50 Years Old and Still Going Strong

Fly ash puts paid to ASR

by Michael Thomas, R. Doug Hooton, Chris Rogers, and Benoît Fournier

The use of fly ash for controlling damaging alkali-silica reaction (ASR) was first reported in 1949 by Robert Blanks of the U.S. Bureau of Reclamation.[1] Since then, hundreds of papers have reported the results of laboratory studies on the efficacy of fly ash in this role. While many specifications now permit the use of potentially reactive aggregates, provided a sufficient level of fly ash (or other preventive measure) is used in the concrete, there have been relatively few documented cases of major structures where fly ash has been successfully used together with reactive aggregates.

A paper on two such cases, the Nant-y-Moch Dam in Wales, U.K., and the Lower Notch Dam in Ontario, Canada, was published by the primary author when those facilities were about 35 and 25 years old, respectively.[2] The dams were revisited in 2010 when they were about 50 and 40 years old; this article summarizes the performance of these structures with regard to ASR. Studies of performance in the field are essential for confirming the efficacy of preventive measures observed in the laboratory and for benchmarking accelerated laboratory tests intended for the rapid evaluation of such measures.

Nant-y-Moch Dam

The Nant-y-Moch Dam is part of the Cwm Rheidol Hydroelectric Scheme, which was constructed between 1957 and 1962 in central Wales, about 17 km (10 miles) east of the town of Aberystwyth. Downstream from Nant-y-Moch is the Dinas Dam, which forms part of the same hydroelectric scheme (Fig. 1). Both dams were built at the same time using aggregates from the same source. Details of the materials and mixture proportions used for these dams are given in Table 1.

Problems with the Dinas Dam were first observed in 1986 in the form of map cracking and the development of a major longitudinal crack in the arch section[3]; ASR was subsequently verified as the cause of deterioration. When the primary author visited the dam in 1991, extensive cracking of the dam was observed at all exposed locations.[2] Horizontal cracks were observed on the downstream face, along the crest, and on the visible part of the upstream face of the arch. The gravity abutments showed random map cracking, with crack widths in excess of 5 mm (0.25 in.). In 1997, survey data was used to show that the dam had experienced a total upstream radial movement of 115 mm

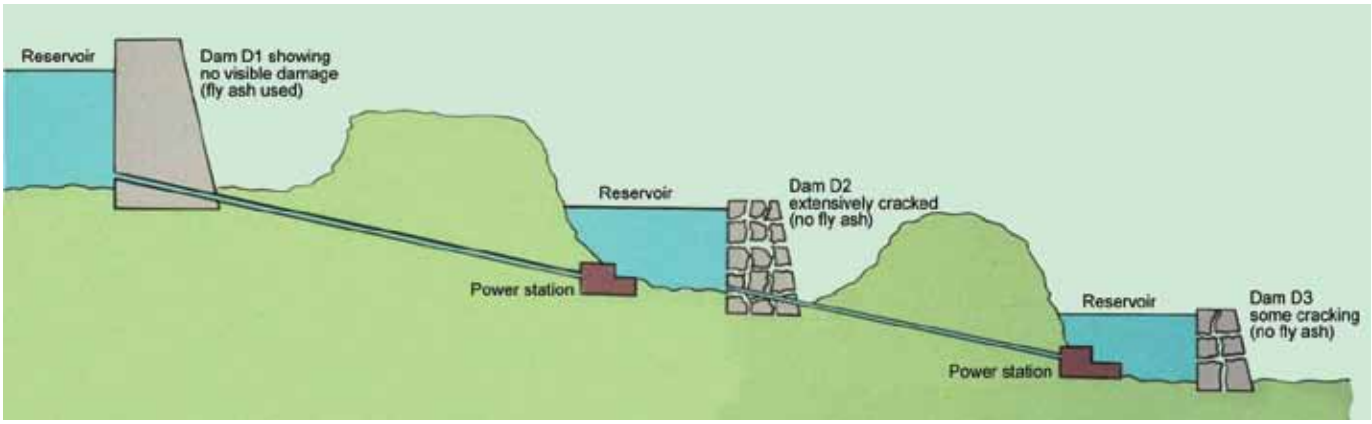

Fig.1: Schematic diagram showing the Cwm Rheidol Hydroelectric system, including the Nant-y-Moch Dam (D-1) and the Dinas Dam (D-2)

(4.5 in.) and an increase in height of 30 to 40 mm (1.2 to 1.6 in.); both movements are relative to the center of the crest at the highest point of the dam.[3] Upper and lower limits were placed on the reservoir draw down due to stability concerns, and this necessitated the installation of post-tensioned horizontal straps on the upstream face of the dam crest (Fig. 2). Visual inspection by the primary author in 2010 revealed that the deterioration had advanced significantly in the 19 years since his initial inspection in 1991; crack widths of 10 to 20 mm (0.38 to 0.75 in.) were observed in the gravity abutments (Fig. 2).

Petrographic examination of cores taken in 1991 confirmed that ASR was the main cause of damage to the concrete. The examination included a semi-quantitative rating of the concrete condition and symptoms of ASR using the procedure developed by Grattan-Bellew[4] to determine a Damage Rating Index (DRI). The concrete sampled from the Dinas Dam had a DRI of 628—well above the DRI level considered indicative of extensive ASR.

It is somewhat alarming to observe this level of ASR activity in a structure built with a cement with an alkali content only slightly higher than the limit imposed by ASTM C150 for low-alkali cement (0.60% Na_2Oe) in conjunction with a relatively low cement content. Based on the cement contribution, the concrete alkali content was just over 1.8 kg/m^3 (3.0 lb/yd^3) Na_2Oe, but there is some conjecture that the greywacke aggregate may have also contributed alkalis to the concrete.[2]

Visual inspection in 1991 revealed no symptoms of ASR in the Nant-y-Moch Dam. Petrographic observations on cores confirmed the absence of ASR, and the DRI for the fly ash concrete was less than 50, indicating no ASR activity. The 1.22 m (4 ft) thick facing concrete used at the upstream face showed no signs of cracking, even though the alkali contributed by the portland cement component of the concrete mixture was slightly higher than that of the Dinas Dam (Table 1), and the fly ash constituent had an alkali content of 3.88% Na_2Oe.[2]

Cores taken from the two structures in 1991 revealed that the concrete from the Nant-y-Moch Dam had significantly higher water-soluble, acid-soluble, and total alkali contents than the concrete from the Dinas Dam. For example, the respective water-soluble alkali contents were 2.35 kg/m^3 (3.92 lb/yd^3) Na_2Oe and 1.65 kg/m^3 (2.74 lb/yd^3) Na_2Oe, indicating that the fly ash has a positive impact on ASR beyond mere dilution of the alkalis contributed by the cement.

The Nant-y-Moch Dam was still found to be in excellent condition when inspected in 2010 (Fig. 3). Apart from some

Table 1:
Details and observations of Nant-y-Moch and Dinas Dams[2]

	Nant-y-Moch Dam	Dinas Dam
Structure type	Massive buttress dam	Partially reinforced arch
Overall length, m (ft)	350 (1148)	108.2 (355)
Maximum height, m (ft)	52 (171)	26.5 (87)
Portland cement content, kg/m^3 (lb/yd^3)	Facing*: 285 (475) Core: 189 (315)	295 (492)
Cement alkalis, % Na_2Oe	0.66	0.62
Total calculated cement alkali, kg/m^3 (lb/yd^3) Na_2Oe	Facing: 1.88 (3.14) Core: 1.25 (2.08)	1.83 (3.05)
Fly ash, kg/m^3 (lb/yd^3)	Facing: 95 (158) – 25% Core: 63 (105) – 25%	None
Aggregates	Coarse: Greywacke-Argillite from Carn Owen Quarry Fine: Local pit sand with some quarry sand (Carn Owen)	
Condition survey, petrographic examination and DRI† performed in 1991[2]	No symptoms of ASR in the field and no microscopic evidence of ASR in core samples (DRI = 45)	Severe cracking observed and confirmed by petrographic examination to be caused by ASR (DRI = 628)
Visual inspection in 2010	No symptoms of ASR	Cracking advanced since 1991 inspection; repairs (post-tensioning) observed at crest level on upstream face

*"Facing" is a 1.22 m (4 ft) thick zone of concrete on the upstream face of the dam; the balance of the concrete thickness is termed "core"

†DRI is Damage Rating Index. This index provides a semi-quantitative rating of the concrete condition and symptoms of ASR and was performed according to the procedure developed by Grattan-Bellew.[4] DRI > 600 indicates extensive ASR

calcite deposits associated with the construction joints on the downstream face, the concrete is unblemished and there are no symptoms of ASR in either the core or the facing concrete.

At the time of the construction of the Nant-y-Moch Dam, ASR was not considered to be a problem in the U.K.—fly ash was used in the concrete for economy and to control the temperature rise in massive concrete placements. Since then, greywacke aggregates with similar mineralogy as that used in the structures at Cwm Rheidol have been implicated as the cause of ASR in other structures in Wales (most notably, the Maentwrog Dam, which had to be replaced in 1992[5]), so the prevention of ASR expansion attributed to the incorporation of fly ash can be considered fortuitous.

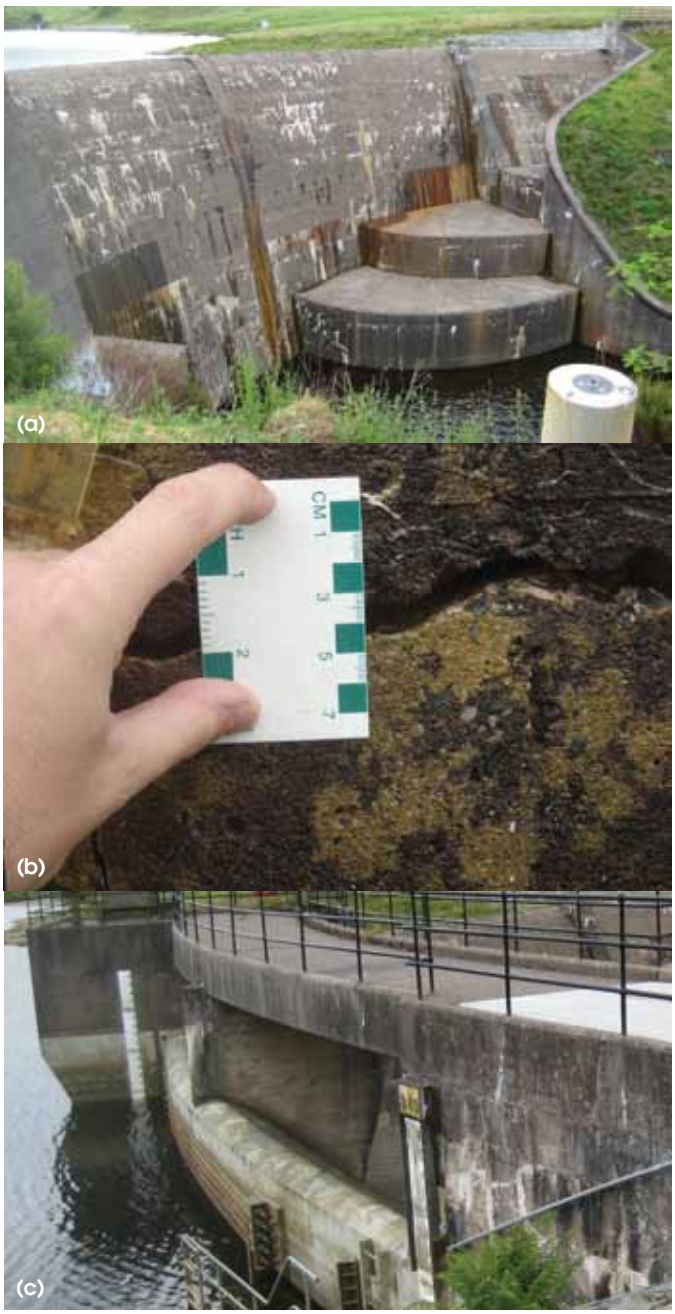

Fig. 2: ASR damage to the Dinas Dam as of 2010: (a) severe cracking of gravity abutments; (b) horizontal cracks on downstream arch; and (c) post-tensioning tendons installed on the upstream face of the arch crest

Lower Notch Dam

The Lower Notch Dam (Fig. 4) is located on the Montreal River just before it flows into Lake Timiskaming south of New Liskeard, ON, Canada; construction was completed in 1969. Coarse aggregate was produced by crushing the rock excavated for the intake channel. Although petrographic examination and expansion testing of mortar bars (ASTM C227) did not identify the aggregate as reactive (expansion < 0.10% at 6 months), similar rock types from the Montreal River area had been implicated in 1965 as the cause of ASR in the nearby Lady Evelyn Dam (Fig. 5).[6] The coarse aggregates used in both dams are from the Huronian Supergroup, an outcrop of middle Precambrian age covering a large part of Northern Ontario. This outcrop includes argillite, greywacke, and quartz-arenites. These rock types are now known to cause ASR damage in concrete, and numerous hydraulic and transportation structures built

Fig. 3: The Nant-y-Moch Dam. As of 2010, the dam exhibited no symptoms of ASR at: (a) the downstream face; or (b) the facing concrete on upstream face

Fig. 4: The Lower Notch Generating Station: (a) general overview; and (b) spillway as it appeared in 2010

Fig. 5: ASR-affected concrete structures constructed using aggregates from the Huronian Supergroup: (a) the Lady Evelyn Dam[6]; and (b) a bridge abutment. The Lady Evelyn Dam was replaced around 1971

using them have suffered damage due to ASR (a second example is also shown in Fig. 5).

A more detailed examination of the aggregates for the Lower Notch Dam revealed that deleterious expansion did occur if the mortar bar test (ASTM C227) was extended beyond the usual 6 to 12 months. Concrete blocks manufactured from the aggregates and stored outdoors under natural exposure also showed deleterious expansion when combined with high-alkali cement. A suitable nonreactive coarse aggregate was not available within a reasonable haulage distance, so tests were conducted to evaluate measures to prevent ASR expansion with the reactive aggregate.

Whereas low-alkali cement was found to be effective in controlling the expansion of blocks stored outdoors for 3 years, fly ash replacement was also found to be effective in controlling expansion. Because of the cost premium for low-alkali cement and because fly ash provided the additional benefit of reduced temperature rise in placements, the dam was constructed with high-alkali cement combined with Class F fly ash at replacement levels of 20 and 30% for structural and mass concrete, respectively.[7] The alkali content of the cement was reportedly as high as 1.08% Na_2Oe.[2] Various concrete mixtures were used in the construction of the dam; the mixture used for the deck of the intake structure and spillway had the highest cementitious material content (231 kg/m^3 [385 lb/yd^3]). Assuming a portland cement alkali content of 1.08% Na_2Oe, this results in a total concrete alkali content of 2.0 kg/m^3 (3.3 lb/yd^3) Na_2Oe from the portland cement component (80% of total cementitious material) of the mixture.

The primary author visited the structure in 1993 when the structure was almost 25 years old, and core samples were taken for analyses.[2] Petrographic examination revealed no evidence of ASR, and the DRI was determined to be only 42. This is dramatically lower than DRI values (ranging from 335 to 683) for nearby dams constructed with similar aggregates but without fly ash (Fig. 6), even though

the water-soluble alkali content of the Lower Notch Dam concrete was significantly greater than the alkali content of the ASR-damaged concrete dams without fly ash (2.82 kg/m^3 [4.7 lb/yd^3] Na_2Oe versus 1.41 to 1.88 kg/m^3 [2.35 to 3.13 lb/yd^3] Na_2Oe).[2]

Core samples from the Lower Notch Dam were also subjected to expansion tests. Cores were fitted with gauge points, resaturated, wrapped in moist toweling and plastic, and then stored initially at 38°C (100°F) for 9 years. Since then, they have been stored at 23°C (73°F) and have exhibited no significant length change over the 18-year period.

All of the authors revisited the Lower Notch Dam in September 2010, 41 years after construction was completed (Fig. 4). Visual inspection revealed no signs of ASR damage. Surveys confirm these observations, as measurements indicate no progressive movements or symptoms of expansion. In contrast, one of the ASR-affected dams without fly ash was extensively repaired since an earlier visit in 1993,[8] and yet another ASR-affected dam has been replaced. Analyses of cores[2] showed that both of these structures had lower available alkali content than cores from the Lower Notch Dam,

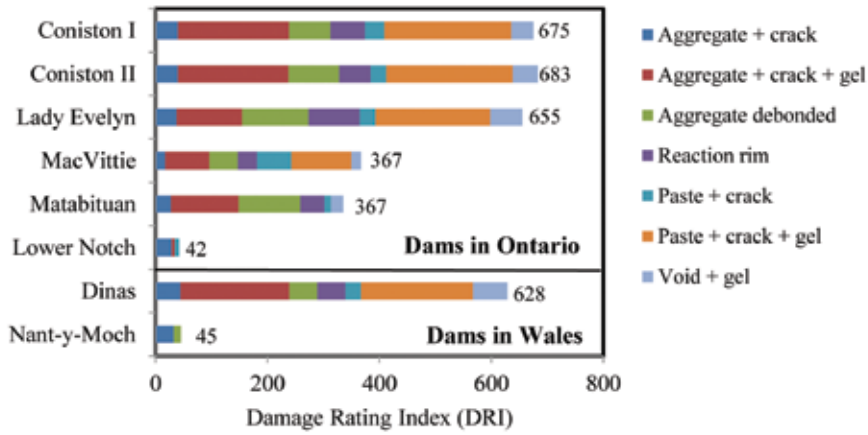

Fig. 6: DRI values for cores taken from dams in Ontario and Wales. DRI > 600 indicates extensive ASR

again indicating that the role of fly ash in controlling ASR extends beyond the simple dilution of the portland cement.

Discussion

The rock types used to construct the Nant-y-Moch Dam and Lower Notch Dam are mineralogically similar and have been implicated in damaging ASR in numerous concrete structures, even when the available alkali content is relatively low. Despite this, both dams remain in excellent condition after 40 to 50 years in service—strong evidence of the benefits of using fly ash. Dams built with similar aggregate but without fly ash show severe ASR-related damage, resulting in costly repairs in two cases and replacement in further two cases. The available alkalis in the two fly ash concretes, either calculated from the mixture proportions and cement analysis or measured as water-soluble, were found to be in excess of or similar to the available alkalis in the ASR-affected concretes in the same region. As indicated by numerous laboratory studies, this confirms that fly ash plays a preventive role beyond mere dilution.

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Note: Additional information on the ASTM standards discussed in this article can be found at **www.astm.org**.

Selected for reader interest by the editors.

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