CONCRETE DISTRESS FROM ALKALI-SILICA REACTION, CURRENT RESEARCH AND MITIGATION IN FUTURE DESIGNS, COUNTY OF ORANGE, STATE OF CALIFORNIA, U.S.A.

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ABSTRACT

Numerous concretes in Orange County's infrastructure contain distress. This distress is attributed to various physical and chemical processes, external and internal to the concretes. The most common cause of distress is from the internal chemical process known as alkali-silica reaction (ASR). ASR-related distress is typically in the form of map cracking (polygonal cracking), pop-outs, and spalling. Micro cracks and associated ASR gel have been observed in these distressed concretes with a petrographic, polarizing microscope. Some damage is so extensive that structures have lost their structural capacity or functionality to the extent where they are partially dismantled and rebuilt, or are totally dismantled. The life of some concretes is shortened far below the design life, resulting in tens to hundreds of thousands of dollars spent prematurely for redesign and reconstruction.
ASR, first identified 64 years ago and presently recognized world wide, involves a chemical reaction of unstable amorphous- to cryptocrystalline-silica, highly metamorphic quartz, chert, optically strained quartz, or micro cracked quartz in the aggregate, in the presence of moisture, with alkalis, calcium, and hydroxyl ions in the cement paste. This reaction produces hydrous, calcium, alkali-silica gel that absorbs moisture, swells, and cracks the concrete where the expansive pressure from formation of the gel exceeds the tensile strength of the concrete. These varieties of silica are more reactive for ASR than other varieties because they are less ordered molecularly, have weaker bonding, have less chemical stability and so they have a higher tendency for reaction. Orange County's current aggregate sources contain such reactive siliceous grains. Aggregates currently proposed for County Public Works concretes are subjected to petrographic analyses and those found to contain potentially reactive siliceous grains in excess of threshold percentages (1-5%), are required to contain 20% substitution of flyash for cement to mitigate ASR in future concretes. The process of petrographic analysis and flyash substitution, where the latter is deemed necessary, is expected to save the County tens to hundreds of thousands of dollars for repair, replacement, or demolition of prematurely deteriorated concrete structures.

Key Words: Concrete, Alkali-silica reactivity, Future mitigation

1 INTRODUCTION

1.1 Background

Investigations, by the authors, of concrete distress of various local structures in Orange County (Fig. 1) began in 1997 and continue to the present date. These concrete structures include the spillway for a dam, a cross-gutter for a road, a recreational fishing pier, building slabs, and a bridge deck. The ages of the structures range from 29 to 40 years. Deterioration of some of these concretes reached the point where the structural integrity was jeopardized so removal or repair

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was required. Initial field observations of the surfaces of these structures revealed common distress characteristics that included map cracking, concave-upward pop-out depressions (pop-outs), and some spalling. It was realized that the map cracking and pop-outs resembled those shown by Stark [12] and Forster [3] as typical for other concretes that have been subjected to alkali-silica reaction (ASR). Petrographic analysis was needed in each of our concrete investigations to confirm the occurrence of ASR.
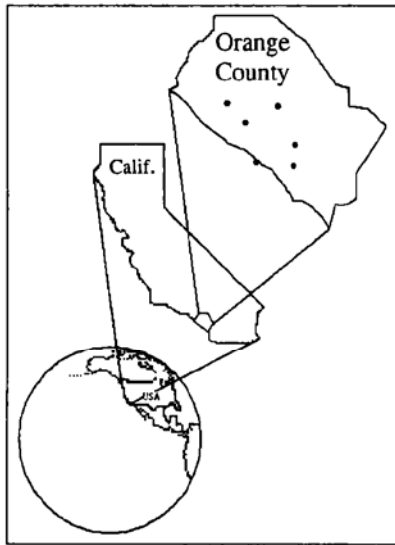

Fig.1 Location map

1.2 Purpose

The purpose of this paper is threefold: (1) to present results of our investigations of six distressed concrete structures in Orange County; (2) to present the evidence for ASR in thin-sections of these concretes, as observed with a polarizing microscope; and (3) to describe the action taken by the County to mitigate this ASR problem in our future concretes in order to save costs of premature repair, replacement, or removal.

1.3 Alkali-Silica Reaction in Concrete - General

ASR was first identified 64 years ago by Stanton, [9] and [10] and is now recognized worldwide. ASR process involves a chemical reaction of any of many types of unstable amorphous- to cryptocrystalline-silica and/or highly metamorphic quartz in the aggregate, in the presence of moisture, with alkalis, calcium, and hydroxyl ions in the cement paste. This reaction produces a hydrous, calcium, alkali-silica gel that may be represented by the generalized compound: $Na_2O \cdot K_2O \cdot CaO \cdot SiO_2 \cdot nH_2O$ [11]. The gel has a great tendency to absorb moisture and swell. Swelling of the gel creates expansive pressures in the concrete and results in cracking of the concrete

when these pressures exceed its tensile strength. The potential for contribution to quick ASR, two months or less for 0.04% expansion (Helmuth and others [5]) depends on the presence of highly reactive, unstable amorphous (non-crystalline) silica including chert, opal, chalcedony, siliceous volcanic glass, cryptocrystalline siliceous volcanic rocks, and synthetic siliceous glass. Slow ASR, 6 months for 0.04% expansion, depends on the presence of slowly reactive aggregate that contains high temperature beta-quartz, cristobolite, tridymite, vein quartz, and rock fragments consisting of, or containing highly metamorphic quartz (beta quartz) including quartzite, some argillites, meta-graywackes, phyllites, and schists. Slow ASR also involves optically strained quartz, microfractured, and microcrystalline quartz. These varieties of silica and quartz, mentioned above are more reactive than other types of quartz and other silicates because these varieties are poorly crystalline to non-crystalline, less ordered on a molecular basis, and the molecular bonding is weaker (Helmuth and others, [5]). Weaker bonding results in less chemical stability and a higher tendency for reaction.

Siliceous minerals and amorphous silica considered potentially reactive for ASR are listed by the American Society for Testing and Materials [1]. Threshold percentages listed by the Guide Specification by the Portland Cement Association [7] are: (a) optically strained, microfractured, or microcrystalline quartz exceeding 5% (a common constituent of granite and granite gneiss), (b) chert or chalcedony exceeding 3%, (c) tridymite or cristobolite exceeding 1%, (d) opal exceeding 5%, and (e) natural volcanic glass in volcanic rocks exceeding 3%.

1.4 Methods

Observations were made of the distressed concrete structures, photographs were recorded, and cores or fragments of concrete were taken for further observations, photographs, and thin-section construction. A private company was contracted for construction of thin-sections. The thin-sections were bound to the microscope slides by epoxy [refractive index (n) = 1.54]. The epoxy was dyed blue to highlight micro cracks and other voids in the thin-sections of concrete. The samples were ground to a standard thickness of 0.03 mm. Feldspar stains including sodium rhodiziate which stains calcic plagioclase pink, and sodium cobaltinitrate which stains potassium feldspar yellow were applied to the thin-sections. Cover-slips were attached with epoxy. Subsequently, petrographic analyses with a polarizing microscope were performed on the thin-sections with emphasis on (a) classification of grains and mineral infillings, (b) percentages of different grain types,

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(c) identification of secondary minerals, (d) micro cracks and their distribution, patterns, and relations to specific grain types known for association with ASR, and (e) types, distribution, and percentage of porosity. Percentages of different grain types and porosity were determined by point counts of 200 points using a mechanical stage.

We used the list of siliceous minerals and amorphous silica considered by the American Society for Testing and Materials [1] as potentially reactive for ASR as our standard for recognizing potentially reactive minerals and grain types. Threshold percentages are listed in the Guide Specification by the Portland Cement Association [7]. We consulted the guidelines for petrographic examination of hardened concrete that are described in reference [2].

Finally, an internal report was completed for each investigation. Six of these investigations are each summarized and presented in chronological order below.

2 SUMMARIES OF INVESTIGATIONS

2.1 Sulfur Creek Dam Spillway

Upper part of the concrete spillway for Sulphur Creek Dam, built in 1966, investigated in 1997, was fractured and deteriorated beyond repair. We were requested by the County's Operations and Maintenance Division to provide recommendations. We observed that the structural integrity of the spillway was jeopardized. The fractures in the concrete were in a grid pattern and the spillway walls and ogee ramp were bulged toward the interior of the spillway. The quartz-feldspathic, sandy siltstone bedrock of the Capistrano Formation had a very severe sulfate content of 15,226 ppm and a medium potential for expansion. Thin-sections of cores showed excessive porosity, gypsum growth from sulfate reaction, and 4% of the concrete aggregate as unstable siliceous minerals and rock fragments with indications of ASR such as micro cracks radiating away from the grains (Figs. 2a and 2b). Our report concluded that the concrete distress resulted from 1) faulty placement of the concrete; 2) excessive permeation of acidic water from the bedrock into the concrete, partially dissolving the concrete, increasing its porosity and decreasing its strength; 3) expansive pressures within the concrete from gypsum growth as a sulfate reaction, oxidation of steel reinforcement bars, and alkali-silica reaction; and 4) from external pressure on the concrete from expansive bedrock. Redesign and reconstruction were recommended with 1) proper mixing of the concrete and elimination of unfavorable voids; 2) a dense concrete using fly ash to minimize sulfate reaction effects and mitigate ASR potential;

3) epoxy coating for steel reinforcement; and 4) consideration of bedrock expansion pressures in redesign of the structure. A greater part of the structure was rebuilt according to our recommendations in late 2001 through early 2002.

2.2 Northwood Cross-Gutter

This concrete cross-gutter was located at the intersection of Culver Drive and Farwell Avenue in the City of Irvine. The investigation and report, in November 1999, were part of the Materials Laboratory's on-going research in concrete distress, particularly alkali-silica reactivity. Distress was characterized by an unusually high extent of fractures, erosion, and pop-outs (Figs. 2c and 2d). A petrographic analysis was performed to determine the cause of the distress. The concrete aggregate was found to be composed of nearly 100% minerals known to be reactive for ASR. These grains included (1) sand consisting chiefly of monocrystalline and polycrystalline quartz, potassium feldspar, granitic- and meta-granitic rock fragments, argillaceous siliceous siltstone, chert, chert-bearing arkosic- and lithic-arkosic-sandstone (see [1]) and -metasandstone, highly-metamorphic pure quartzite sandstone, crystalline and minor glassy volcanic and hypabyssal rocks, biotite, argillaceous quartz siltstone, plagioclase feldspar, and micrographic potassium feldspar with quartz; and (2) gravel clasts of chert-bearing arkosic- and lithic-arkosic-sandstone and -meta-sandstone, and volcanic and hypabyssal rocks. The concrete binder was stained brown in the upper 8 to 10 mm. The porosity averaged 4 to 5% in most parts of the concrete binder. However, in some other areas it was as high as 30 to 40%. Vertical to near-vertical cracks were present within the upper 5 to 18 mm of the concrete, mostly within the brown-stained region in the binder and within and through grains of sand and gravel. Sand grains that contained the cracks were chert or highly metamorphic quartz. The gravel clasts that contained micro cracks were arkosic and lithic-arkosic sandstone and meta silty-sandstone that were in turn composed of fine to medium, sand-sized and silt-sized chert, phyllosilicates, microcrystalline quartz, arkosic sandstone, and meta-silty sandstone. Most of the micro cracks that were within the gravel clasts are oriented oblique to normal to the edge of their host gravel clasts. Some of these micro cracks that were very near the surface of the concrete were curved and oriented concave-upward with respect to the top or surface of the concrete (Figs. 2c and 2d). Some of these micro cracks extended to the area outside of the clasts, into the concrete binder. Other micro cracks were present along the margins of the clasts, outside of the clasts, and between the clasts and the concrete binder. These

micro cracks passed between and around clasts and they were anastomosing, interconnected with spherical voids in the cement binder, and some were arranged subparallel to the surface of the concrete. ASR gel was observed in parts of some of these micro cracks and is described below.

The high 30% to 40% porosity in some parts of the concrete, in contrast to the standard 4% to 5% maximum porosity, contributed to its lower than standard strength, its lower than usual resistance to fracturing and erosion, and entrance of excessive moisture. Conditions necessary for ASR that were present included: potentially reactive aggregate, porous concrete with higher than standard porosity, and plenty of water (the concrete comprised a cross-gutter). Petrographic analysis confirmed that distress in the concrete was attributable to ASR. Fractures in the sand and gravel grains were located where mineralogy of grains was reactive for ASR and consisted of chert, microcrystalline quartz, and phyllosilicates. The concave upward cracks in both clasts and cement paste would have been precursors to future conically-shaped pop-out depressions in the surface of the concrete. Pop-out depressions result from expansive pressures, such as from ASR that cause sand and gravel clasts to expand and "pop-out" from the surface of the concrete, leaving conically-shaped depressions in the surface of the concrete. ASR gel was recognized, based collectively on five criteria: 1) index of refraction of ASR gel (n = 1.46 to 1.53 [10]) was less than epoxy (n = 1.54) and quartz (n = 1.46 to 1.53); 2) yellow color or colorless in plane polarized light with lower nicol; 3) very dark brown to isotropic in polarized light with crossed nicols; 4) association with grains known to be reactive for ASR, particularly in sheltered micro environments such as micro cracks within some of the reactive grains (Figs. 2c and 2d); and (5) potassium feldspar stain appeared to stain the ASR gel yellow, a process recognized by Guthrie and Carrie [4] and by Powers [8] in other concretes. Most ASR gel was apparently washed away from the perimeter voids and from radiating micro cracks. The washing-away of some ASR gel is an understandable process in the low-flow condition and wetting and drying environment of the cross-gutter.

2.3 Aliso Pier

The 572 foot long Aliso Pier on Aliso Beach, constructed in 1971, was composed of pre-cast and pre-stressed concrete piles, pile caps, and planks that connected the pile caps. Extensive cracking and spalling occurred progressively during the 1970's, 1980's, and 1990's. The County concluded in 1998 that (a) the pier structure was still deteriorating, (b) it was not cost effective to repair

the structure, and (c) the pier was losing its structural capacity and functionality. The concern was due to loss of structural integrity of the pier due to cracking, pop-outs, and spalling of some of the concrete in the piles, pile caps, and lightweight concrete deck The pier had a short life span and was dismantled in late 1998 and early 1999.

We made observations during the dismantling in 1999. The concrete had large concave outward depressions where pieces of concrete had fallen out or popped-out. These depressions ranged in size to numerous square cm. Some of these depressions exposed oxidized, steel reinforcement bars. The aggregate in the deck was light-weight, porous, artificial aggregate. Petrographic analysis of fragments of concrete from the piles, pile caps, and deck revealed a high percentage of the aggregate consisted of reactive grains that had experienced ASR. These grains had micro cracks inside of them, perimeter voids, and micro cracks radiating from them as shown in Figs. 2e and 2f. Other grains that were present and that are not listed by the American Society for Testing and Materials [1] and Portland Cement Association [7] as potentially reactive for ASR and these did not contain micro cracks or perimeter voids, nor did micro cracks radiate away from the edges of those grains. Therefore, it is concluded that the perimeter voids and the micro cracks that radiated away from the grains that are known as potentially reactive grain types, particularly from grains containing micro cracks, likely formed as a result of ASR. Some ASR gel, which has distinctive optical properties, is preserved in sheltered microenvironments in micro-cracks within some of the reactive clasts. The ASR gel was recognized collectively by 1) index of refraction (n = 1.46 to 1.53 [2]) less than that for the epoxy (n = 1.54) or grains of quartz (n = 1.54 to 1.55); 2) yellow (from potassium feldspar stain) to pale brown color in plane polarized light with the lower nicol; 3) very dark brown to isotropic in polarized light with crossed nicols, and 4) occurrence in association with grains known to be reactive for ASR, particularly in the fractures within, around the grain perimeter, and radiating from such a grain. Most ASR gel was apparently washed away from the perimeter voids and radiating microfractures. The washing-away of the ASR gel is an understandable process in the wetting and drying environment where the pier was situated on the coast. Some remaining ASR gel, with its distinctive optical properties, is preserved in sheltered micro-environments, in micro cracks within some of the reactive clasts.

Fracturing of the concrete was a result of internal expansion. The expansion resulted from alkali-silica reaction (ASR) simultaneously with oxidation and resulting expansion of steel
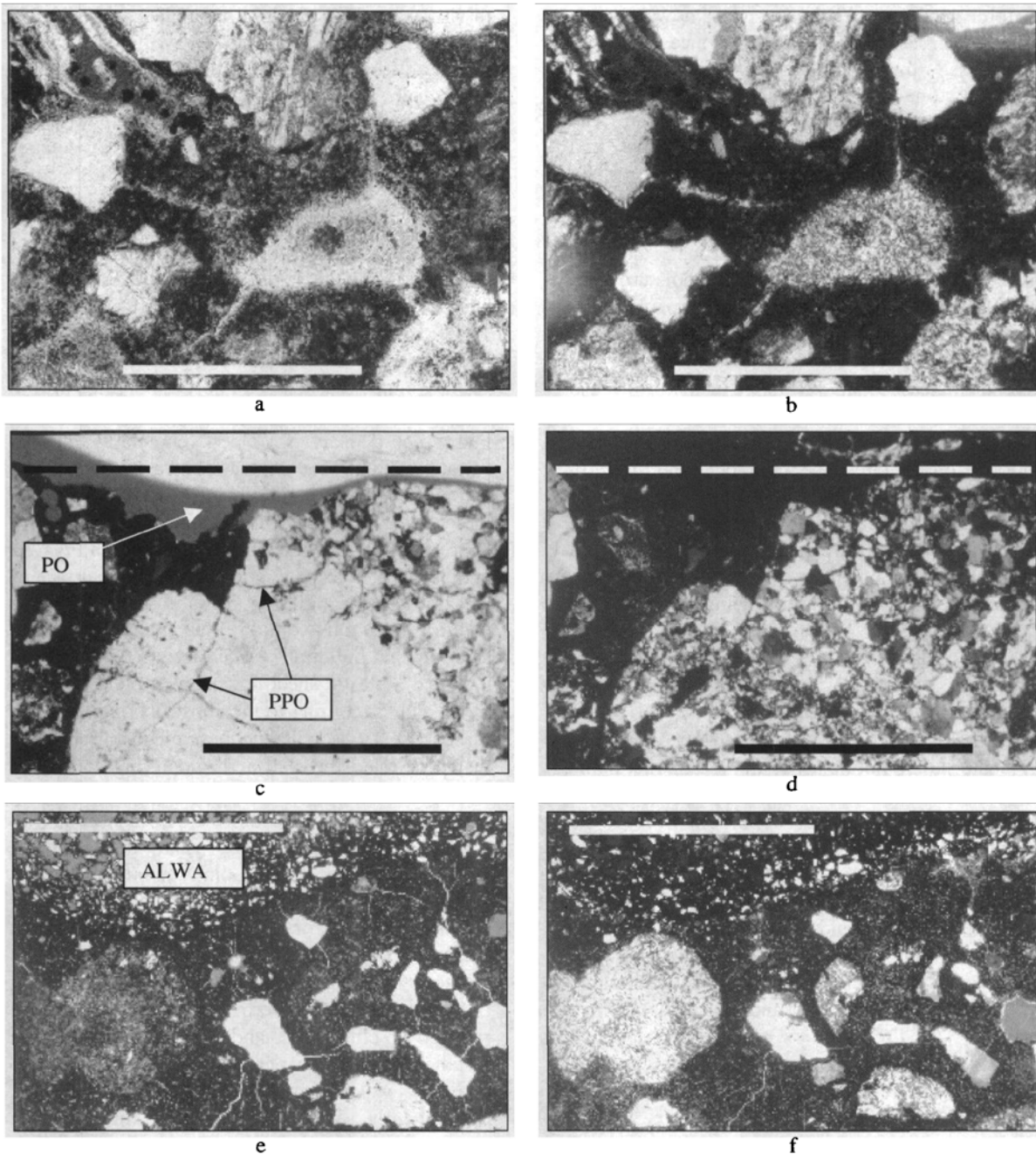
Fig. 2. a, Photomicrograph, thin section 8-5-97 h, plane polarized light with lower nicol, showing recrystallized ASR-reacted cherty grain in center of field of view with radiating micro cracks and with nucleus that is partly ASR gel, in concrete from Sulfur Creek Dam Spillway, bar scale is 0.5 mm. b, Photomicrograph, same field of view as Fig. 1a except in polarized light with crossed nicols. c, Photomicrograph, thin section 6-23-99 a, plane polarized light, showing cross-section of concave-upward pop-out (PO) at top or surface of cross-gutter (top of photograph) and also showing precursors to pop-outs (PPO) consisting of concave-upward ASR cracks within ASR-reacted metamorphosed silty sandstone grain in Irvine cross-gutter concrete, some relatively dark ASR gel remains within micro cracks, dashed line is surface of concrete, bar scale is 1.0 mm. d, Photo-micrograph, same field of view as fig. 1c except in polarized light with crossed nicols. e, Photomicrograph, thin section 3-26-99 a, plane polarized light with lower nicol, showing ASR reacted grains of highly metamorphic quartz and optically strained quartz with radiating micro cracks in concrete deck of Aliso Pier, and showing grain of non-reactive artificial lightweight aggregate (ALWA), bar scale is 1.0 mm. f, Photomicrograph, same field of view as Fig. 1c except in polarized light with crossed nicols.

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reinforcement bars. It is not known which expansion process started first, but once they were both onset, these adverse chemical processes enhanced one-another, and so the concrete degradation increased at an increasing rate. The initial fracturing allowed more moisture and chloride ions from sea water and from the salt in the air to enter the concrete. Porous aggregate in the concrete of the deck allowed excess moisture into this concrete. The additional moisture enhanced ASR. The additional moisture and chloride ions also enhanced oxidation of the steel reinforcement bars. The additional ASR and oxidation of the steel bars resulted in an additional volume increase and further expansion of the concrete. This further expansion of the concrete resulted in more fracturing, thus more moisture and chloride ions entered the concrete, and in turn, more ASR in the concrete and more oxidation of the steel occurred, resulting in more expansion and fracturing of the concrete, and the cycle repeated over and over again.

Our report included the following recommendations for similar structures in the future: (1) Concrete for structures such as the Aliso Pier should be composed of dense concrete with minimal porosity and very low transmissivity so that entry of water can be minimized; (2) Porous aggregate should not be used; and (3) Chairs, joints, and related areas of potential water entry should be well-sealed to minimize water entry into the concrete. Because adverse entry of water would enhance any tendencies in the concrete for the ASR process or for oxidation of steel reinforcement, both of which would fracture the concrete; (4) Potential for ASR of aggregate that is proposed for the concrete mix design should be determined by petrographic analysis and mitigated where necessary; (5) Oxidation of steel in the concrete should be minimized, and all steel in the concrete, including reinforcement bars, tie wires, and wire supports for adobe blocks should be epoxy coated. Cathodic protection should be applied to the steel reinforcement bars in the concrete in chemically harsh environments including those along coastlines or where sulfate exposure is high. All steel should be covered by a minimum of 6.5 to 8 cm of concrete; (6) Concrete should be protected to 3 m above mean sea level with a two-coat epoxy or polymer-concrete slurry-coat in order to significantly reduce wetting and its adverse effects on the concrete.

Our report of August 1999 recommended that the potential for ASR can be mitigated when the concrete aggregate contains potentially reactive silica, by either (a) using an aggregate that contained no minerals that were potentially reactive for ASR; (b) using a very low alkali cement,   (c)

mixing potentially reactive aggregate with less- or non-reactive aggregate to lower the amount of potentially reactive minerals to acceptable low percentage values that are below threshold percentages, or by (d) mixing with cement that contains 20% substitution of flyash to counter potential reactivity.

2.4 Harbor Court and Justice Center

The County's Harbor Court and Justice Center, located within the City of Newport Beach, was built in two sections. The north half was built in 1973, and the south half in 1987. We were requested to investigate and report on water seepage and cracked points of bulging in the concrete slab and overlying floor tile in July, 2000. Petrographic analysis of concrete cores found a sulfate reaction product in the form of the calcium sulfate mineral gypsum ($CaSO_4 \cdot H_2O$) and indications of alkali-silica reaction in the cherty aggregate of the concrete such as shown in Figs. 3a and 3b. Water seepage into and onto the surface of the floor in the building resulted from excessive exterior irrigation and poor drainage away from the slab of the building. The design for the slab included a plastic sheet under and around the edge of the slab, according to the construction plan. The plastic sheet was not encountered in our borings that penetrated the slab and underlying soil. Our conclusions included that excess moisture rising from the subgrade soil into the slab contributed to ASR and sulfate reaction, and the resulting expansion, cracking, and points of bulging on the surface of the slab. We recommended: (a) the points of bulging of the slab be ground to a flat surface, (b) the thin, brittle asphalt floor-tile be replaced by a thick soft floor cover, and (c) that irrigation around the perimeter of the building be reduced or eliminated, and (d) that a subdrain be installed around the perimeter of the building to convey water away from the building. Subsequently, a private firm was hired by the County to design the mitigation for excess water and oversee the installation of drainage devices.

2.5 County Materials Lab

A petrographic analysis of the concrete floor of the Physical and Chemical Testing Section of our own County Materials Laboratory, constructed in approximately 1963/64, was performed in November, 2001. This concrete slab floor was characterized by fine map cracking. A 6.5 cm diameter core was taken from the floor and thin-sectioned for petrographic analysis.

The concrete aggregate included (1) sand consisting chiefly of (a) monocrystalline quartz, (b) poly-crystalline quartz, (c) potassium feldspar, (d) plagioclase feldspar, (e) granitic- and meta-

granitic rock fragments, (f) argillaceous siliceous siltstone, (g) chert, (h) chert-bearing arkosic- and lithic-arkosic-sandstone and -metasandstone, (i) highly metamorphic pure quartzite sandstone, (j) crystalline and glassy altered volcanic and hypabyssal rocks, (k) biotite, (l) argillaceous quartz siltstone, (m) hematite, (n) highly metamorphic stretched quartzite, (o) meta-quartz sandstone, (p) meta-quartz siltstone; and (2) gravel clasts of (a) meta-rhyolitic volcanic rock with highly-undulose sutured quartz; (b) metagranitic rock fragments with strained-feldspars, sutured and highly strained quartz, and some which were mylonitic; (c) metagranitic rock fragments that were sheared and granulated and contained sutured highly strained quartz and microcrystalline quartz; (d) cherty micro-micaceous argillite (altered volcanic rock); (e) quartz-hornblende schist; (f) cherty argillaceous quartz siltstone; (g) chert (altered volcanic rock fragment with altered quartz and amphibole phenocrysts); and (h) cherty phyllosilicate. Greater than 90% of these sand and gravel grains were types known as potentially reactive for ASR according to the American Society for Testing and Materials [1] and Portland Cement Association [7].

Porosity visible with 40X magnification was approximately 5%. In the cement paste, entrained voids were approximately 3%. Entrapped air voids were approximately 2%. Entrapped voids were much more abundant in the upper 5-mm of the concrete, where the concrete was stained brown due to oxidation. Porosity comprising 1% was voids in silt- or sandstone rock fragments that developed from erosion, dissolving, or plucking of sub grains from individual whole rock fragment grains. Open micro cracks contributed to less than 1% and were most abundant in the upper 10-mm of the concrete. These micro cracks existed within sand grains and gravel clasts, and within the cement paste. Sand grains and gravel clasts that contained the micro cracks were mostly very cherty, altered porphyritic volcanic rock fragments with a groundmass of mostly chert with some microcrystalline quartz. Some highly metamorphic quartzite and metamorphic, optically strained granitic rock fragments also contain some micro cracks. Micro cracks that were within these sand grains and gravel clasts were oriented (a) oblique to normal to the edge of their host clasts, or (b) concave outward with respect to the grain boundary. Some of these micro cracks extended from the interiors of the grains or clasts to the area outside of the grains, into the cement paste. Furthermore, some of these micro cracks extended all the way to the surface (top of the slab) of the concrete. Micro cracks in the cement paste that were very near the surface of the concrete include some traces that are curved and oriented concave-upward with respect to the top or surface of the concrete. Some of these micro cracks were filled or partially filled with ASR gel that was pale yellowish brown in plane polarized light with the lower nicol, nearly isotropic in polarized light with crossed nicols (Figs.3c and 3d), and that had an index of refraction less than that of the epoxy.

Petrographic analysis confirmed that this concrete distress in the form of map cracking was attributable to ASR. Fractures in the sand and gravel clasts are where the mineralogy of these clasts is chert, microcrystalline quartz, optically strained quartz, and phyllosilicates that are potentially reactive for ASR. The concave outward fractures in sand grains and gravel clasts, and concave upward microfractures in the cement paste, containing some ASR gel, occurred as a result of the ASR gel formation and resulting expansive pressures within the grains and cement paste, respectively.

It was concluded that the distress in this concrete could have been avoided by either: (a) using an aggregate that contained no minerals that were potentially reactive for ASR; (b) using a very low alkali cement; (c) mixing potentially reactive aggregate with less- or non-reactive aggregate to lower the amount of potentially reactive minerals to acceptably low percentages; or by (d) mixing with cement that contained 20% substitution of flyash to counter potential reactivity.

2.6 Warner Avenue Bridge

The Bridge crosses the Santa Ana River on Warner Avenue, between Harbor Boulevard in the City of Santa Ana to the east and Newhope Street in the City of Fountain Valley to the West. Two parallel adjacent structures comprise the whole bridge. These structures are the north bridge, built in 1960 with a 9.8-m-width and the south bridge, built in 1969 with a 13.4-m-width. Both have a "T" beam superstructure on pier walls with precast concrete pile foundations. These adjacent bridges have six spans with an overall length of 77 m. The north bridge contains two west-bound lanes. The south bridge contains three east-bound lanes.

Our investigation was initiated in December 2001 after it was learned that the concrete deck contained cracks. Field observations and taking digital images of the deck, drilling in the deck for four 4-cm-diameter cores, and petrographic analyses of the cores were performed.

Cracking of the concrete on the bridge deck was extensive. These cracks were divided into two major types. The first type was map cracking. Map cracking in concrete can be a product of ASR ([3], [12]), although it can also form by other processes. The second major type of cracking
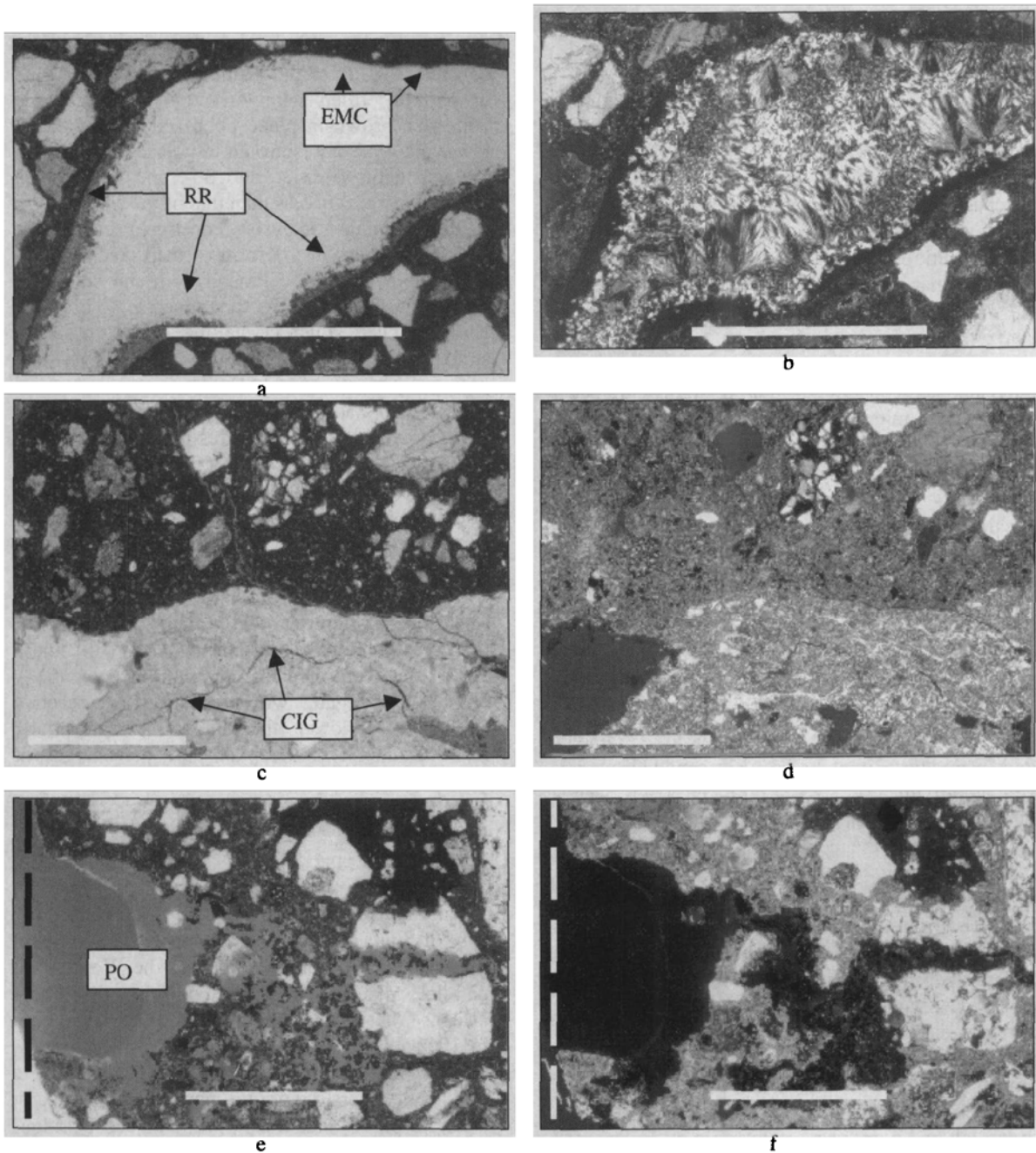
Figure 3. a, Photomicrograph, thin section 8-28-00 b, plane polarized light with lower nicol, showing ASR-gel reaction-rim (RR) around scalloped (replaced) edge of a chert (chalcedony) grain, and showing early ASR micro cracks (EMC) in this grain in concrete floor of the Harbor Court and Justice Center building, bar scale is 1.0 mm. b, Photomicrograph, same field of view as Fig. 3a except in polarized light with crossed nicols. c, Photomicrograph, thin section 3-13-01 d, polarized light with lower nicol, showing cherty gravel grain in lower half of field of view that contains ASR micro cracks extending from inside the grain outward to along the grain perimeter and further outward such that it radiates away from grain, additional ASR micro cracks also inside the grain contain some ASR gel (CIG), bar scale is 1.0 mm. d, Photomicrograph, same field of view as Fig. 3d except in polarized light with crossed nicols. e, Photomicrograph, thin section 11-22-02 1b, plane polarized light with lower nicol, upward is toward the left of field of view, dashed line represents top of core or surface of bridge deck, showing ASR pop-out (PO) and underlying remnant of ASR crack at top of core 1b or surface of concrete deck of Warner Avenue Bridge, crack contains visible fragments of ASR gel, this ASR crack splits a reacted grain of highly metamorphic quartz-feldspathic quartzite into two pieces in right side of field of view, some ASR gel within the crack through the grain is adhered to the grain along the wall of the crack, bar scale is 0.5 mm. f, Photomicrograph, same field of view as Fig. 3e except in polarized light with crossed nicols, shows that ASR gel fragments within crack are isotropic or nearly so in polarized light.

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consisted of two sets of relatively straight cracks that were oriented at 90° to each other. One set trended parallel to the length of the bridge. The other set trended perpendicular to the length of the bridge and 90° to the first set. Cracks of the map cracking type of cracks and cracks of the relatively straight cracking type of cracks tended to join together, or interconnect to each other. The relatively straight cracks in the same given set tend to join one another by oblique cracks. Pop-outs are lined-up along some of the relatively straight cracks that are oriented parallel to the length of the bridge and also along those oriented at 90° to the length of the bridge. A given pop-out results from internal pressure in the concrete that causes a chunk or chunks to "pop-out" leaving the characteristic concave-upward, conically-shaped depression in the surface of the concrete. These pop-outs in some places are lined-up and correspond to the steel reinforcement bars that in some places are as shallow as 5 mm beneath the surface of the concrete deck.

The four cores were recovered in good condition. Core 1, taken through a vertical crack in the deck, recovered 2.8 cm. The imprint of a steel reinforcement bar is preserved on the bottom of this core at 2.8 cm below the top of the core, or surface of the deck. Visible sand and fine gravel appeared well mixed. No porosity was visible to the unaided eye. Core 2, about 15 cm long, was composed of moderately well-distributed sand and fine gravel. Slightly excessive porosity (greater than an acceptable 3 to 4%) was visible near the base of the core. Core 3 contained well mixed sand and fine gravel. A rebar imprint on the bottom of the core, 6.6 cm below the top of the core or below the surface of the deck, was the acceptable depth of rebar. Porosity due to entrapped voids was excessive. Core 4, 15-cm-long, contained well distributed sand and fine gravel, but contained excessively high entrapped porosity.

A thin-section of each core was examined with a polarizing microscope. All four thin-sections contained concrete deterioration in the form of micro cracks due to (ASR). An example of a micro crack formed by ASR is shown in Figs. 3e and 3f. This micro crack extends from the surface of the bridge deck downward through the middle of a reacted grain of highly metamorphic quartzite that was split into two pieces by expansion from ASR inside the grain. ASR gel is visible in this thin-section. All four thin-sections each contain at least 25% potentially reactive grain types. These potentially reactive grain types that are present include microcrystalline quartz, optically strained quartz, and highly metamorphic quartz with sutured sub-grain boundaries, meta-granitic rock fragments with optically strained quartz, quartz siltstone with optically strained siltstone sub-grains, altered volcanic rocks with microcrystalline quartz, and medium to high grade metamorphic rocks with highly metamorphic and optically strained quartz.

It was concluded that the cause of the distress and deterioration of the bridge deck in the form of cracking and pop-outs of the concrete was a result of expansion within the concrete that resulted from (1) ASR, and (2) oxidation of steel reinforcement bars. Thin-sections show excessive porosity. Excessive porosity would have allowed more water to enter the concrete. More water would have enhanced ASR and oxidation of steel reinforcement. Any influence on cracking in the bridge deck by early shrinkage of the concrete during the process of hardening is unknown.

ASR and oxidation of the steel reinforcement was enhanced by (1) excessive porosity in the concrete, that allows too much moisture to enter the concrete, (2) too thin a concrete cover over the steel reinforcement, (3) excessive moisture reaching the steel reinforcement resulting in oxidation and expansion of the steel, (4) absence of epoxy coating on the steel to mitigate its oxidation, (5) excessive moisture reaching the highly reactive aggregate in the concrete, resulting in formation of ASR gel and resulting expansion, and (6) absence of flyash or some pozzolan to counter ASR. This bridge was constructed before the time that it was a common procedure to perform a petrographic analysis on proposed concrete aggregate to determine the potential for alkali-aggregate reaction, and to apply mitigation if necessary.

The concrete deterioration of the bridge deck, including very visible, extensive cracks and some associated pop-outs had progressed to the degree where it is considered to have possibly affected the structural integrity of the bridge deck. Decreased structural integrity of the bridge deck would have caused the bridge to loose load bearing capacity.

We recommended that an additional, more thorough investigation be initiated to determine (a) the extend of ASR and associated cracks beyond the deck, through the whole bridge structure, (b) the amount of strength loss that has occurred due to the fracturing of the deck, and (c) the depth of steel reinforcement and associated cracks in the deck, and locations of any of these cracks in other parts of the bridge structure. Such an additional investigation is currently underway by private firms contracted by the County.

3 CONCLUSIONS

Six distressed concretes, poured during the 1960's, 1970's, and 1980's in Orange County were

evaluated and it was found that alkali-silica reaction (ASR) had occurred in all of them. ASR contributed to 100% of the distress in some of the examples. In some other examples, ASR did not contribute to 100% of the distress but it was a significant contributory factor.

Aggregate sources are becoming scarce within Orange County and in neighboring areas. Almost all local sources contain potentially reactive silica in amounts exceeding threshold percentages. Prior to 1995, the County did not evaluate aggregates proposed for use in concrete for their potential for contributing to ASR. In 1995, County Public Works construction projects that involved concrete began to include petrographic analysis of the proposed concrete aggregate for quantification of grain types known to have potential for ASR. Cases where the aggregate was found to contain an amount of potentially reactive silica greater than a threshold percentage necessitated mitigation for ASR. Mitigation was recommended by either
(a) use of a different aggregate that did not contain an amount of potentially reactive silica greater than the threshold percentage; (b) use of a very low alkali cement, (c) mixing potentially reactive aggregate with less- or non-reactive aggregate to lower the amount of potentially reactive minerals to percentages less than threshold values, or by (d) mixing with cement that contained 20% substitution of flyash (see [6]) to counter potential reactivity. If the six cases of distressed concretes that we investigated had originally contained 20% substitution of flyash then distress due to ASR would have been reduced or eliminated. Currently, all aggregate sources proposed for use in County Public Works concretes are required to be subjected to a petrographic analysis with a polarizing microscope. Aggregates that contain potentially reactive silica in excess of a threshold percentage are required to have 20% substitution of flyash for cement to mitigate ASR in future concretes. The results of these requirements will be (1) increased life spans of some future Public Works concrete structures that will more closely approach their design life spans, and (2) potential savings of hundreds of thousands of dollars, or more, for premature repair, replacement, or demolition of structures that otherwise, without petrographic analysis and substitution of flyash, if the latter is necessary, could experience premature deterioration and loss of structural integrity.

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