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ALKALI SILICA REACTIONS IN CONCRETE STRUCTURES OF WATER RESOURCES SECTOR

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ABSTRACT

It is a well known fact that alkali aggregate reactions are one of the predominant causes of concrete deterioration. Swelling phenomenon in the form of expansion of the cement matrix by formation of ettringite due to sulfate-rich water and some external factors such as cycles of freezing and thawing or the attack on concrete by water in some forms such as extremely pure water, acidic water play a deleterious role for concrete durability. In alkali silica reaction, aggregates containing certain forms of silica will react with alkali hydroxide in concrete to form a gel that swells as it adsorbs water from the surrounding cement paste or the environment. These gels can swell and induce enough expansive pressure to damage concrete. Such damage has been reported in many countries, particularly in those with hot-wet climates. Quality of construction materials especially coarse and fine aggregates contribute towards durable structures. Several methods have been formulated to characterize the aggregates viz. mortar bar method, chemical method, petrographic examinations and accelerated mortar prism test methods. The present paper discusses the characterization of aggregate samples from various projects across the country as per chemical method, methods to prevent ASR in the hydraulic structures and some of the case histories from India and abroad where the alkali silica reaction was reported also have been mentioned.

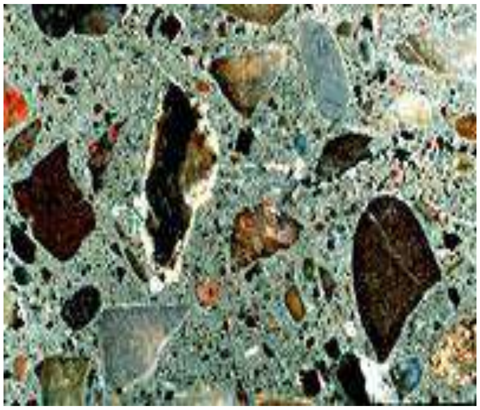
KEYWORDS: Aggregates, Alkali Aggregate Reactivity, Fly Ash, Deleterious Category, Expansion.

INTRODUCTION

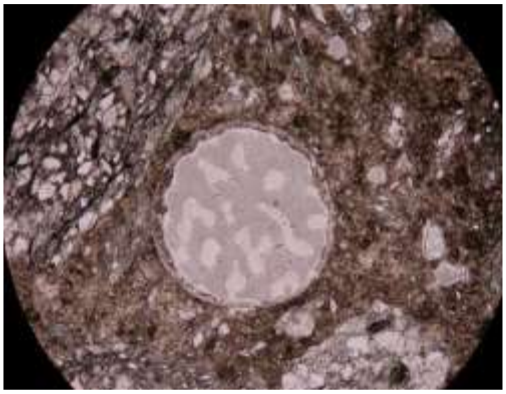
Alkali aggregate reaction (AAR) can cause serious expansion and cracking in concrete, resulting in major structural problems and sometimes necessitating demolition. Alkali aggregate reaction is caused by a reaction between the hydroxyl ions in the alkaline cement pore solution in the concrete and reactive forms of silica in the aggregate (eg: chert, quartzite, opal, strained quartz crystals). A gel is produced, which increases in volume by taking up water and so exerts an expansive pressure, resulting in failure of the concrete. Gel may be present in cracks and within aggregate particles. The identification of AAR can be done by examination of concrete in thin section, using a microscope. Typical indicators are random map cracking and, in advanced cases, closed joints and attendant spalled concrete.

ALKALI-SILICA REACTION

This is the most common form of alkali aggregate reaction and results from the presence of certain siliceous aggregates in the concrete found in some granites, gneisses, volcanic rocks, greywackes, argillites, phyllites, hornfels, tuffs, and siliceous limestones. In ASR, aggregates containing certain forms of silica will react with alkali hydroxide in concrete to form a gel that swells as it adsorbs water from the surrounding cement paste or the environment. These gels can swell and induce enough expansive pressure to damage concrete. The product of the alkali-silica reaction is a gel that absorbs water and increases in volume. Pressure generated by the swelling gel ruptures the aggregate particles and causes cracks to extend into the surrounding concrete. Typically, alkali-silica reaction results in the formation of map-pattern cracking of the concrete.



(a)



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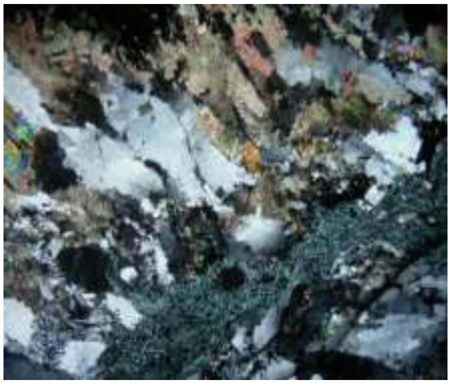

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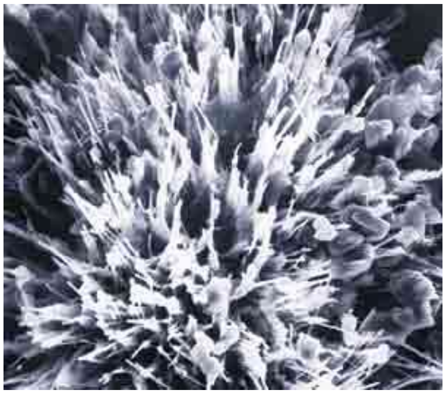

Fig 2 (d)

Fig 1 : Showing the gel formation around the aggregates (a ,b & c)
Fig 2 : Showing the Structure of gel under Scanning Electron Microscopy (d)

Alkali Reaction with Amorphous Silica

Amorphous silica is a form of loose arrangement of tetrahedra around a silicon atom bonded to oxygen ions and OH ions. When placed in a soda solution, there is first an acid-base reaction between the silanol groups (Si - OH) and the OH ions from the alkaline solution, followed by neutralisation of the resultant negative charge by a Na^+ ion. (reported by Dent-Glasser and Kataoka).

The next reaction is an attack on the siloxane bridges by the OH ions. This leads to disintegration of the structure and the silica enters into solution in the form of protonated ions (H_2SiO_4) Both reactions take place simultaneously and show the importance of the OH ions. They eventually lead to the formation of expansive sodium silicate gels. Alkali reaction with silicates caused by reactions in polyphase siliceous aggregates (shale, granite, sandstone).

Deterioration of polyphase siliceous aggregate appears under the microscope as a dark zone between the aggregate and cement paste and by a white deposit on the aggregate and in cleavage planes. The dark zone is due to an alkaline silicate gel. The white deposit consists of flaky crystals containing Si, K, and Ca. Between the white deposit and the dark zone, there is often an area with an intermediate texture. There thus seems to a tendency for the gel to develop highly organised structure. A gel whose CaO/SiO_2 ratio is lower than in the cement but higher than in the gel in contact with the aggregate is observed in the larger pores in the cement paste (Fig. 1 & 2).

There may also be some gelling of the cement paste around the aggregates. Thus, a low viscosity gel forms and is able to migrate away from the aggregate. Thaumasite and silica-rich ettringite are also present near the aggregate. This is proof of multiple corrosion of the concrete, where the expansive gel produces cracks that provided access for the SO_4^{-} ions.

Alkali-Carbonate Reaction

With the alkali-carbonate reaction, certain dolomitic limestone aggregates react with the hydroxyl ions in the cement (or other sources such as de-icing salts) and cause swelling. The swelling of the limestone particles causes the concrete to expand and crack. Dedolomitisation from reaction of the calcium and magnesium carbonate with an alkaline solution involves the formation of Brucite [$Mg(OH)_2$] and regeneration of the alkaline hydroxide.

The Brucite may be isolated from the interface between aggregate and cement paste or in the middle of the aggregate. It can also react with the silica around the aggregate and form magnesium silicate. The porous zone created around the aggregate by extraction of the Mg++ ions weakens the cement-aggregate bond. Cracks appear, although some may heal through precipitation of $Ca(OH)_2$.

Dedolomitisation does not produce an expansive gel. The expansion sometimes observed has been associated with the presence of clays either as inter granular material or as inclusions in the carbonate crystals. These clays cause the concrete to deteriorate by absorbing the OH ions.

The deterioration caused by ACR is similar to that caused by ASR; however, ACR is relatively rare because aggregates susceptible to this phenomenon are less common and are usually unsuitable for use in concrete for other reasons. Aggregates susceptible to ACR tend to have a characteristic texture that can be identified by petrographers.

Mechanism of ASR

The alkali-silica reaction 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. The reaction can be visualized as a two-step process:

Alkali hydroxide + reactive silica gel → reaction product (alkali-silica gel)

Gel reaction product + moisture → expansion

The amount of gel formed in the concrete depends on the amount and type of silica and alkali hydroxide concentration. The presence of gel does not always coincide with distress, and thus, gel presence does not necessarily indicate destructive ASR.

SYMPTOMS OF ALKALI AGGREGATE REACTION

Typical indicators of ASR might be any of the following: a network of cracks; closed or spalled joints; relative displacements of different parts of a structure; or fragments breaking out of the surface of the concrete (pop outs) (Fig. 3). Due to slowness of ASR deterioration, the risk of catastrophic failure is low. However, ASR can cause serviceability problems and can exacerbate other deterioration mechanisms such as those that occur in frost, deicer, or sulfate exposures.

Fig 3: Showing the spalling of concrete

3.1 Typical Cracking due to Alkali- Aggregate Reaction

Relatively equi-dimensional pattern cracking is characteristic of non-reinforced or lightly reinforced concrete affected by alkali- aggregate reaction (Fig. 4 & 5). But when there is a significant amount of reinforcing steel, cracking tends to be more prominent in the direction parallel to the reinforcement (Fig. 6). However, map-cracking can also result from other causes such as drying shrinkage (sometimes referred to as plastic cracking), particularly in slabs on grade that were placed in hot windy weather without proper curing. This type of cracking appears within hours, or days after casting the concrete. In contrast, cracking due to alkali aggregate reaction usually becomes evident only after 5 to 10 years.

Fig 3: Spalling of concrete

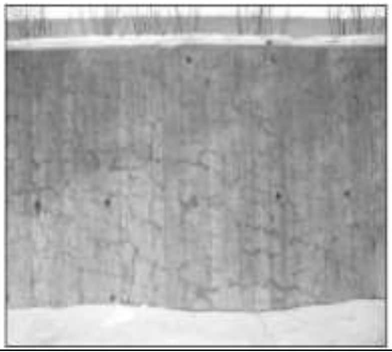

Fig 4: Typical map-pattern cracking due to alkali-silica reaction

Fig 5: Map-pattern cracking and extrusion of joint filling material due to expansion of concrete affected by alkali-carbonate reactivity

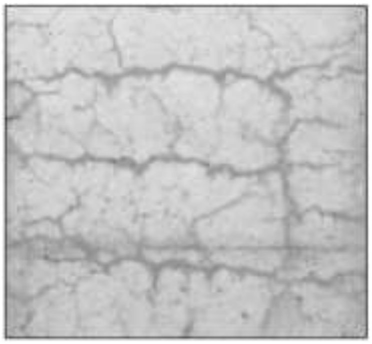

Fig 6: Prominent cracking runs parallel to reinforcing bars

Swelling of the Concrete due to Alkali-Aggregate Reaction

Both alkali-silica and alkali- carbonate reactions result in swelling of the concrete. The amount of swelling or expansion depends on the reactivity of the aggregates, the alkalinity of the cement solution, and the ambient moisture conditions of the structure. Expansions of over 0.1% are not uncommon. An expansion of 0.1% would result in an increase in length of 1 cm for every 10 m length of an unreinforced structure. In many structures this amount of expansion may not cause problems, but in long sidewalks or median barriers, for example, the expansion may cause compression and heaving. Expansion in large structures like dams, powerhouses and locks can interfere with the operation of the flow gates or turbines.

METHOD OF TEST OF AAR

Indian Standard 2386 Part VII – 1963 illustrates four methods of test to identify the aggregates susceptible to alkali aggregate reactivity.

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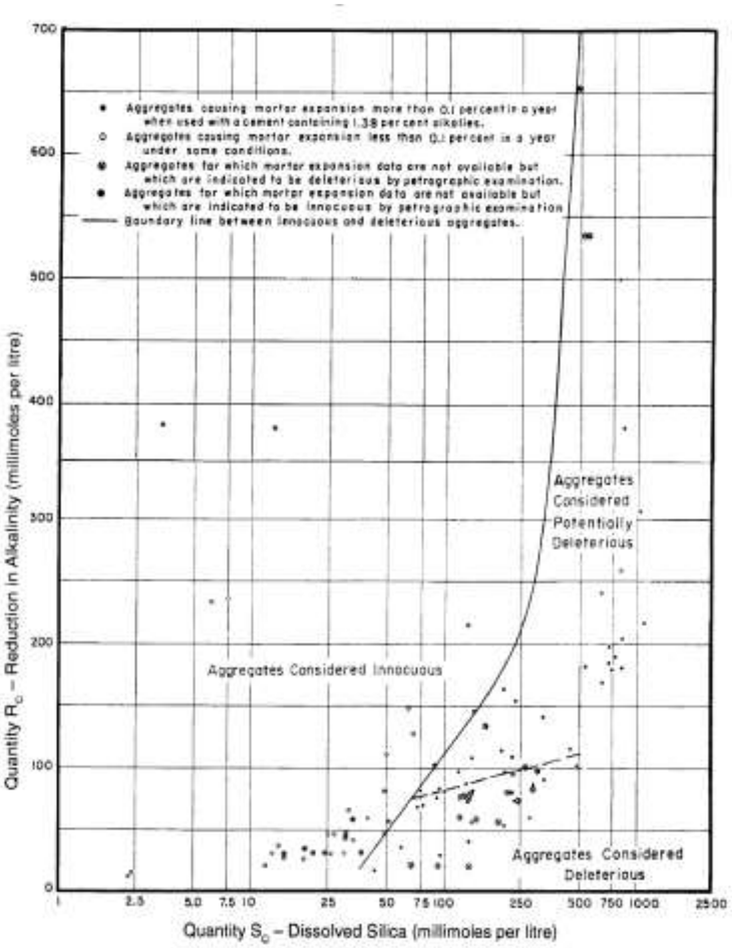

FIG 7 : Illustration of Division Between Innocuous and Deleterious Aggregates on Bases of Reduction in Alkalinity Test

- Mortar bar expansion method
- Accelerated mortar prism test method
- Petrographic examination method
- Chemical method

Out of these four methods, mortar bar method and accelerated mortar prism tests are time consuming. Petrographic examination is an optical inspection for identification of potentially reactive silica which is costly and needs accuracy. The chemical method requires less time and with much accuracy the characterization of aggregates can be done. The present paper illustrates the examination of aggregate samples in the Research Station, received from the various river valley projects being constructed in India, using chemical method of characterization of aggregate samples as given in IS 2386 – 1963 (Part VII).

Potential Reactivity of Aggregates (Chemical Method) – Methodology

IS 2386 – 1963 (Part VII) covers a chemical method for determining the potential reactivity of fine or coarse aggregate indicated by the amount of reaction of aggregate samples during 24 h at 80ºC with 1 N sodium hydroxide solution. A 25.00 g portion of the dry prepared sample is allowed to react with 25 milliliter of 1 Normal sodium hydroxide solution at the temperature of 80ºC for 24 hours in a specialized stainless steel air tight container. After the completion of the reaction, filtrate is tested for silica release and reduction in alkalinity parameters as per the procedure given in the code. Data correlating the results of with performance of aggregates in structures, expansion of mortar bars containing high alkali cement, or petrographic examination should be reviewed before results of the method are used as a basis for conclusions and recommendations concerning the properties and use of the aggregates for concrete. For most aggregates, a potentially deleterious degree of alkali reactivity is indicated if the plotted data point falls to the right of the boundary line shown in Fig 7.

CSMRS investigations

Forty nine numbers of aggregate samples were received from the following projects for testing of alkali aggregate reactivity test for 24 hrs using chemical method as given in IS 2386 – Part VII (1963).

- BariyarpurUrmil Project, Circle Ward, Chhatarpur, MP
- D'zuzaSissiri, Arunachal Pradesh
- Doyang HE Project, Nagaland
- T Surang HE Project, Nagaland
- DikhuTamulu HE Project, Nagaland
- Greater Shillong Water Supply Scheme, Shillong, Meghalaya

Public Health EngineeringDeptt, Sagar, MP

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Table 1 : Results of Reduction in Alkalinity (Rc) and Silica Release (Sc) in millimoles/litre

Name of the project	**Project no.**	**Reduction in alkalinity (Rc) in millimoles/litre**	**Silica release (Sc) in millimoles/litre**	**Sample No.**
BariyarpurUrmil Project, Chhattarpur (MP)	CA/95	70	30.70	**1**
	FA/51	110	24.08	**2**
D'zuza, Sissiri, Arunachal Pradesh	DZR 2	230	24.64	**3**
	S-2	180	10.99	**4**
	S-3	120	27.97	**5**
	S-4	170	32.30	**6**
	S-5	100	33.63	**7**
	SS-2	65	35.30	**8**
KamlongDeopani, Arunachal Pradesh	KS 1	145	26.97	**9**
	KD	90	24.31	**10**
	DZS 2	120	27.97	**11**
	DS 2	60	22.31	**12**
Doyang HE Project, Nagaland	DY 1	150	54.28	**13**
	DY 2	245	42.62	**14**
	DY 3	210	91.24	**15**
T. surang HE Project, Nagaland	TS 52	260	33.00	**16**
	TS 1B	215	20.60	**17**
	TS 2	220	26.00	**18**
	TS 3	250	23.60	**19**
	TS 4	250	24.60	**20**
DikhuTamulu HE Project, Nagaland	DT 52	175	27.97	**21**
	DT B1	145	50.28	**22**
	DT B2	150	54.95	**23**
	DT T1	185	57.94	**24**
	DT T2	215	41.96	**25**
	DT BK	135	39.96	**26**
	DT DR	130	33.30	**27**
Public health Engg. Deptt, Sagar, MP	SG	40	18.00	**28**
	SS	40	16.30	**29**
	SD	175	13.00	**30**
	TD	320	42.60	**31**
	RT	255	40.30	**32**
Greater Shillong water Supply Scheme, Shillong, Meghalaya	GS 1	190	4.00	**33**
	GS 2	235	2.33	**34**
	GS 3	245	2.66	**35**
	GS 4	85	14.65	**36**
	CG5	25	148.19	**37**
	CG 64	165	4.33	**38**
	CG 65	110	18.32	**39**
	CG 66	180	9.32	**40**
	CG 67	135	9.99	**41**
	CG 68	70	20.98	**42**
	CG 69	95	8.66	**43**
Kolodyne HE Project, Mizoram	KR 1	200	38.30	**44**
	KR 2	95	31.00	**45**
	KR 3	80	29.60	**46**
	KR 4	M	22.60	**47**
	KCS 1	50	33.00	**48**
	KCS 2	55	39	**49**

The values of reduction in alkalinity (Rc) and silica release (Sc) were marked in the standard graph (Fig.7). The graphical representation for each sample is given in Fig 8 a to d. It can be seen from the graphs that barring sample Nos. 27 and 37, all the samples are falling under ***innocuous*** category.

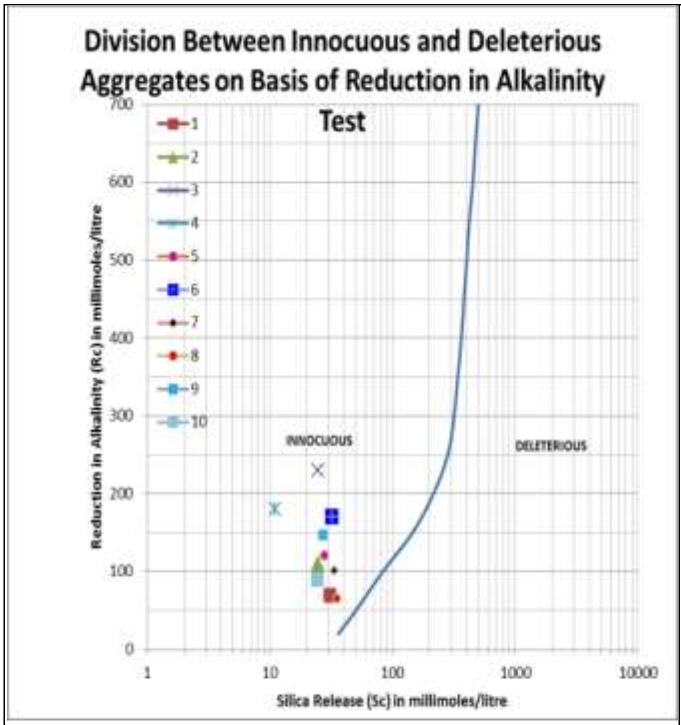
PREVENTION OF ALKALI SILICA REACTION IN CONCRETE

In case of reactive aggregates the alkali silica reaction in concrete can be prevented in hydraulic structures, by taking the following points in consideration:

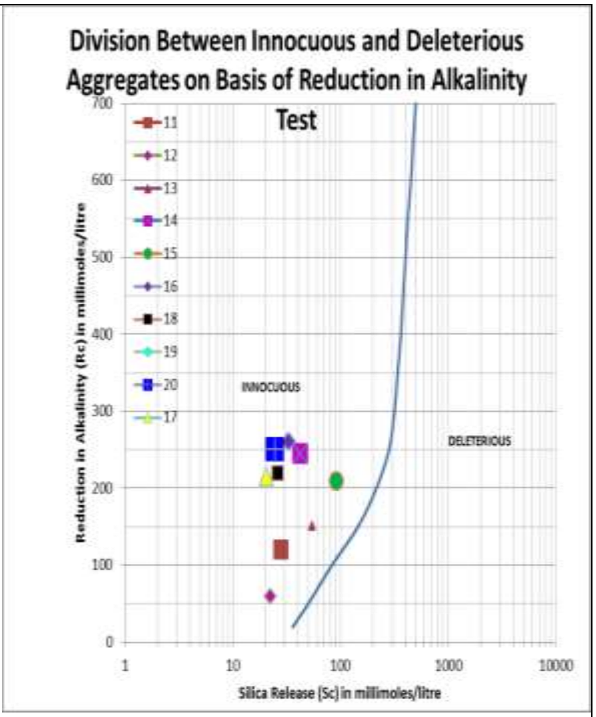
- Use of non reactive aggregates
- Use of OPC having total alkali content is less than 0.6% by mass, as Na_2O eq.
- Use of slag/pozzolans/Silica fume to replace a portion of the cement (including blended cements)
- Limiting cement content in concrete mix

Use of non reactive aggregates cannot always be possible as it may sometimes out of control. It is uneconomical too particularly when the non reactive aggregates are identified from far off sites. Therefore, the use of ordinary Portland cement with an alkali content of 0.6% as Na_2O eq. or less is acceptable worldwide which is the best means of limiting total alkali content and hence alkali silica reaction.

Portland Pozzolana Cement (with flyash content=25%) : British Cement Makers' Federation and Building Research Establishment (UK) No. 330; March, 1998 recommends one sixth of alkali content of flyash to be considered as the reactive alkali.



a



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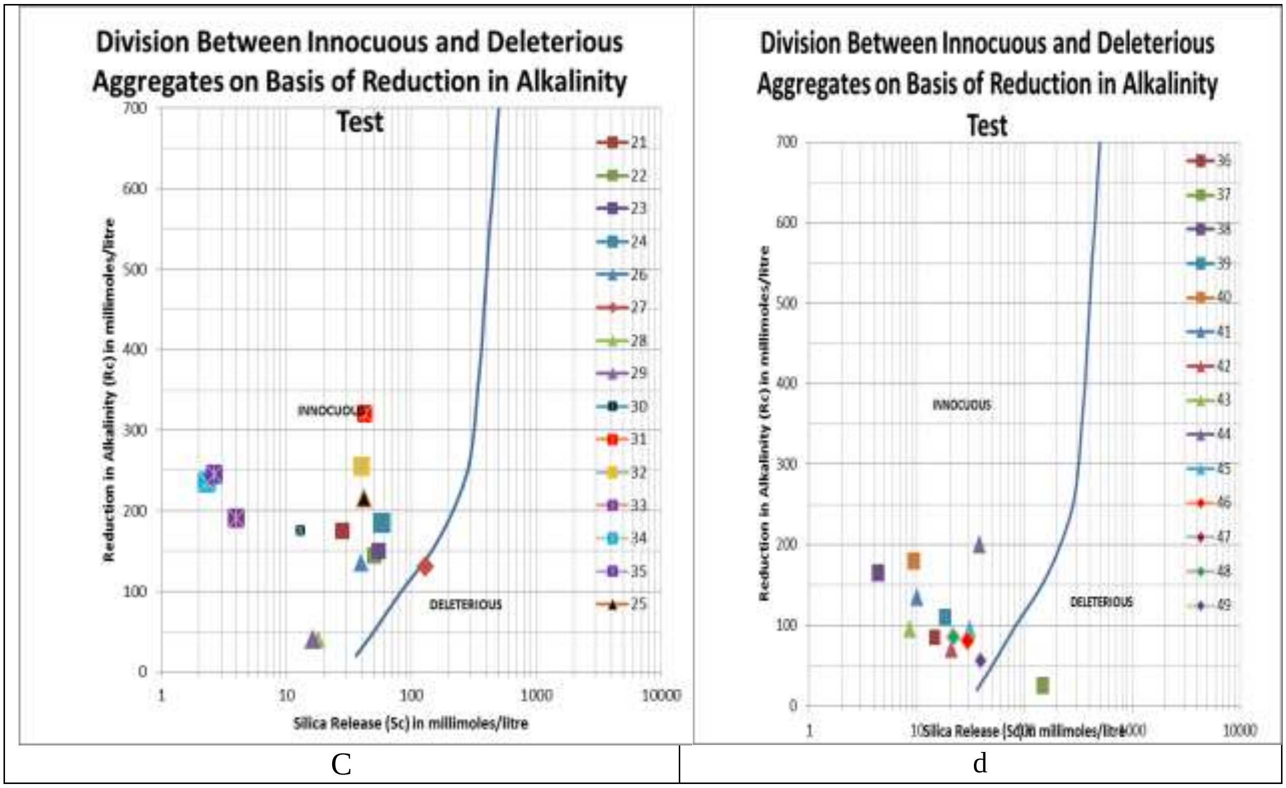

C

d

Figure : 8 (a, b, c, d) – Graphical representation for characterization of aggregates

Calculation of alkali content in flyash based Portland pozzolana cement may be done as follows:

$$Aeff = \frac{(X\ x\ C)}{100} + \frac{(1-X)F}{600}$$

Where,

X = % of OPC/Clinker in Portland Pozolana Cement; C = Alkali content in OPC/Clinker cement (as Na_2O eq.), % by mass; F = Alkali content in flyash (as Na_2O eq.),% by mass and A_{eff}= Effective alkali content in PPC, % by wt.

Furthermore, BS 3892 has suggested that the damage to concrete is likely to occur if any OPC is replaced by 25% or more pulverized fuel ash, provided that the alkali content of the concrete is not more than 3.0Kg/M^3. Therefore, limiting alkali contribution to less than 3.0Kg/M^3 is the key factor for all types of cementitious materials.

As per the ICOLD Bulletin 79 "Alkali Aggregate Reaction in concrete dams, review and recommendations", 1991, a distinction is needed between those with a medium slag content and high slag content in case of Portland blast furnace slag is used. In that case, to be considered as low alkali cement, they should meet following recommendations:

More than 50% slag : Less than 0.9 % Total alkali as Na_2O eq.
More than 65% slag : Less than 2.0 % Total alkali as Na_2O eq.

CASE STUDIES

The following case studies from India and all over the world where alkali silica reaction has encountered in hydraulic structures.

Hirakud Dam, Orissa

The distress were observed and experienced since 1974 nearly 18 years after completion of the dam. Horizontal cracks in the operation gallery, gates haft, sluice barrel and to a small extent in the foundation gallery in all right spillway block. Width of cracks varying from hair cracks to a max. of 6 to 9 mm at the surface. Some of the cracks were found to extent to a maximum depth of about 2 meter. Extensive horizontal cracking on the U/S face of the dam with width of cracks up to 12mm.

Horse Mesa, Arizona

The 93 m (305 ft) high Horse Mesa Dam with a crest length, including the abutment spillways, of 201 m (660 ft), is a thin arch dam completed in 1927. Located about 65 miles northeast of Phoenix, the dam impounds Apache Lake on the Salt River in central Arizona. After the discovery in 1946 of AAR problems at Stewart Mountain Dam, cores were taken from the Horse Mesa Dam.

Owyhee, Oregon

Constructed between 1928 and 1932, Owyhee Dam is a concrete thick-arch structure with a maximum height of 127 m (417 ft) and a crest length of 183 m (600 ft). Deterioration and cracking of concrete, which first appeared in 1948, is continuing and is thought to be caused by AAR. An investigation conducted in 1988 concluded that AAR is occurring at varying degrees in the dam. It is strong in the upper and outer portions of the dam, and only mild to non-existent in the lower and deep interior portions.

Fontana Dam, United States

The Dam is a gravity-type concrete structure, 480 ft (146.3 m) high, located in North Carolina, USA. This dam, constructed in the early 1940s, began cracking distress in about 1972. At that time a 4-year program of investigation, analysis, and repair was undertaken. Results revealed that the cracking resulted from stresses caused by both thermal and AAR expansions in the concrete. The primary reactive rock type is a metagray wacke to quartzite aggregate. In the laboratory, concrete samples were subjected to a variety of temperature and moisture conditions to determine the rate and magnitude of growth from AAR.

Matilija Dam, United States

This dam located near the central California coast, USA, is a 190-ft (58-m) high, thin arch dam constructed in 1947. The dam has experienced some foundation problems, having been located on highly sheared and fractured sandstones and shales. In spite of these serious foundation problems, it was the alkali-aggregate reaction of the local aggregates in the dam concrete that was responsible for the ultimate demise of the structure.

Stewart Mountain Dam, United States

It is a 207-ft (63.1-m) high, thin arch concrete dam flanked by concrete thrust blocks, was constructed during 1928-1930 near Phoenix, Arizona, USA. Field reports as early as 1937 reported excessive movements and cracking on the downstream face, on thrust blocks, and elsewhere. Deflections were sufficient to require severing reinforcing between the dam and powerhouse located at the downstream toe. Laboratory tests conducted in 1943 on cores extracted from the dam confirmed that the concrete was experiencing a phenomenon described as alkali-aggregate reaction. The reactive aggregate particles in the concrete were glassy to cryptocrystalline volcanic materials of andesitic to rhyolitic composition. with the lower anchorage in sound bedrock, to restore the structural integrity of the dam.

Beauharnois Project, Quebec Province, Canada

The project was completed at different stages from 1932 through 1960. It has a 2720-ft (829-m) long powerhouse with a concrete gravity wing dam located at each end. Movements and cracking have been experienced in all of the project structures for years.

Mactaquac Generating Station, New Brunswick, Canada

Alkali-aggregate reaction also occurred in the concrete of Generating Station. This 600-MW power project includes a rock fill dam and a concrete powerhouse. The concrete structures were built during 1964-1968. The greywacke aggregate and the alkalis in the cement (0.7 percent Na20 equivalent) have reacted causing destructive expansions and attendant high stresses.

CONCLUSION

The aggregate samples tested for various river valley projects were innocuous in nature barring few samples from north east region. Identification of reactive aggregates using alkali aggregate reactivity test (Chemical method) mentioned in IS: 2386 – 1963 (Part VII)is the quickest and much preferable technique. Further, cement and cementitious materials should be chemically analyzed for its alkali content. High alkali materials should be avoided for use in construction to prevent alkali silica reaction. Use of blended cements should be preferred over the Ordinary Portland Cement.

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