REMEDIATION STRATEGIES INTENDED FOR THE RECONSTRUCTION OF THE ASR-INDUCED MACTAQUAC DAM

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Abstract

The Mactaquac Dam Generating Station is located on the Saint John River approximately 30-km outside of Fredericton, New Brunswick, Canada and was opened for service in the late 1960's. Approximately ten years after power had begun being generated, significant deterioration and cracking was observed which was diagnosed as ASR in the mid 1980's. In its current state, the dam has expanded approximately 6,000 microstrain (με), which has resulted in expansion within and around the intake structure, powerhouse and spillways. Due to the ongoing deterioration, which has resulted in more than 600-mm to be removed by slot cutting, the dam is proposed to be rebuilt in 2030. Since a highly reactive greywacke aggregate is abundant within the region and may possibly be used in reconstruction, preventative measures including the use of supplementary cementing materials have been studied in order to mitigate the risk of ASR. A research study initiated in 2008 resulted in the production of five monolithic (3 x 3 x 3-m) concrete blocks produced at the foot of the generating station. Test specimens consist of a control containing a high-alkali Portland cement, three containing a low-calcium oxide fly ash with various replacement levels (30, 40 and 50%) and finally a block containing a reclaimed fly ash (50% replacement). Length-change and surface resistivity measurements have been conducted on a yearly basis to determine if or when expansion will initiate. This paper describes a research study, which was conducted in order to determine the appropriate remedial steps required to eliminate ASR using a locally available extremely reactive siliceous aggregate. The options being evaluated include the use of both high and low-CaO fly ash as well as limiting the alkali content in the concrete. Methods for the evaluation of ASR include accelerated laboratory specimens of various sizes as well as large exposure blocks.

Keywords: alkali silica reaction, pozzolans, fly ash, mitigation, field exposure

1 INTRODUCTION

The Mactaquac Dam is located on the St. John River approximately 30-km west of Fredericton, New Brunswick. Construction of the dam began in 1964 and by 1970, six generating units were installed. The Mactaquac Dam is the second largest hydroelectric plant in Atlantic Canada and has a generating capacity of 653 MW, which represents approximately 20% of New Brunswick's power demand. In the early 1980's concrete within the intake structure, powerhouse and two spillways started to exhibit distress, which was attributed to alkali-silica reaction (ASR). Since its discovery, millions of dollars are spent on an annual basis to mitigate the expansion and prolong the service life of the structure. Since the early 1980's, the Mactaquac Dam has grown almost 230-mm in height and approximately 635-mm has been removed from the structure as a result of slot cutting. The current expansion of the dam is estimated to be between 120 and 150 microstrain per annum (με/y) and approximately 6000 με since the 1960's. If the government of New Brunswick decides to go ahead

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with rebuilding the dam, it is expected be completed by 2030, to coincide with the predicted end of the practical service life of many of the electrical and mechanical equipment (e.g. turbines and generators).

In 2005, a research study was established to conduct testing in order to mitigate ASR using materials that are locally available. Unfortunately a non-reactive aggregate is not available within the vicinity of where the dam is to be constructed, therefore mitigation techniques need to be determined using the locally available aggregate. Currently, the most obvious strategy is to use a low-calcium (type F) fly ash, which is currently available from Belldune, New Brunswick.

The use of fly ash to mitigate ASR was first discovered in 1949 by Robert Blanks and since then has been used in various structures around the world (Blanks, 1949). The Nant-y-Moch Dam was constructed between 1957 and 1962 as part of the Cwm Rheidol Hydroelectric Scheme in Wales and cast with 25% low-calcium fly ash (Thomas et. al, 2012). The Dinas dam, which is found just downstream was cast during the same time using the same cement and greywacke-argillite aggregate although without fly ash. In 1986, expansion of the Dinas dam was attributed to ASR whereas the Nant-y-Moch Dam has yet to show any signs of expansion.

This paper presents the use of fly ash in order to mitigate ASR expansion using a reactive aggregate that will likely be used to reconstruct the Mactaquac Dam. Since a source of low-calcium fly ash may not be available for use in 2030, a source of reclaimed fly ash was also studied.

2 MATERIALS AND METHODS

2.1 Aggregates

The construction of the Mactaquac Dam resulted in an extensive amount of aggregate to be excavated in order to house the intake and spillways channels. During construction, this aggregate was tested to determine its reactivity using the mortar bar test (ASTM C227), although failed to identify its reactivity. This aggregate is primarily composed of greywacke with lesser amounts of slate where the reactive minerals are strained and microcrystalline quartz in the greywacke.

Two aggregates were used in this study, (i) Mactaquac, obtained by crushing bore hole samples taken from the proposed location of the new power generating station and (ii) Springhill, which is a quarry located approximately 10km from the Mactaquac Dam. Springhill was chosen as a second aggregate to study due to its mineral makeup, which is very similar to that of the Mactaquac aggregate and has shown to cause ASR in structures, cast around the Fredericton area. The proposed excavation site of the new intake channel and powerhouse will create millions of tons of the same reactive aggregate. Since a non-reactive aggregate is not available within close proximity, economy dictates that if at all possible, this reactive aggregate should be used again.

In order to draw comparisons with the Mactaquac and Springhill aggregates, sources of aggregate were also collected from the Carn Owen quarry in Wales, which was the aggregate used to produce the Nant-y-Noch and Dinas dams. Aggregate was also collected from the site of the Lower Notch dam. Both the Nant-y-Noch and Dinas dams were produced with a reactive aggregate although ASR was mitigated by the replacement of 20 to 30% (class F) fly ash.

2.2 Cementitious materials

Mortar and concrete specimens were cast using a Portland cement meeting the requirements of CSA A3001 Type GU (general use). Two batches of the same cement were used with alkali levels of 0.91% Na_2O_e and 0.86% Na_2O_e. In order to study the effect of fly ash in mitigating ASR, a fly ash from the Belldune generating station in New Brunswick was used. This fly ash meets the requirements of CSA A3001 for type F (low-calcium, < 8% CaO). In a separate study, Hayman et al. (2012) looked into the effect of other pozzolans and slag as well as the use of a low-alkali cement.

In order to study the effect of fly ash in mitigating deleterious expansion, a low CaO (class F) fly ash was used. This source of fly ash was collected from the generating station in Belldune, New Brunswick, which burns a combination of bituminous coal and petroleum coke. Belldune is located 300 km north of Mactaquac and is expected to be the source of fly ash if the Mactaquac Dam is replaced. Since it is possible that a source of low-calcium fly ash will not be available in 2030, other options were studied including the use of reclaimed fly ash from the Belldune landfill site adjacent to the plant. In 2006, 50-mm split cores samples were extracted from the Belldune landfill and treated using electrostatic separation. The use of

reclaimed fly ash resulted in a number of modifications to the mortar and concrete mixes, which included:

- reducing the water content of the mixture due to the high moisture content of the ash

- only using sub-75 μm material towards the fly ash content of the mixture and the remainder as sand
- increasing the air dosages from approximately 50mL/100 kg to 750mL/100 kg

The use of reclaimed fly ash in concrete is beginning to be used in areas all over the world due to its cementing properties which are very similar to fly ash. As of 2013, 53.4 million tons of fly ash is produced in United States on am annual bases and approximately 50% is landfilled resulting in an excess of amount available to be reclaimed (ACAA, 2013).

2.3 Methods for assessment and analysis

In order to study the availability of the various systems to mitigate ASR, both laboratory and field experiments were conducted.

Accelerated mortar bar tests (AMBT) were conducted in accordance with ASTM C1260 (for mixtures without pozzolans) or ASTM C 1567 (for materials with pozzolans). The test was carried out until 28 days unlike the minimum required length of 14 days. In addition, laboratory specimens were cast and tested following the concrete prisms test (CPT) in accordance with ASTM C1293.

Concrete blocks measuring 0.4 x 0.4 x 0.7 m were produced using either Mactaquac or Springhill aggregate and a cementitious content of 420 kg/m^3. For some mixes, the level of alkali was boosted (as per ASTM C1293) to 1.25% Na_2O_e by adding NaOH to the mix water. All concrete mixtures were air-entrained with 5 to 8% air. The majority of these blocks are located on the concrete exposure site at the University of New Brunswick where others are located on the CANMET exposure site outside of Ottawa, Ontario and four are located in the inspection gallery in the Mactaquac Dam. All blocks are measured periodically to determine expansion using a 500-mm Demec gauge to determine the length change between 4 pairs of stainless steel pins embedded within the concrete surface.

In addition, five concrete monoliths, 3 x 3 x 3 m, were cast in 2008 just downstream from the toe of the Mactaquac Dam generating station. All blocks were cast using Springhill aggregate and a cementitious content of 420 kg/m^3. The water content was adjusted for each block in order to produce a 75 to 100 mm slump and the alkali content was boosted to 1.25% Na_2O_e. The first of five blocks was cast as a control and contains 100% high-alkali Portland cement whereas the other four contain various levels of Belldune (type F) fly ash. Fly ash contents of 30, 40 and 50% were used where the fifth block was cast using 50% reclaimed fly ash from the landfill site at Belldune. Similar to the smaller blocks, these monoliths were instrumented with both stainless steel pins located on each of the four vertical surfaces as well as two invar bars, which were cast through each block. One end of the invar bar was cast into place where the other end is free to move and used to measure expansion using a hand-held length comparator.

3 RESULTS

Figure 1 and 2 present accelerated mortar bar (AMBT) and concrete prism test (CPT) data, respectively using both Mactaquac and Springhill aggregates in addition to a low-calcium (class F) fly ash from Belldune, NB. In addition to these aggregates, a comparison is shown with aggregate from the Carn Owen dam and the site of the Lower Notch dam. A strong correlation is observed between both Springhill #1 and #3, and aggregate from Mactaquac, whereas aggregate from Carn Owen and Lower Notch are showing less expansion which may be indicative of a lower reactivity. A replacement level of 20% fly ash is shown to mitigate ASR below 0.10% after 14 days for all aggregates replacement levels of approximately 25-30% is required after 28 days.

CPT data is presented in Figure 2 for both Mactaquac and Springhill #1 aggregate with and without the replacement of fly ash. CPT results without the addition of fly ash result in expansion of approximately 0.4 and 0.5% for both Mactaquac and Springhill #1 after 12 months and approximately 0.55% for both after 24 months which is significantly higher than the allowable expansion limit of 0.04%. A replacement level of 20% (class F) fly ash is shown to mitigate expansion using the Mactaquac aggregate although 30% is shown to not be enough to reduce expansion below 0.04% when using Springhill #1. This difference is assumed to represent noise in the data or could be that Springhill #1 is slightly more reactive than Mactaquac as discussed previously.

The replacement level of various fly ashes based on both calcium and alkali content was previously studied by Hayman et. al (2010) using Springhill aggregate. A replacement level of 20 to 30% fly ash was required when limiting the CaO content to below 16% in order to limit expansion below 0.10% according to AMBT after 14 days. When increasing to levels between 16 to 24% CaO, higher replacement levels of approximately 35 to 45% after 14 days and up to 60% after 28 days were required.

By maintaining a replacement level at 25% fly ash in mortars cast according to the AMBT, the effect of composition (calcium and alkali contents) of the fly ash is presented in Figure 3. Hayman et. al (2010) found that low-alkali fly ashes (<4% Na2Oe) resulted in expansion less than 0.1% with CaO contents below 15% although increased to 0.25 to 0.5% expansion after 14 and 28 days respectively, at CaO levels of approximately 29%. High-alkali fly ashes on the other hand resulted in expansion of 0.38 to 0.50% with a CaO content of 17.6%. Therefore, by limiting the level of both alkali and CaO within the fly ash can mitigate expansion when using 25% fly ash.

4 DISCUSSION

Based on research previously conducted by Hayman et. al (2013) and expansion tests presented in Figures 1 and 2, fly ash is shown to mitigate ASR provided it is of the proper composition and a sufficient amount is used. Although fly ash has been shown to mitigate deleterious expansion, the required amount to maintain expansion below a respectable limit, unfortunately varies amongst the various laboratory and field tests that are currently being used.

According to the CSA A23.2-27A Prescriptive Approach, at least 35% (class F) fly ash and no more than 1.2 kg/m^3 Na_2O_e Portland cement is required to mitigate expansion when using an extremely reactive aggregate such as the aggregate that is planning to be used to reconstruct the Mactaquac Dam. On the other hand, the Performance Approach as outlined in CSA A23.2-28A requires only 20 to 25% (Class F) fly ash to mitigate ASR according to the accelerated mortar bar test (AMBT) whereas 25 to 30% (Class F) fly ash is required under the concrete prism test (CPT) as previously presented.

Figure 4 presents CANMET expansion data for Springhill aggregate with a low-CaO (2.06% CaO) fly ash tested in the accelerated mortar bar test, concrete prism test and exposure slabs and blocks. All specimens were produced using a high-alkali Portland cement (0.90% Na_2O_e) and a fly ash similar to that from Belldune (Fournier et. al, 2004). The replacement of various levels of fly ash (20, 30 and 56%), results in significantly less expansion compared to the control, although a variety of replacement levels required to limit expansion is found between laboratory and field specimens after 2 and 19 to 20 years, respectively. In the CPT, 20% (class F) fly ash was sufficient to limit the expansion below 0.04% in the unboosted system, whereas 30% was required in the boosted (1.25% Na_2O_e) system. All specimens in the field resulted in expansion greater than 0.10% after 19 and 20 years of exposure when cast with 20 and 30% replacement levels, although very little expansion was observed in specimens cast with a replacement of 56%. Although a different Portland cement and fly ash was used in the CANMET study, a significantly higher replacement level of fly ash is shown to be required to combat ASR, which raises concerns to the lower levels of fly ash required in both the CSA Prescriptive and Performance approaches.

The replacement of 56% fly ash in mitigating expansion in the CANMET blocks was the motivation for the replacement levels used to cast the monolith blocks at the foot of the Mactaquac Dam. Expansion measurements relative to invar bars placed through each of the five blocks is presented in Figure 5. Replacement levels of 30, 40 and 50% (class F) Belldune fly ash have resulted in an expansion less than 0.04% after 7 years compared to the control, which has expanded almost 0.3%. The use of 50% reclaimed fly ash has also resulted in expansion less than 0.04%, which would assume that it is acting very similar to the unclaimed fly ash at the same replacement level.

Although it may be a concern to many, that the locally available highly-reactive Mactaquac aggregate is being recommended as the aggregate to reconstruct the Mactaquac Dam, a number of other dams have yet to show signs of ASR with the addition of fly ash when using a similar aggregate. Figure 6 presents the Damage Rating Index (DRI) of a number of dams located in both Wales and Ontario, Canada (Thomas et al., 2012). The Damage Rating Index (DRI) is a quantitative petrographic assessment used to classify the degree of ASR, by observing a polished section and counting the number of ASR properties. A weighting factor is then assigned to each property and then normalized over the area of the specimen (Dunbar and Grattan-Bellew, 1995; Grattan-Bellew, 1992). The DRI for a number of dams in both Ontario, Canada and Wales is presented in Figure 6. The variance in results is attributed to the preventative measures taken to mitigate ASR in a few of these dams. Both the Lower Notch and Nant-y-Moch dams show a much lower DRI in comparison to the other dams as a result of the replacement of 25% (class F) fly ash. These results are promising considering the Mactaquac aggregate is very similar to both that used to construct the Lower Notch and Nant-y-Moch dams.

5 CONCLUSIONS

Based on the results presented within this paper, the following conclusions can be made:

- The use of fly ash is shown to mitigate expansion using both the Mactaquac and Springhill aggregates.
- Due to the extremely reactive nature of both Mactaquac and Springhill aggregates, replacement levels of fly ash ranging from 30-56% are required to mitigate expansion under both laboratory and field experiments.
- Although laboratory and field tests show that ASR using the highly reactive Mactaquac aggregate can be prevented using various replacement levels of fly ash, it is recommended that a replacement level in excess of 50% be used to reconstruct the Mactaquac Dam.
- The levels of fly ash required to mitigate ASR between the various tests is a concern, which raises a number of questions into whether or not the laboratory tests currently being used are underestimating preventative levels required to mitigate ASR.
- If in 2030, a suitable source of low-calcium fly ash is not available, than the use of reclaimed fly ash is being recommended at a replacement level in excess of 50%, which has shown to eliminate expansion after approximately 10 years.

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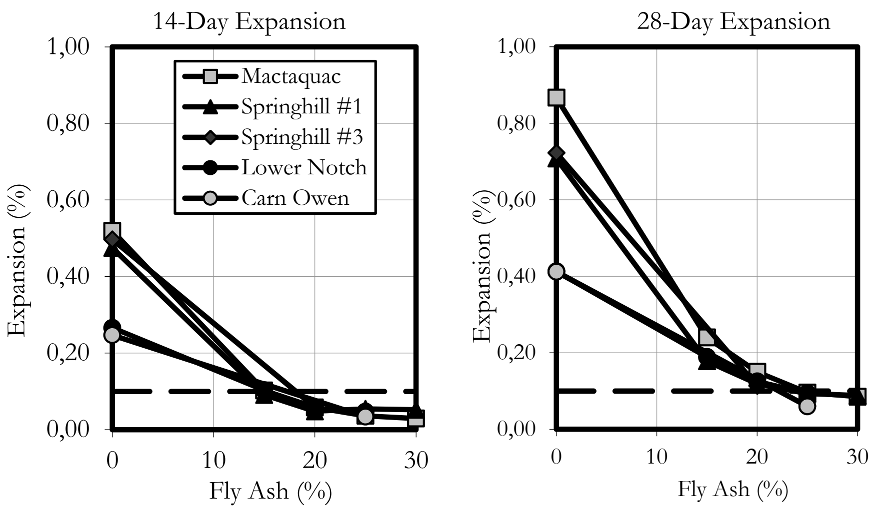

FIGURE 1: Accelerated mortar bar test results for Belldune (Type F) fly ash after a) 14 days and b) 28 days.

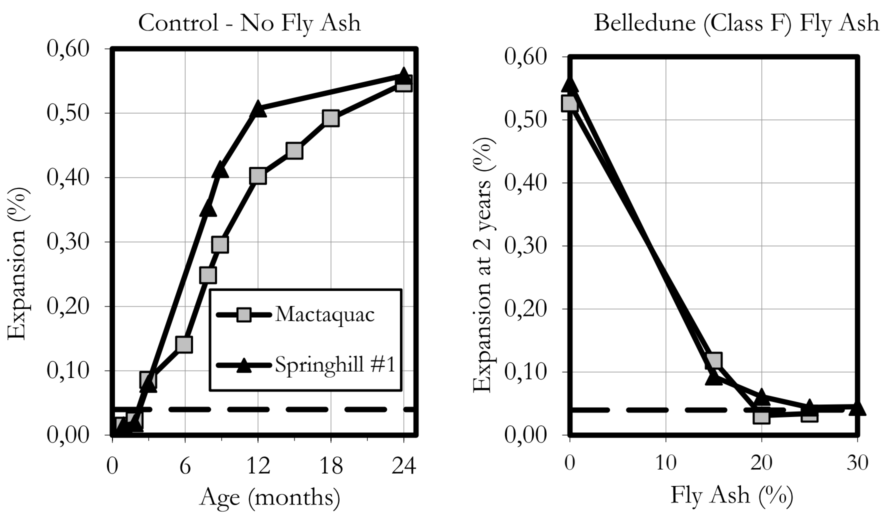

FIGURE 2: ASTM C1293 Concrete prism test results for Bellldune (type F) fly ash for both Mactaquac and Springhill aggregate.

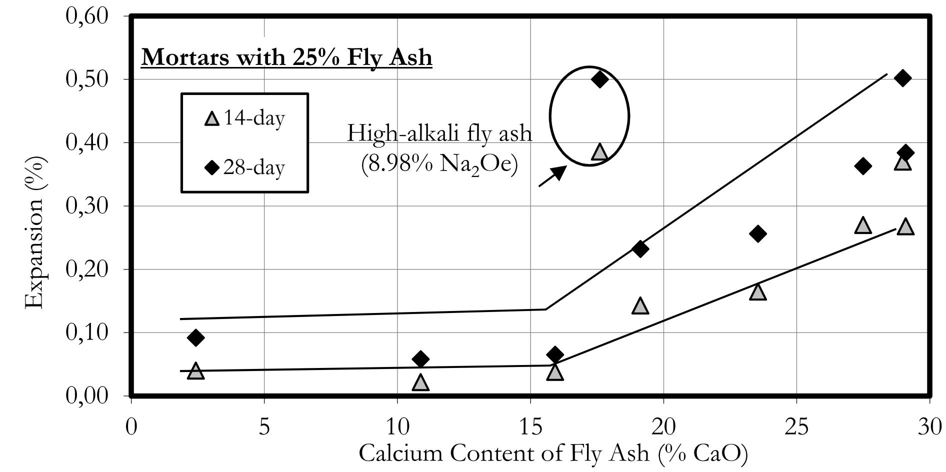

FIGURE 3: Effect of calcium content on expansion of mortar bars containing Springhill aggregate and 25% fly ash (Hayman et al., 2010).

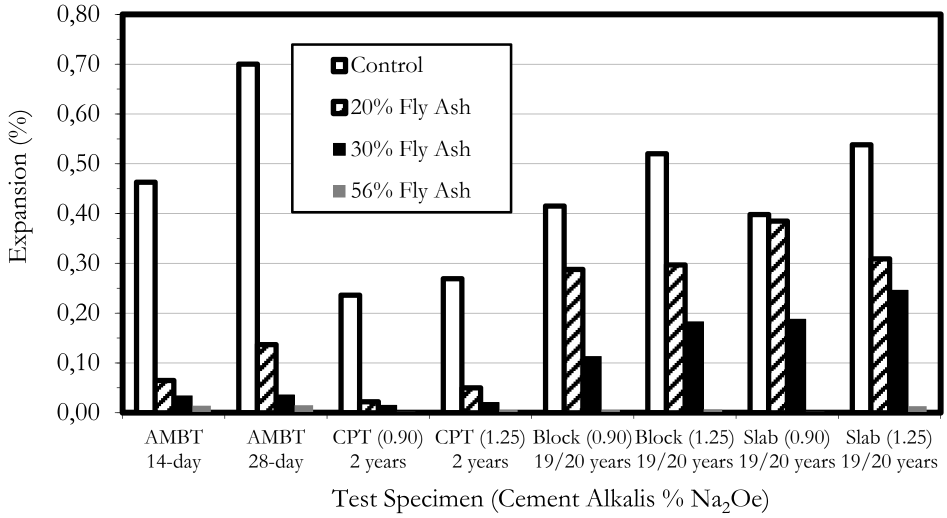

FIGURE 4: CANMET expansion data for Springhill aggregate with a low-CaO (2.06% CaO) fly ash tested in the AMBT, CPT and exposure blocks and slabs.

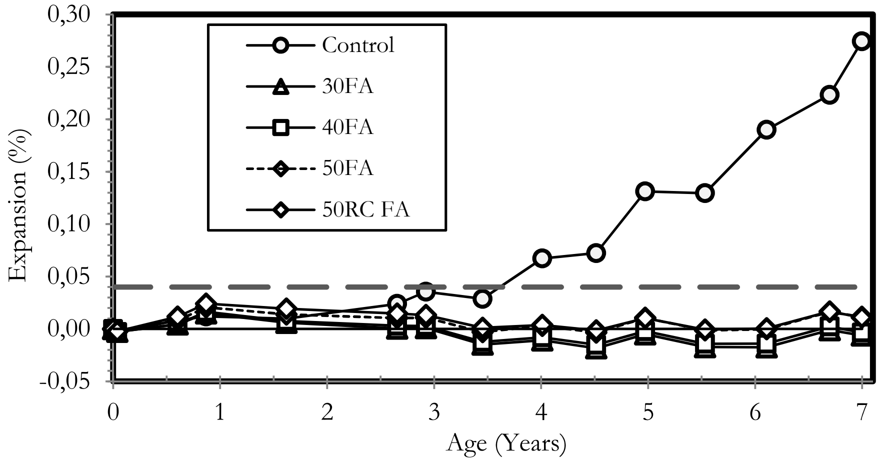

FIGURE 5: Mactaquac Dam monolith block expansion data relative to the invar bar.

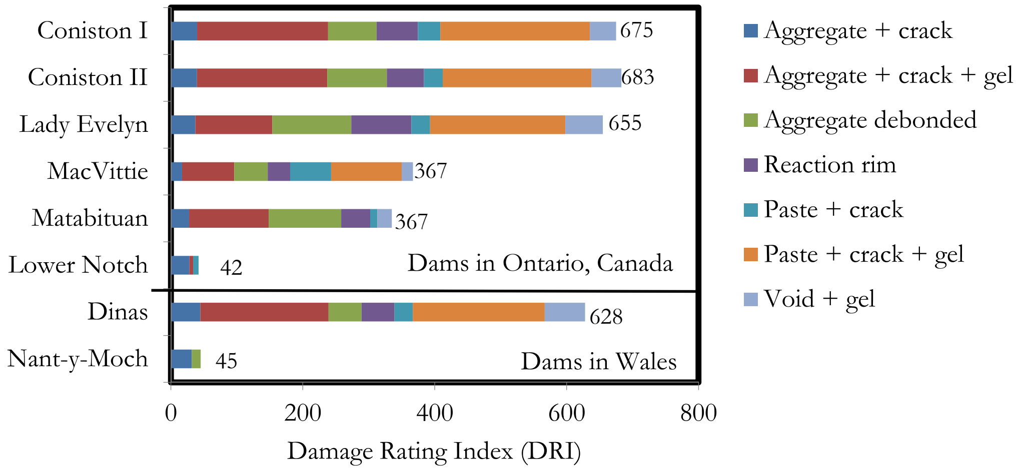

FIGURE 6: Damage Rating Index (DRI) of Dams in Ontario, Canada and Wales produced with and without Fly Ash (Thomas et al., 2012).