Table 2. Considerable evidence of alkali silica reaction was found in the concrete from the Dinas dam and the reaction was invariably associated with the coarse fraction of the aggregate. There was no indication of reaction of the chert in the fine aggregate. Evidence of frost damage in the form of cracking parallel to the surface was also found in the section that included the original dam surface, but these features were not observed at greater depths.

No evidence of asr or frost damage was detected in the concrete from the Nant-y-Moch dam.

Chemical Analyses

A sample of the concretes from Nant-y-Moch (hearting concrete) and Dinas dams and the aggregate from Carn Owen were crushed (sub-75 μm) and subjected to determinations of water-soluble (10:1 water extract shaken for 24h), acid-soluble (heated with dilute HNO_3) and total (breakdown by HF and H_2SO_4 and extracted with dilute HCl) alkali content. In addition, the alkalis leached by $Ca(OH)_2$ were determined for the aggregate sample by agitating a 5g sample of aggregate in 25ml of saturated $Ca(OH)_2$ solution at 38°C for 28 days. In all cases the extracts were analyzed for alkali ions by atomic absorption.

The results of these analyses are given in Table 3.

Expansion tests

Sections of cores were selected for expansion testing using the BCA standard method of test (5) of storing specimens over water in sealed containers at 38°C. Following 6 months storage none of the specimens had expanded significantly, all expansions being less than 0.025%. These results suggest that there is little potential for further expansion due to alkali silica reaction in these concretes.

Expansion measurements were also made on cores stored in 1M NaOH at 80°C. After 6 months, samples from Dinas dam had expanded by 0.305% compared with 0.122% for Nant-y-Moch dam. Expansions of this order would suggest that a significant quantity of reactive aggregate is still present in both structures.

A sub-sample of the material collected from Carn Owen quarry was crushed to produce both coarse and fine aggregate. Expansion tests were then carried out on concrete prisms cast using this aggregate. These tests were carried out using a draft British Standard for determining the reactivity of aggregate. Briefly this tests consists of manufacturing prisms with the test aggregate at a cement content of 700kg/m^3 and alkali content of 7 kg/m^3 Na_2O_e (adjusted by adding K_2SO_4 to mixing water) and carrying out expansion measurements on prisms stored under moist conditions at 38°C.

Concrete prisms cast with greywacke aggregate from Carn Owen quarry showed expansions of 0.22% after 12 months which is characteristic of aggregate of moderate to high reactivity. Expansion tests on concretes with lower proportions of greywacke (greywacke blended with "inert" limestone) showed reduced

TABLE 2 - Summary of findings from Petrographic Examination of Concretes

Section location		Petrographic observations			
Dam	Depth (mm)	General	Coarse aggregate	Fine aggregate	Diagnosis
Nant-y-Moch (facing and hearting concrete)	0-100	Fly ash present. Slight microcracking (<10 μm) typical of paste shrinkage during specimen preparation	Crushed sandstones and sub-greywackes with small proportions of mudstones and siltstones.	Crushed material with same mineralogy as coarse aggregate combined with quartz-rich gravel with acid volcanics, metaquartzite, limestone and chert.	Integrity of concrete intact with no evidence of damage
	300-400				
Dinas	0-100	No fly ash. Cracking sub-parallel to surface diminishing with depth (typical of frost damage). Gel present in some cracks and around coarse aggregate particles	Crushed sandstones and sub-greywackes with small proportions of mudstones and siltstones.	Predominantly quartz-rich gravel with metaquartzite and chert. Some crushed material similar to coarse fraction.	Alkali-silica reaction has occurred throughout the concrete and appears to be the primary mechanism for deterioration at depth. Cracking close to the surface is typical of frost damage. It is not possible to determine whether asr or frost damage is the predominant cause of deterioration in the surface concrete.
	370-470	No fly ash. Cracking widespread and severe (>500 μm) associated with coarse aggregate particles. Gel abundant in cracks and around coarse aggregate.			

TABLE 3 - Alkali Content of Concrete and Aggregate Samples

Sample	Alkali content (% Na_2O_e)			
	Water sol.	Acid sol.	Total	Leached by $Ca(OH)_2$
Nant-y-Moch	0.10	0.15	2.36	n.d.
Dinas	0.07	0.12	1.89	n.d.
Carn Owen Aggregate	<0.01	0.08	1.47	0.036

expansions indicating that the aggregate does not have a pessimum proportion.

Expansion testing of concretes containing this aggregate with a range of alkali levels and both with and without fly ash is currently under way at BRE. To date, expansion has only been observed in concretes without fly ash and at alkali contents above 5 kg/m^3 Na_2O_e. Concretes with fly ash show no expansion even when the alkali content from the ordinary Portland cement (disregarding any contribution of alkalis from the fly ash) is significantly greater than 5 kg/m^3 Na_2O_e.

Alkali-immersion test.

Ground surfaces were prepared on some sections of the concrete cores and these were immersed in a solution of NaOH (20g/l), KOH (28g/l) and CaO (0.2g/l) at 38°C. After 28 days immersion, gel growths were detected on all the ground surfaces irrespective of which dam they originated from. Most of the gel was associated with greywacke particles in the coarse fraction either exuding from the ground surface of the aggregate or filling discontinuities within the aggregate. Small quantities of gel were also identified on the ground surfaces of a limited number of chert particles in the fine fraction of the concrete from both dams. These occurrences became more frequent as the duration of immersion was extended.

These observations confirm that alkali-reactive aggregate is present in both concretes.

Properties of concrete cores

The results of compressive and tensile strength and the UPV testing are given in Table 4. The tensile strength was determined by a gas pressure test (6) which has been found to be particularly sensitive to the effects of alkali silica reaction and other forms of internal distress (7). The concrete from the Nant-y-Moch dam has greater strength and UPV compared with the concrete from Dinas dam. This is particularly noteworthy as these tests were performed on the hearting concrete from Nant-y-Moch which has a much lower cement content than the concrete tested from Dinas. The differences between the properties of the concretes are particularly marked for tensile strength, the tensile/compressive strength ratio being 0.03 for Dinas and 0.07 for Nant-y-Moch. A value of 0.07 is consistent with normal concrete (8) whereas the lower value of 0.03 falls within the range previously reported for concrete affected by alkali silica reaction (9).

TABLE 4 - Properties of Concrete Cores

Sample	Strength (MPa)		UPV (km/s)
	Compressive	Tensile	
Nant-y-Moch	56.0	3.8	4.96
Dinas	39.5	1.3	4.41

Other relevant data

The greywacke deposits of the United Kingdom have been extensively examined at BRE and the deposits from Wales have been found not to be moisture- or frost-susceptible (unpublished data).

DISCUSSION

Collectively the results show that alkali silica reaction has occurred in the Dinas dam. The source of reactive silica is a locally quarried greywacke. Greywacke has previously been implicated as a cause of damaging alkali aggregate reaction in a structure in the same region as the Dinas dam (10) and in many other structures around the world (11-15). Recent studies have indicated that the reaction with the Welsh greywacke involves silica minerals (10) as opposed to the silicate minerals proposed in the reaction of a similar greywacke in the Malay Falls Dam in Canada (11).

The Dinas dam is extensively cracked with some crack widths at the surface measuring in excess of 5mm. Examination of the concrete has indicated alkali silica reaction to be the primary mechanism causing cracking at depth. However, there is evidence of the co-existence of frost damage at the surface. The aggregates used are not frost-susceptible and no evidence of frost damage was observed in the fly ash concrete containing this aggregate (Nant-y-Moch) and subjected to similar exposure. The susceptibility of concrete to frost damage will be increased by the effects of alkali silica reaction due to the loss of tensile strength and formation of cracks, which will permit the ingress of water and form sites of expansion during freezing. The frost damage observed in the Dinas dam may have occurred as a result of early alkali silica reaction, although this has not been confirmed.

Expansion testing of cores from the Dinas dam show that there is no potential for further expansion due to alkali silica reaction unless the concrete is exposed to an external source of alkali. However, in its present condition the structure is extremely vulnerable to further frost damage.

The original alkali content of the concrete used in the Dinas dam may be calculated from assumptions of the cement content and alkali level of the cement (see section 2.0) to be of the order of 2.4 kg/m^3 Na_2O_e. This assumes that no alkali contribution is made by the aggregate. However, it has been suggested that some of the alkalis in greywacke may be leached out by solutions of $Ca(OH)_2$ (16), and this was confirmed in the present study for the Carn Owen aggregate. The total alkali leached was 0.036% Na_2O_e (by mass of aggregate) and if all of this alkali were to be released from the coarse aggregate fraction in the Dinas dam, the available alkali level in the concrete would be increased by more than 0.5 kg/m^3 Na_2O_e. The calculated total available alkali content would then be consistent with the measured acid soluble alkali content of the concrete which was 0.12% (equivalent to 2.8 kg/m^3 Na_2O_e). The close agreement between calculated and measured alkali levels, however, does not allow for the inevitable loss of alkalis due to leaching which should lead to a lower measured value following thirty years exposure.

It is interesting that only the greywacke aggregate showed signs of reaction in the concrete from the Dinas dam although potentially reactive chert was also present. This would suggest that greywacke reacts at a lower alkali level than chert.

Current U.K. guidelines for avoidance of damage due to alkali silica reaction (1,2) specify a maximum permissible alkali level of 3kg/m^3 Na_2O_e in concrete containing potentially reactive aggregate. From a consideration of the above discussion it is likely that the damaging alkali silica reaction observed in the Dinas dam occurred at alkali levels below 3kg/m^3 Na_2O_e and thus adherence to the existing recommendations would not have prevented it.

The use of fly ash to suppress expansion due to alkali silica reaction is permitted by these same guidelines but there is not currently a consensus regarding how fly ash should be specified. There is conflicting evidence concerning the contribution of alkalis from fly ash to the reaction and it has been suggested that one sixth of the total (acid-soluble) alkalis in fly ash should be considered when calculating the total available alkalis in concrete (1,17). In contrast, other workers have shown that fly ash concrete can tolerate higher alkali contents than concretes without fly ash even when the alkalis from the fly ash are disregarded (18-21).

It is apparent from this investigation that the partial replacement of ordinary Portland cement with fly ash was sufficient to completely suppress damage due to alkali silica reaction in the Nant-y-Moch dam. The presence of a reactive aggregate in this dam was established by alkali-immersion and expansion tests and petrography confirmed the evidence from site records that the aggregate was mineralogically similar to the reactive aggregate in the Dinas dam.

The Portland cement used in the Nant-y-Moch dam had a similar alkali content to that used in the Dinas dam. The alkali content of the fly ash used was moderately high by U.K. standards resulting in a concrete with a significantly higher alkali content compared with the concrete in the Dinas dam (see Table 3). The adoption of a procedure based on assuming an alkali contribution from the fly ash of one sixth of its total alkali would clearly have been a conservative approach in this case.

Taking together the findings of this study and the lack of evidence of alkali silica reaction in fly ash concrete structures in the U.K., it is clear that fly ash has considerable potential as a means of suppressing damaging alkali silica reaction in field situations.

ACKNOWLEDGEMENTS

The authors would like to thank the Mr. D. McFarlane of PowerGen for his co-operation and Mr. D. Harrison and Mr. L. Faulkner of National Power and Mr. C. Haynes of BRE for their assistance on site.

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