Journal of Asian Concrete Federation
Vol. 5, No. 2, pp. 27-36, December 2019
ISSN 2465-7964 / eISSN 2465-7972
https://doi.org/10.18702/acf.2019.12.5.2.27

Technical Paper

Diagnosis of alkali aggregate reaction in concrete dams: an Indian case study

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(Received July 9, 2019; Revised November 9, 2019; Accepted December 7, 2019; Published online December 31, 2019)

Abstract: Deterioration of concrete structures have been observed in various dams in India and abroad. One of the critical deterioration mechanism involved in concrete hydraulic structures, such as dams and powerhouses can be attributed to the alkali aggregate reaction. Arch Dam in this case study is double curvature large thin arch dam, which features horizontal as well as vertical arches. Said dam suffered a continuous upstream deflection along with signs of minor distress. This paper provides a case study on systematic evaluation techniques adopted for diagnosis of Alkali Aggregate Reaction in Arch Dam in India. The study on arch dam constructed four decades ago in India included a field inspection of concrete dam structures with subsequent concrete cores drilling for laboratory investigation. The investigation included detailed petrographic evaluation of aggregates covering morphological microstructural and mineralogical analysis as per IS: 2386 Part VIII, mineralogical analysis covering the absence / presence of reactive aggregates prone to alkali-silica reaction, evaluation of concrete using petrographic analysis including study of pore structure and presence of micro cracks and abnormal reactive products, surface morphology study of concrete samples by Scanning Electron Microscopy (SEM) method and residual expansion on concrete cores.

Keywords: Alkali aggregate reaction, arch dam, petrographic analysis, scanning electron microscopy.

1 Introduction

Certain concrete aggregates react with the alkaline pore solution in concrete, which produces expansion leading to the cracking and deterioration of concrete. These reactions are known as alkali aggregate reactions (AAR). Among the first cases of AAR in India were a gravity dam and a power house built in the early sixties [1]. In an Australian dam, the occurrence of AAR was confirmed visually and with SEM [2]. XRD was additionally used. The first case identifying AAR in Switzerland reported in the literature is the Illsee dam [3]. Cracking of the concrete and displacements of up to 3 centimeters led to misalignments of machinery and difficulties to operate the installed equipment, like gates. Alkali-silica reaction is of more concern than alkali carbonate reaction because the occurrence of aggregates containing reactive silica minerals is more common. Alkali reactive carbonate aggregates have a specific composition whose occurrence is relatively rare [4,5]. Specifically with regard to the alkali aggregate reaction (AAR) due to the reactive aggregates, the study of this disease has been gaining increasing attention of the technical community due to several reports of this type of concrete deterioration. The AAR reaction leads to an expansion of the concrete and induce cracking and degradation of the mechanical properties. This implies problems in terms of serviceability, structural integrity [6,7,8] and durability since cracking favors the ingress of external species prone to initiate other degradations [9,10]. To deal with the affected structures, it is thus necessary to precisely understand the chemo-mechanical effects of each reaction. The potential for AAR in a large hydraulic structure should be thoroughly explored. Necessary measures should be taken to prevent or suppress the potential expansion within a tolerable limit.

AAR can significantly damage concrete structures. The gel produced by the reaction increases in volume by taking up water. This exerts an expansive pressure, causing unrestrained concrete to expand and restrained concrete to develop large compressive

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forces. The rate of expansion caused by AAR typically has been found to be 20 to 200 × 10^{-6} mm/mm/yr, depending on the severity of the reaction and the degree of restraint [11]. The volumetric increase can reach a maximum value of 0.2 to 0.5% [12]. The expansion becomes detectable in about five to ten years after construction, and the most noticeable expansion may be detected in about 15 to 25 years. The expansion may continue for more than 50 years, although in some instances the expansion may cease after 20 to 30 years. The compressive stresses directly caused by AAR are usually within 3 to 4 MPa [11].

Fig. 1 – Crack measurement on upstream and downstream side of upper gallery-3

Table 1 – Concrete mix design details

Ingredients	Quantity – Mix Design (kg/m^3) Not Used	Quantity – Actual Used (kg/m^3) Adopted for Dam Construction
Cement	245	327
Fly ash	43	0
Sand	511	447
4.75 – 10 mm	82	144
10 – 20 mm	163	165
20 – 40 mm	266	267
40 – 75 mm	348	347
75 – 150 mm	675	670
Water	118	121
Admixture	0.88%	%

Diagnosing AAR in this study included steps starting with the inspection of the structure. Based on the inspection and the available data, coring locations were defined and the samples taken were analyzed with different methods, starting with a visual assessment and finally extending to the residual expansion potential of concrete cores samples. The study on alkali silica reaction (ASR) is presented in this paper, in order to facilitate its identification and diagnosis in dams. Microscopy is emphasized as the major tool, as it makes possible to reliably identify even weakly developed ASR. In case of arch dam under investigation, the cracks were noticed in Gallery-3 on both upstream and downstream faces. These cracks were dispersed mainly in horizontal direction as shown in Figure 1. The width of cracks inside Gallery-3 on downstream face near rock and dam joint i.e. near abutment was more as compared to middle portion of Gallery-3. The crack width near abutment was around 0.45 mm and near central part of Gallery-3 was around 0.25 mm. The width of cracks in case of upstream part inside Gallery-3 was around 0.2 mm and was visible only in few portions.

During the construction OPC-33 grade cement was used. The two types of OPC-33 grade cement with 28 days strength of 38.83 N/mm^2 and 36.28 N/mm^2 were used. In the beginning, trial mix using available fly ash (Table-1) with cement OPC 33 grade were done but based on data available from the Quality Control Report of Dam during construction it has been found that use of fly ash was not adopted. The reason for not using fly ash as stated in the Quality Control Report of Dam is that fly ash was not conforming to the specification and there was large variation in the fineness of fly ash. The standard mix design adopted during the construction is given in Table-1. The alkali content of cement is a key property in the development of ASR and it should be determined for estimating the possibility of the reaction. Alkalinity of Portland clinker consist of sodium and potassium. Alkali content of cement can be determined as a Na_2O equivalent: Na_2O Equivalent ($Na_2O\% + 0.658\ K_2O\%$). To avoid ASR Na_2O equivalent should be less than 0.60% according to standards. Na_2O equivalent in the used cement types varied between 0.80% and 1.35%. The alkali content is therefore can be considered sufficient for the development of ASR if aggregates are reactive. Though through petrography aggregates were found to be innocuous, aggregate expansion study was not carried out at the time of construction and if same was conducted the selection of pozzolanic cement might have been used in order to have better resistance to alkali aggregate reactivity. The second way out was to adopt of low-alkali cement, namely cement with an equivalent sodium oxide (Na_2O) content of 0.6% by mass or less to have better resistance to alkali aggregate reactivity.

2 Methods for Alkali Silica Reaction Identification

ASR is a reaction in concrete between the alkali hydroxides, which originate mainly from the Portland cement and certain types of aggregate. The ASR forms a gel that swells as it draws water from the surrounding cement paste. Reaction products from ASR have a great affinity for moisture. In absorbing water, these gels can induce pressure, expansion, and cracking of the aggregate and surrounding paste. To study ASR tests conducted includes visual inspection of concrete core samples, color test method for identifying concrete gels form by alkali silica reaction, petrographic analysis, XRD test, SEM, and residual expansion of concrete core samples.

2.1 Visual observation

Visual observation of all the accessible portions of three Galleries including upstream and downstream portion of dam were carried out at site and on the concrete core samples extracted from different locations. The visual inspections of concrete cores indicated rims indicating chances of ASR (Fig. 2). Thereafter, samples from rim portion were also sent XRD, Chemical analysis, SEM, and petrography studies.

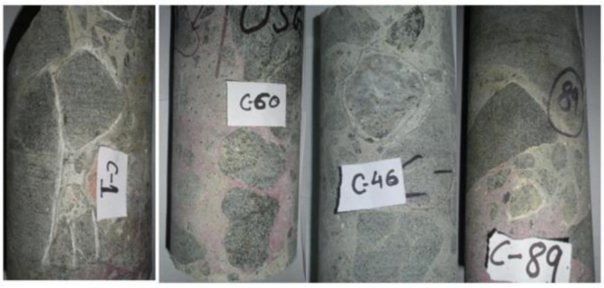

Fig. 2 – ASR rims from concrete cores extracted from different locations

2.2 Concrete core extraction for lab test and test performed

After the visual inspection of a dam, coring locations were identified. The choice was strongly influenced and limited by accessibility, usually more than in other structures. Survey data about the deformation of the dam is helpful in determining where expansion is relatively large or small, respectively. Special attention was given to areas where an expansion is critical for the integrity of the structure or where concentrations of stresses are likely to occur. The number of cores taken were based on the type and complexity of the dam under investigation and on the level of detail and representativeness required. Concrete cores of 150 mm and 100 mm diameter were extracted from all three galleries (inside and outside), downstream bottom and upstream side of dam. Total about sixty concrete cores were extracted covering entire dam structure. The tests included evaluation of aggregates (taken out from concrete core) using petrographic analysis including morphological microstructural and mineralogical analysis as per IS: 2386 Part VIII (1963) [19], detailed mineralogical analysis covering the absence/presence of reactive aggregates prone to alkali-silica reaction, evaluation of concrete using petrographic analysis including study of pore structure and presence of micro cracks and abnormal reactive products, surface morphology study of concrete samples by SEM including detection of fracture pattern and residual expansion of concrete core samples.

Table 2 – Test results of water samples

Location	pH	SO_3 mg/*l*	Cl mg/*l*	Solids (mg/*l*)			Alkalinity (m*l*)	Acidity (m*l*)
				Inorganic	Organic	Suspended		
Downstream	6.59	34.30	10.76	32.00	9.00	18.00	5.90	0.80
Upstream	6.78	15.43	16.14	20.00	4.00	8.00	2.30	0.40
Gallery-1	7.56	42.18	16.14	102.00	54.00	16.00	19.00	Nil
Gallery-2	6.92	40.47	23.32	612.00	66.00	33.00	70.00	1.20
Gallery-2 Drain	6.33	28.81	16.14	22.00	6.00	4.00	1.80	0.80
Gallery-3	7.38	37.38	17.94	92.00	10.00	7.00	11.00	0.40
Limiting Value for RCC works as per IS:456-2000	>6	400	500	3000	200	2000	25	5

2.3 Chemical analysis of concrete samples of dam

The chloride, sulphate, pH and other chemical parameters are within the permissible limit given in IS: 456 (2000) [19] for both dams. No adverse chemical presence in concrete and water samples in general is seen in Table 2. The SO_3 content calculated from chemical analysis of concrete core samples in case of arch dam varied from 0.30 to 0.50% per m^3 of concrete and Na_2O equivalent (water soluble acid method) in concrete of arch dam varied from 0.16 to 0.30 per m^3 of concrete.

2.4 Mineralogical studies in arch dam

The petrographic analysis was done for evaluation of aggregates (taken out from core). The study included Petrographic and Mineralogical analysis of the samples as per IS: 2386 Part VIII [19]. Mineralogical details were analyzed covering the absence/presence of reactive aggregates prone to Alkali-Silica reaction. Thin sections of the selected samples were prepared. The samples were studied in NIKON POL-600E microscope under polarized light. The modal analysis, granulometry and microstructures were done using the Image Analysis System attached with the microscope. The petrographic study of aggregate taken from concrete core samples extracted randomly from entire dam indicated aggregate type as Hypersthene-Granite (Fig. 3). The major mineral constituents were orthoclase-feldspar, quartz, hypersthene and plagioclase-feldspar. Accessory minerals were pyrite, microcline-feldspar & iron oxide. Grain size of quartz varied from 18 μm to 478 μm with an average of 264 μm. Majority of quartz grains were in the size range of 200 μm to 260 μm. The strained quartz percentage is about 16% and their undulatory extinction angle (UEA) varied from 190 to 210. Lath shaped hypersthene grains were partially altered. The modal composition obtained was: (a) Trade Group: Granite (Igneous Rock), (b) Petrological name: Hypersthene-Granite, (c) Particle shape: Irregular and (d) Surface texture: Crystalline.

Based on petrographic studies, it was also observed that, orthoclase grains present in coarse aggregate were affected more than other feldspar. However, alterations of minerals were not very common hence petrographically it is concluded that aggregates were partially affected by hydration reactions and their hydration products. The petrography analysis of concrete samples indicated presence of onset of ASR (preliminary stage) and examination of ASR rims indicated that the infection was due to presence of orthoclase.

The detection of Alkali Silica Reaction swelling in concrete by staining method (color test) was done based on method proposed by GD Guthrie et.al [13]. The study included the sequential application of solutions of each of two water soluble compounds. Concentrated solutions of sodium cobaltinitrite and rhodamine B in water are prepared. The concrete surface to be examined was treated by pre-rinsing with water and subsequently applying each solution to the surface. After 30-60 seconds, the concrete was rinsed thoroughly with water. The treated surface will show yellow and pink regions where ASR gel is present, yellow regions indicate the presence of K-rich, Na-K- Ca-Si gels. While pink regions indicate alkali-poor gels. The final rinse step was required, since the yellow sodium cobaltinitrite solution will coat the entire concrete surface as will the pink rhodamine B solution, thereby obscuring the stained gel regions. Best results were obtained when the sample is treated first with the sodium cobaltinitrite solution; however, the application of the rhodamine B solution first gave adequate results (Fig. 4).

The slices of core samples were rinsed with water and rinsed surfaces were searched for regions of yellow staining and regions of pink staining whereby K-rich i.e. Na-K-Ca-Si gels generated from ASR were identified by yellow staining and alkali poor, Ca-Si generated from ASR were identified by pink staining. The test results indicated light to dark pinkish color in all cases indicating presence of ASR.

Table 3 – Modal composition of the coarse aggregate (results in %)

Sl. No.	Sample No.	Rock type	Minerals						
			Ortho-clase-feldspar	Quartz	Hyper-sthene	Plagio-clase-Feldspar	Py-rite	Micro-cline-feldspar	Iron oxide
1	Coarse aggregate	Hypersthene-granite	35	27	18	14	3	2	1

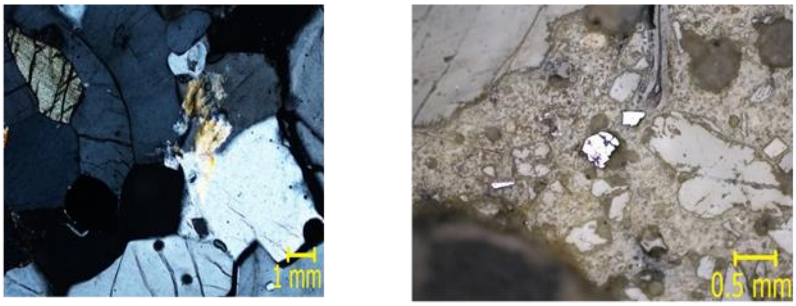

Fig. 3 – Optical microscopic images of aggregates (0.5 mm)

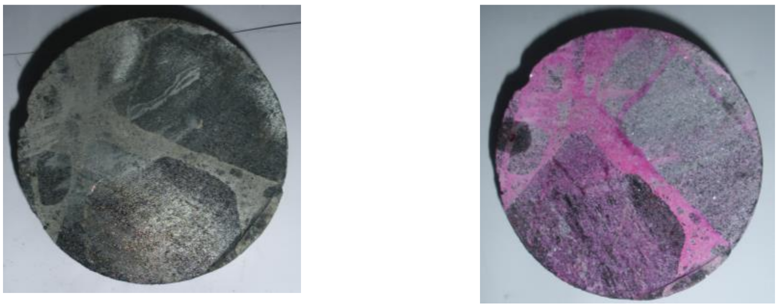

Fig. 4 – Color test method for identifying concrete gels form by ASR

2.5 Scanning electron microscopy studies

The most widespread tool to characterize the microstructure and the local chemical composition of cement-based materials is the SEM. Samples for SEM were selected, dried and impregnated. After removing 1-2 mm by polishing to avoid artifacts introduced by cutting and grinding the sample before impregnation, the surface to-be-investigated were polished. The concrete core samples were examined under SEM and based on study carried out it was seen that numerous microcracks were observed at the interfacial zone and in the paste (Fig. 5). Ettringite formation of size ranging less than 2 microns to 60 microns was observed in most of the samples. Pyrite (FeS_2) crystals were present as minor constituents in Hypersthene granite (up to 1-4%). Microscopic studies revealed that pyrite was mainly outsourcing sulphur for formation of ettringite which was randomly distributed in the coarse aggregate. To ascertain the ettringite formation in terms of percentage, ten samples from each concrete core were taken under observation. The studies were carried out with 1000 counts from each core. The percentages of ettringite formation vary from less than 1% to 3% of 5% to 8% of open air voids present in the concrete. The ettringite formation of order 1% to 3% is not likely to cause any expansion.

When pores were studied under microscope, it was observed that ettringite formation had taken place with three types i.e. crystalline, semi-crystalline and gel (Fig. 6).

Due to the ageing effect on concrete, the three types of feldspars and pyrite present in the coarse aggregate may lead to disintegration and transformation into either in other mineral or by-product. However, this disintegration would most likely get deposited in-situ. Under conditions of extreme deterioration and repeated wetting and drying, ettringite crystals can appear to completely fill voids or cracks. However, ettringite, found in this benign state as large needle-like crystals, should not be interpreted as causing the expansion of deteriorating concrete (PCA R&D 2002) [14].

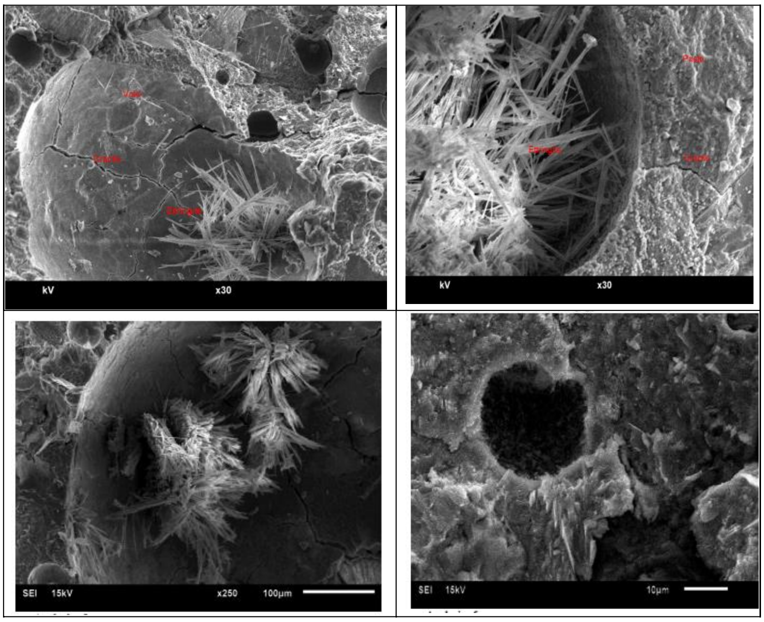

Fig. 5 – SEM images indicating ettringite in concrete samples

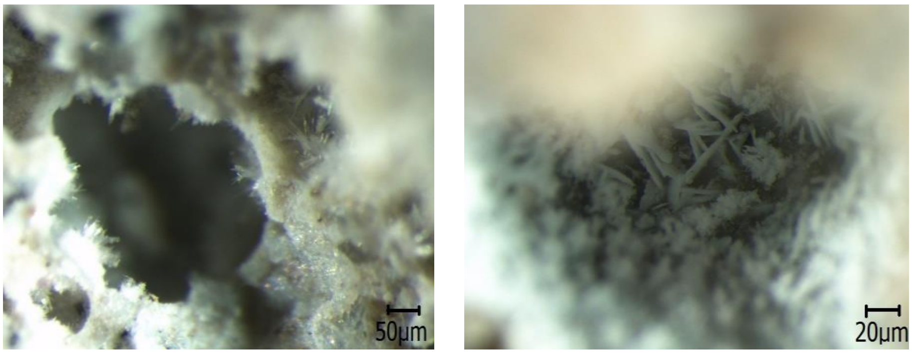

Fig. 6 – Optical microscopic images of concrete samples

2.6 X-Ray Diffraction (XRD) Analysis

The XRD test was carried out on the concrete core samples to determine their mineral composition. XRD is based on principle of diffraction of X-rays by atomic planes of the material. When mono chromatic X-ray beam falls on the crystalline material the scattered X-rays from the atomic planes get interfere with each other to produce constructive or destructive interference depending on the inter atomic planes distance.

$$2d \text{ Sin } \Phi = n\lambda \qquad (1)$$

where d = inter planar distance $[A^0]$, λ = wavelength $[A^0]$, Φ = angle by the incoming beam with the normal of the plane, and n = order of diffraction.

If Bragg's law is satisfied, it results in constructive interference. The basic parts of XRD include X-ray tube, Sample Holder, Gonio meter and Detector. X-ray tube generator the X-rays by the interaction of fast moving electrons with target metal & generated X-rays are made palled using soller slits & allow to fall on sample. The diffracted X-rays from the sample are detected by detection system. Gonio meter allows the measurement at different angles for e.g. from 00 to 650. The recorded intensity pattern over range of 20 is processed for phase identification using software. The X-Ray Diffraction (XRD) Analysis is conducted on concrete core samples from all the ten locations. The each concrete core sample is analyzed for aggregate, mortar and concrete part. The typical results of XRD test is given in Table 4. The X-Ray Diffraction (XRD) analysis was conducted on powder obtained from concrete cores and based on test results, it is seen that there is no significant unhydrated part left in the samples and no extraordinary phases are identified. The sulphate was found in the form of either Pyrite or Chalcopyrite. Minor ettringite formation is also detected.

ASR and thaumasite were also identified in the few samples under SEM study. ASR rims were also checked for Alkali Silica Reaction products. The results obtained revealed that initial stage of ASR was observed on the boundaries between coarse aggregate and cement mortar. Aggravated ASR reactions were more on the boundaries between partially altered coarse aggregate used and mortar part. The thickness of ASR rims varies from few microns to 50 microns in size. In few instances, the pores containing crystalline mass were observed on the boundaries of ASR rims. Microcline grains were also partially affected by ASR but effect of ASR on Microcline was less aggressive than orthoclase. In few instances, some plagioclase grains had also shown effect of ASR on the grain boundaries.

2.7 Residual expansion test on concrete cores and accelerated mortar bar test on aggregates

Accelerated mortar bar test as per ASTM C-1260 (2014) [15] for evaluating residual expansion of coarse aggregate was carried out on coarse aggregate samples taken from concrete cores. For this purpose, the aggregates removed from the concrete cores were fragmented to artificial sand to obtain the necessary fractions to cast mortar bars measuring 25 mm x 25 mm x 285 mm with a standard cement by proportioning one part of cement to 2.25 parts of graded aggregates by mass, a fixed w/c ratio of 0.47. The sample after 24-hours was demolded and then cured in hot water at 80℃ for 24-hours. Finally, the specimen is stored in 1N NaOH solutions at 80℃ for 14 days. The length change observations were taken in hot condition (within 20 seconds after taking out from the solution). The samples were stored in plastic containers and the use of glass or metal container for this purpose was not recommended as the same get corroded by NaOH solution. As per ASTM criteria, the aggregate showing 14 days expansion less than 0.10% are classified as innocuous (non-reactive), whereas the aggregates showing more than 0.20% expansion are classified as potentially reactive. For aggregates showing expansion between 0.10% and 0.20%, the aggregates reactivity is classified as inconclusive and the results are to be supported by another test. The test results of accelerated Mortar Bar Test as per ASTM C-1260 (2014) [15] indicated that the net expansion in coarse aggregate sample is 0.04 %. However, since the coarse aggregate seems to be non-reactive, there is possibility of fine aggregate being reactive.

The 14 days test results of accelerated Mortar Bar Test conducted on concrete core of 150 mm diameter and 280 mm length in similar lines to ASTM C-1260 (2014) [15] for determining residual expansion indicated the residual expansion of 0.17%. As the residual expansion of concrete samples even after the age of 40 years are between 0.10 to 0.20 there is possibility of aggregate being slow reactive though not under potentially reactive category. To cross-check this, the concrete core specimens from both wet and dry portions of dam were selected for residual expansion testing in similar line to procedure in ASTM C 1293 (2018) [16] to determine the susceptibility of a concrete to the alkali-silica reaction. The concrete core was tested with deviation that temperature was changed from 38˚C to 60˚C. The change in temperature was done from 38˚C to 60˚C because it was seen in the past studies done by NCB that the slow reactive aggregate gives expansion at 60˚C. The higher temperature has been also recommended in IS: 2386 Part VII (1963) [18] and IS: 383 (2016) [20] also. The reading was taken up to one year. An average expansion was calculated from measurements on three replicate specimens. If the average expansion of the three concrete bars is equal to or greater than 0.04% at an age of one year, then the aggregate is considered to be potentially reactive. The humidity level of 100% was maintained during testing. The average residual expansion of concrete cores in case of arch dam varied from 0.0392 to 0.0396% (Fig. 7). This average residual expansion at more than 40 years age is significant keeping in view that the limit of 0.04% at the age of one year is for one year old concrete and this indicates that there may be the chance of slow ASR. The same was also indicated in preliminary stage by SEM and Petrography studies.

Table 4 – X-ray diffraction (XRD) analysis of concrete sample

Sl. No.	Location	Findings from X-Ray Diffraction (XRD) Analysis
1	Downstream	Minor Sulphates in the form of Chalcopyrites and Pyrites. Major Portlandite and Minor Calcite. Minor Ettringite
2	Upstream	Minor Sulphates in the form of pyrites and Chalcopyrites. Major Portlandite and Minor Calcite (CaCO3). No significant unhydrated part left and no extraordinary phases are identified. Minor Ettringite
3	Gallery-3	Minor Portlandite and Sulphates in the form of pyrite and Chalcopyrite. Minor Ettringite and Minor Calcite. No significant unhydrated part left in the sample and no extraordinary phases are identified

The study on expansion potential of aggregates expansion indicates that the aggregate may not be under potentially reactive category and the typical pattern cracking due to ASR will not occur but length change can be caused even by small amount of ASR expansion. With the end restraints in case of arch dam, this small expansion has contributed to the movement of mid-point of dam towards upstream side. Keeping in view the support conditions and shape of dam structure there is need to review the limits of ASR test value of aggregate to be used in Arch dam.

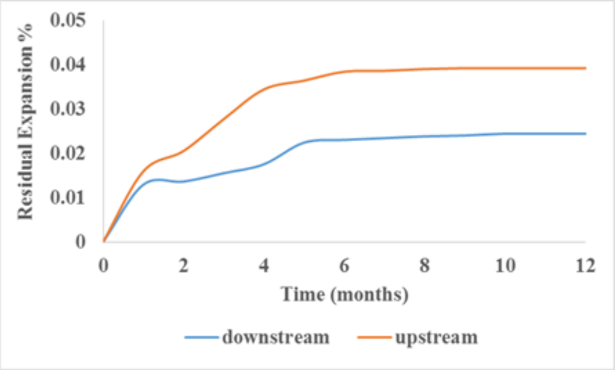

Fig. 7 – Residual expansion of concrete cores by ASTM C1293 (2018) method

3 Results and Discussion

From the study done, it can be seen that even though there was no visual impression of Alkali Silica Reaction evident. However the detailed investigation covering visual inspection of inside concrete by coring, color test method for detection of ASR, petrographic analysis for evaluation of aggregate type and its mineral composition, X- Ray diffraction and SEM study including the residual expansion of aged concrete all together needs to be done for proper understanding of distress mechanism due to ASR. In the current study, the ettringite growth was noticed along with ASR but ettringite percentage was very less and literature study also indicates that the ettringite in the benign stage may not be the cause of distress in dam. No adverse chemical presence in concrete and water samples in general is seen. However, alkali content in concrete by water soluble acid method is high and this high alkali may cause some ASR reaction even if aggregate is moderate reactive. The petrographic analysis of coarse aggregate indicates aggregate type as Hypersthene-Granite. The strained quartz percentage and their UEA are within permissible limits. Feldspar grains are partially fractured, shattered and altered. Reaction rims are developed mostly on the margins of the euhedral pyrite grains. In few instances pyrite grains are completely consumed during hydration reaction. The Petrography analysis of concrete samples indicates presence of onset of Alkali Silica reaction (preliminary stage). The slice of concrete core samples were rinsed with water and rinsed surfaces were searched for regions of yellow staining and regions of pink staining whereby K-rich i.e. Na-K-Ca-Si gels generated from ASR were identified by yellow staining and alkali poor, Ca-Si generated from ASR were identified by pink staining. The test results indicated light to dark pinkish colour in all cases indicating presence of ASR. The sulphate in the form of pyrite and chalcopyrite is found from petrographic, SEM and XRD studies and this is the reason for ettringite formation. The percentages of ettringite formation vary from less than 1 percent to 3 percent. The ettringite formation of order 1 percent to 3 percent is not likely to cause any expansion. Based on the test results of XRD samples from all the locations, it is seen that there is no significant unhydrated part left in the samples and no extraordinary phases are identified. The sulphate in the samples is found in the form of either Pyrite or Chalcopyrite in aggregates. Minor ettringite and ASR formation is also detected in few cases from XRD test results.

ASR though seen in the preliminary stage and validated through residual expansion test may cause expansion in dam keeping in view that the dam is restrained from both ends as the 14 days test results of accelerated Mortar Bar Test conducted on concrete core indicated the residual expansion of 0.17%. As the residual expansion of concrete samples even after the age of 40 years are between 0.10 to 0.20 there is possibility of aggregate being slow reactive though not under potentially reactive category. The average residual expansion of concrete cores by long term test varied from 0.0392 to 0.0396% indicating that the average residual expansion at more than 40 years age is significant keeping in view that the limit of 0.04 % at the age of one year is for one year old concrete and this indicates that there may be the chance of slow Alkali Silica Reaction. With the end restraints in case of arch dam, this small expansion has contributed to the movement of mid-point of dam towards upstream side. Keeping in view the support conditions and shape of dam structure there is need to review the limits of ASR test value of aggregate to be used in Arch dam.

4 Conclusions

Diagnosis of Alkali Silica Reaction in aged concrete dams is important for deciding measures to prevent further distress in the hydraulic structures such as dams. The detailed investigation of dam covering visual inspection of inside concrete by coring, colour test method for detection of ASR, petrographic analysis for evaluation of aggregate type and its mineral composition, X- Ray diffraction and SEM study including the residual expansion of aged concrete all together is essential for proper understanding of distress mechanism due to ASR. The study also indicated that the small amount of expansion due to slow reactive aggregates can be critical in Arch dam considering the end restraints. The study indicated the simultaneous occurrence of ettringite formation in the dam but the percentage of ettringite formation was less than 1-3% of 5-8% of open air voids. The ettringite in such small quantum may not be interpreted as cause of expansion. The results of Accelerated Mortar Bar Test conducted on cores in similar lines to ASTM C-1260 (2014) for determining residual expansion indicated the net expansion 0.17%. The average residual expansion of concrete cores in similar to procedure of ASTM C-1293 (2018) varied from 0.0392 to 0.0396%. This average residual expansion at more than 40 years is significant keeping in view that the limit is 0.04% at the age of one year for one year old concrete and this indicates that there may be the chance of slow ASR. The expansion study indicates that though the aggregate is not under potentially reactive category and the typical pattern cracking due to ASR will not occur but length change can be caused even by small amount of ASR expansion. With the end restraints in case of arch dam, this small expansion may also add to the movement of mid-point towards upstream side. Keeping in view the support conditions and shape of dam structure there is need to review the limits of ASR test value of aggregate to be used in arch dam.

Acknowledgements

The authors would like to acknowledge the NCB laboratory technical officers and technical assistants, Central Project Management Unit DRIP, Central Water Commission-India, Kerala State Electricity Board (KSEB) as well as World Bank for their assistance in carrying out this sponsored project.

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