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CALIFORNIA'S EXPERIENCE WITH REACTIVE AGGREGATES

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ABSTRACT

California has a long history of research into alkali-silica reactivity (ASR) in concrete. Stanton and coworkers at the Division of Highways laboratory in Sacramento (now TransLab) undertook several research programs and published much needed information on alkali-silica reactivity in concrete during the 1940s and 1950s.

In the last decade many more cases of ASR in concrete structures have been discovered in California and a considerable number of potentially reactive aggregates have been identified.

A review of historical ASR work in California and recent case histories of some of the structures affected by ASR are presented. Also reported are the results of testing performed on aggregates from throughout the State of California using ASTM C 289 and AASHTO T 303/ASTM C 1260 test methods. Interpretation of AASHTO T 303 results using innovative methods developed by others is also included in this paper.

Keywords: alkali-silica reactivity, reactive aggregates

HISTORY OF ALKALI-SILICA REACTIVITY AFFECTED STRUCTURES IN CALIFORNIA

The first structure to develop distress, which is now identified as Alkali Silica Reactivity (ASR), to such an extent as to attract attention, was the King City Bridge built in 1919 – 1920 across the Salinas River at King City in Monterey County. Within three years after construction, well defined cracks were evident that extended from some of the pier caps into the columns. By July 1924, all of the piers were similarly affected. Elsewhere in Monterey County, other concrete structures made with Salinas River fine sand also showed serious distress. The failure of King City Bridge was investigated by a number of agencies and each put forth different theory, but without any convincing explanation (Stanton 1947).

In 1938, a section of concrete pavement, built in 1936 north of Bradley in the Salinas Valley, Monterey County, failed through excessive expansion. The expansion caused buckling at the joints and severe cracking throughout the entire length of certain slabs. On inspection, it was found that expansion and cracking was due to the use of local sand in the concrete (Stanton et al. 1942, Stanton 1947).

This pavement failure culminated a series of concrete failures along the coast area from Monterey County south to the western part of Los Angeles County. All the failed concrete had used the same fine aggregate.

At the same time, it was also noted that many other structures that had used the same Salinas sand showed no evidence of deterioration. Stanton carried out tests in the laboratory with various cements of different alkali contents and different aggregates. It was determined that the failed Bradley concrete pavement contained portland cement that had 1.14% alkali content. Those concrete structures that had no evidence of deterioration were made with cement of 0.45% alkali content. Two of the mineral constituents that contribute to ASR expansion were identified as opal in the opaline cherts and the glass matrix of some volcanic rocks. It was, therefore, concluded that expansion excessive enough to rupture concrete will take place when high alkali cement was used with aggregates of opal bearing cherts and shales from the upper miocene sedimentary deposits. These deposits lie along the coast from the Palos Verdes area in Los Angeles County in the south to Monterey County in the north.

The flurry of research on alkali-silica reactivity in the late 1940s and early 1950s established the use of low alkali cement containing not more than 0.6% alkalies (sodium oxide equivalent) (Stanton et al. 1942). With the adoption of such a specification, the California Department of Transportation (Caltrans) had considered the issue settled. However, in 1983 alkali silica reactivity damage was again identified and since 1985 pozzolanic materials have been required in concrete containing potentially deleterious aggregates (Glauz and Jain 1996).

Caltrans used ASTM C 289 method to assess the potential reactivity of aggregates. However recent work indicates that C 289 may not be a reliable predictor of aggregate performance (Stark et al. 1993).

EVALUATION OF TEST METHODS FOR IDENTIFICATION OF REACTIVE AGGREGATES

With the advent of requiring pozzolans in some concrete, Caltrans adopted test method ASTM C 289 for the determination of potential reactivity of aggregates. It was felt that ASTM C 227 was not satisfactory because it took too long to get results (one year) and did not reveal slowly reactive aggregates. With the creation of the new test method, AASHTO T 303 or ASTM C 1260 for detection of reactive aggregates, it was thought worthwhile to perform T 303 and C 289 tests on a large number of California aggregates to determine whether any relation exists between the two methods. Caltrans laboratory tested 68 coarse and fine aggregate samples received from various sources in California using these two methods. The test results are presented in Table 1.

Results and Discussion

The R_c (reduction in alkalinity) and S_c (dissolved silica) results of 68 aggregates were plotted on the standard curve shown in Figure X1.1 of ASTM C 289 for classifying the reactivity of aggregates. Out of the 68 aggregates tested, only 10 were found to be deleterious or potentially deleterious and the rest were innocuous (see Fig. 1).

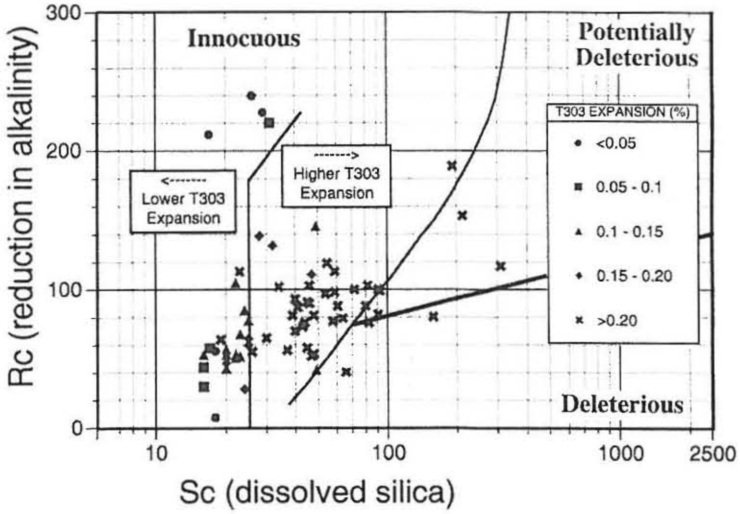

Fig. 1: ASTM C 289 Results with AASHTO T 303 Expansion Values

TABLE 1: AASHTO T-303 and ASTM C-289 Test Results of California Aggregates

A	B	C	D	E	F	G	H
275	102	0.377	-2.78	E	I	89	46
276	102	0.307	-2.69	E	I	112	59
064	109	0.343	-2.84	E	I	69	40
281	109	0.267	-3.00	E	I	80	39
282	109	0.320	-2.88	E	I	80	48
339	109	0.270	-3.12	E	I	90	45
059	110	0.362	-2.56	E	I	75	44
273	110	0.282	-2.89	E	I	55	37
274	110	0.265	-3.09	E	I	101	34
369	110	0.348	-2.40	E	I	57	45
307	404	0.248	-3.24	E	I	72	43
308	404	0.143	-3.96	PE	I	51	23
355	809	0.313	-2.66	E	I	64	30
356	809	0.253	-3.20	E	I	54	26
325	1007	0.197	-3.57	PE	I	138	28
326	1007	0.230	-3.48	E	I	112	23
330	1009	0.267	-2.75	E	I	102	82
331	1009	0.277	-2.81	E	PD	98	93
055	1103	0.432	-2.53	E	I	52	48
269	1103	0.307	-2.86	E	I	92	40
295	1214	0.153	-4.20	PE	I	131	32
069	1229	0.330	-2.75	E	I	99	72
292	1229	0.272	-3.46	E	I	118	55
357	1401	0.645	-1.83	E	PD	116	310
358	1401	0.515	-1.94	E	D	79	158
332	1907	0.135	-4.18	PE	I	84	24
333	1907	0.143	-4.63	PE	I	56	20
334	1907	0.145	-4.37	PE	I	42	20
298	1912	0.157	-4.25	PE	I	59	25
300	1912	0.113	-4.51	PE	I	52	20
344	1912	0.142	-4.77	PE	I	50	22
073	1916	0.112	-4.77	PE	I	52	22
296	1916	0.147	-4.17	PE	I	104	22
299	1916	0.153	-4.22	PE	I	64	25
345	1916	0.132	-4.75	PE	I	67	23

A	B	C	D	E	F	G	H
049	1923	0.135	-4.38	PE	I	52	16
266	1923	0.167	-4.42	PE	I	46	20
309	1925	0.135	-4.04	PE	I	77	25
310	1925	0.152	-3.84	PE	I	27	24
067	1938	0.013	-9.29	NE	I	55	18
287	1938	0.020	-5.72	NE	I	7	18
068	2308	0.082	-5.10	NE	I	219	31
290	2308	0.048	-6.42	NE	I	239	26
291	2308	0.047	-5.45	NE	I	227	29
270	3005	0.112	-4.66	PE	I	145	49
056	3010	0.192	-4.05	PE	I	110	47
267	3010	0.142	-4.98	PE	D	41	49
268	3010	0.207	-4.07	E	I	51	47
293	3010	0.263	-3.46	E	I	86	41
327	3673	0.065	-4.89	NE	I	29	16
328	3673	0.062	-5.37	NE	I	57	17
329	3673	0.085	-6.98	NE	I	43	16
352	3914	0.342	-2.97	E	I	76	58
353	3914	0.342	-2.77	E	D	75	83
354	3914	0.345	-2.79	E	D	81	91
061	3919	0.207	-2.71	E	I	102	46
075	4543	0.232	-3.22	E	I	92	40
305	4543	0.258	-2.93	E	I	78	64
306	4543	0.267	-2.95	E	I	96	54
324	4802	0.013	-7.13	NE	I	211	17
272	5505	0.455	-3.61	E	PD	152	213
071	5617	0.422	-2.48	E	I	97	59
297	5617	0.575	-2.27	E	I	188	193
283	5708	0.315	-2.65	E	PD	99	91
284	5708	0.365	-2.80	E	D	39	66
065	5708	0.360	-2.76	E	I	63	19
350	5711	0.292	-3.12	E	PD	87	80
351	5711	0.305	-2.92	E	I	87	61

A = Sample Number
B = Aggregate Source Number
C = T-303 Expansion Results @ 14 Days
D = Avrami Intercept (Ln (k))
E = T-303 Rating
F = C-289 Rating
G = C-289 Reduction in Alkalinity (Rc)
H = C-289 Dissolved Silica (Sc)

Notes:
E = Expansive
NE = Non-expansive
PE = Potentially Expansive
D = Deleterious
PD = Potentially Deleterious
I = Innocuous

The results of the rapid immersion test (AASHTO T 303) show that only nine aggregate samples have expansion less than 0.1%, which is indicative of innocuous behavior. The remaining 59 aggregates show expansion more than 0.1% indicative of a potentially deleterious character.

The results of ASTM C 289 and the expansion results of AASHTO T 303 were plotted against each other in Fig. 1 in the hope of finding a relationship between the two sets of results. Though the final answer derived from the two procedures do not correlate, there is an apparent relation between the data generated by each test.

An analysis of the expansion data (T 303) shows that nine aggregates from four sources had expansion less than 0.1%, which classifies them as innocuous. Sixteen aggregates from seven sources showed expansion between 0.1% and 0.15%. Based on a maximum expansion limit of 0.1%, these aggregates are deleterious. However, in the author's opinions, this threshold is debatable until field data in the California environment support it. We are currently in the process of collecting the required data on various aggregates. In Canada, 14-days expansion limit of 0.15% has been adopted.

Based on the expansion value of 0.15% (Hooton 1996), a boundary line can be drawn on the R_C, S_C plot to indicate an aggregate's expansion potential. With little exception, aggregate samples that have an S_C value greater than 25 and an R_C value less than 200 will have an expansion greater than 0.15%. Similarly, samples with an S_C value less than 25 or R_C value greater than 200 usually have a low expansion by T 303.

It is worth mentioning here that in the absence of a quick, definitive test method for determining the alkali silica reactivity of aggregates, Caltrans has included in all specifications for portland cement concrete mandatory use of Class F as well as low alkali cement. The percentage of flyash to be used in concrete as a replacement of portland cement is 15% to 25% depending on the amount of calcium oxide in the flyash, and the maximum amount of calcium oxide allowable in flyash is 10%.

Kinetic –Based Method for Interpreting Results of Accelerated Mortar Bar Method (AASHTO T 303 or ASTM C 1260)

A kinetic-based method has been proposed (Johnston, et al. 1996) to overcome some of the problems in using a percent expansion criterion for identifying potentially reactive aggregate. The method is based on Avrami nucleation and growth reaction kinetics where the expansion is exponentially related to a power of time. The slope and intercept are calculated by linear regression on the transformed data of time and expansion. Johnston examined the calculated slope and intercept and found that only the intercept ln(k), the log of the Avrami rate constant, is predictive of innocuous behavior in field use.

To test the applicability of the method to aggregates in California, a number of coarse and fine aggregates from various sources in California were fit to the Avrami equation. The test results of 14 days expansion values and Avrami constant, ln(k), are given in Table 1. The results show that aggregates with expansion more than 0.1% that are considered deleterious by T 303 interpretation, have intercept ln(k) values greater than –5 which, by Johnston's criterion (Johnston et al. 1996) classifies them as deleterious aggregates.

The 14 day expansion results are plotted versus ln(k) in Fig. 2. An examination of the data indicates a linearity between the two parameters that can be interpreted to mean that they are interdependent. When one considers using the value ln(k) as a criteria for classifying aggregates, the data presented suggest a value of –5 as being an appropriate threshold, as it strongly correlates to a 14-day expansion limit of 0.1%. However, one should also consider that the presented data in some cases represent multiple sizes from a single source that may confound the interpretation. The source 3673 has three tests conducted on various sizes of coarse aggregates – "pea gravel," 25 x 4.75 mm, and 37.5 x 19 mm. In this example, the expansion varies from 0.062% to 0.085% and ln(k) varies from –4.89 to –6.98. These aggregates are from a gravel source of mixed petrologic composition, which could explain the variation in values. However, the aggregates are all reduced from larger sizes so the three tests could be considered replications and the variation may be primarily due to the precision of measuring very small expansions, especially in the early ages.

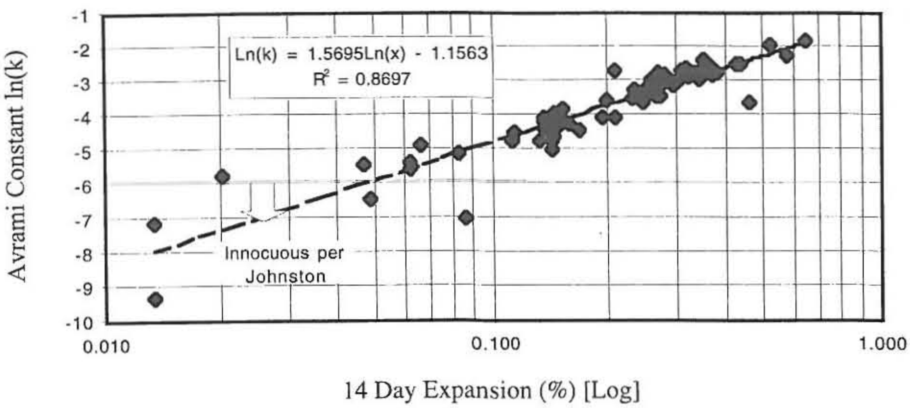

Fig. 2: Ln (K) vs. T-303 14-day Expansion

FIELD INVESTIGATIONS OF CONCRETE STRUCTURES AFFECTED BY ALKALI-SILICA REACTIVITY

During the time period of late 1980s and early 1990s, many bridge structures were identified that were affected by ASR in the desert regions of San Bernardino County. The severity of the ASR problem was not fully understood until a coring and testing operation was conducted in May 1994 on ten multi-span structures on Interstate 15 between post mile (PM) 160.7 and 162.5. The investigation comprised of coring girders of the precast deck units, bent caps, abutment walls and wing walls, visually inspecting all structural elements and testing of concrete cores in the laboratory. It was determined that approximately 90% of these structures units exhibited varying extents of ASR deterioration (Campbell et al. 1998).

Based on the earlier survey results, a larger survey was conducted on 161 bridge structures in the same general vicinity in San Bernardino County. The structures were inspected for ASR damage using visual observation, uranyl acetate test, and concrete cores for strength and petrographic examination of cores.

Based on the tests performed, over 80% of the structures showed some evidence of ASR at various stages of deterioration.

Mitigation Measures

Repair of concrete structures damaged by ASR has been undertaken in the last 20 years. Various methods and materials have been used to combat the ASR problem. The remedial measures carried out on one pavement and two structures are described below.

Route 58, Eastbound Pavement in Boron, California -- State Route 58 is a four-lane limited access highway built in 1971 of portland cement concrete. In 1988, a portion of map cracked pavement in the travel lane (lane 2) was treated with high molecular weight methacrylate. In 1995, test sections were established in both the passing lane (lane 1) and lane 2. The test sections are Control 1, Methacrylate 1 and Methacrylate 2 in lane 2 and in lane 1, Control 2, Control 3, and Methacrylate 3. At that time, a second treatment of methacrylate was applied to section Methacrylate 2, to evaluate effectiveness of repeat treatment, and a first treatment was applied to section Methacrylate 3. A survey of the test sections was done in April 1997 to evaluate the performance of the methacrylate treatments (Sherman et al. 1997). Methacrylate can act as a remediation by filling cracks thereby reducing direct water penetration and "gluing" together the pieces of concrete and restoring some of the structural integrity. An evaluation of the test results showed that application of methacrylate coating on the ASR affected pavements helps prolong the life of the pavement.

Los Carneros Road Overcrossing -- Los Carneros Road Overcrossing is a two span prestressed precast girder structure built in 1968 near Santa Barbara. In the mid 1980s, ASR cracks were observed in both abutments including diaphragms and wingwalls. In 1990, a silane-based sealer was applied to the deck and sidewalk and to the columns at Bent 2. There has been no change in the condition of the deck and sidewalk since the treatment with the silane sealer, based on biennial visual inspection.

Cold Springs Canyon Bridge -- High molecular weight methacrylate (HMWM) is typically applied to horizontal surfaces as a flood coat and cracks are filled by gravity. Caltrans has successfully sealed cracks in vertical surfaces by gravity fed application of HMWM. The principle is to hold the liquid resin against the vertical surface in a reservoir and allow the resin to penetrate the horizontal cracks by static head. (Fig. 3)

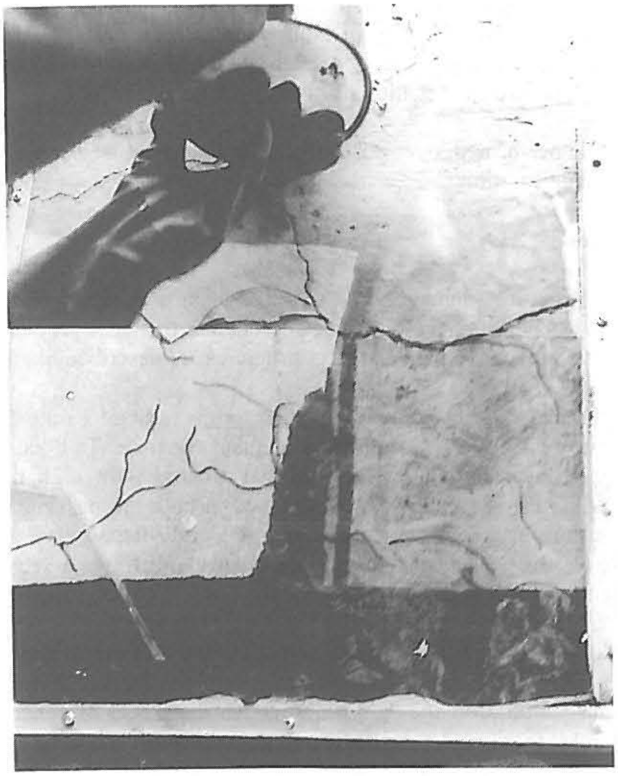

Fig. 3: Placement of Methacrylate into Acrylic Reservoir

A massive concrete support for a large steel arch bridge at Cold Springs Canyon in Santa Barbara County was treated with methacrylate. After treatment, concrete was cored to determine the depth of penetration of the HMWM. A core 50 mm in diameter by 0.4 m long was extracted. Before treatment such a core would have come out as rubble, but in this case it was entirely intact. Methacrylate penetrated the entire length of the core. The HMWM concrete treated was monitored for two years and no additional expansion was observed.

CONCLUSIONS

1. There is a relation between ASTM C 289 values of R_c and S_c, and the 14 days expansion of AASHTO T 303 mortar bars.
2. Interpretation of AASHTO T 303 expansion data using Avrami nucleation and growth equation is inconclusive.

3. AASHTO T 303, rapid immersion test method for identification of reactive aggregates needs adjustments in expansion limits to correlate well with the actual field performance of aggregates.

4. High molecular weight methacrylate (HMWM) treatment can extend the service life of ASR damaged concrete pavement and structures by restoring structural integrity and reducing moisture penetration by filling the cracks.

5. Silane treatment on concrete structures appears to arrest ASR deterioration by reducing the internal humidity through allowing evaporation and preventing wetting.

6. To combat ASR deterioration in new structures and pavements, Caltrans has taken important steps in using low alkali portland cement and pozzolanic materials in all concrete constructions.

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