

FINAL REPORT

# ALKALI-SILICA REACTIVITY IN VIRGINIA



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Senior Research Scientist

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Abstract <p>This project examined occurrences in Virginia of alkali-silica reactivity, which is a major cause of the deterioration of concrete. Concretes were studied to determine the mineral aggregates being affected, and test methods for identifying such aggregates were evaluated. Technical literature on alkali-silica reactivity was reviewed to develop a way of dealing with this problem.</p> <p>The results of this study reveal that the mineral primarily affected by alkali-silica reactivity in Virginia is quartz, particularly when microcrystalline or metamorphically strained. Quartz in these forms is present in most aggregate resources in Virginia. The results obtained in evaluating a proposed aggregate test method did not permit the establishment of acceptable criteria for differentiating between those aggregates that were susceptible to this reaction and those that were not.</p> <p>Specific issues regarding alkali-silica reactivity in need of further research are delineated. However, because of the numerous aggregate resources in the state that are potentially susceptible to alkali-silica reactivity, the way to prevent this problem in new construction is to use cementitious materials that minimize the potential for the reaction to occur. The Virginia Department of Transportation implemented specifications that require the use of pozzolans or ground slag in concretes made with cements with an alkali content greater than 0.40.</p>				

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(The opinions, findings, and conclusions expressed in this report are those of the author and not necessarily those of the sponsoring agencies.)

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## ABSTRACT

This project examined occurrences in Virginia of alkali-silica reactivity, which is a major cause of the deterioration of concrete. Concretes were studied to determine the mineral aggregates being affected, and test methods for identifying such aggregates were evaluated. Technical literature on alkali-silica reactivity was reviewed to develop a way of dealing with this problem.

The results of this study reveal that the mineral primarily affected by alkali-silica reactivity in Virginia is quartz, particularly when microcrystalline or metamorphically strained. Quartz in these forms is present in most aggregate resources in Virginia. The results obtained in evaluating a proposed aggregate test method did not permit the establishment of acceptable criteria for differentiating between those aggregates that were susceptible to this reaction and those that were not.

Specific issues regarding alkali-silica reactivity in need of further research are delineated. However, because of the numerous aggregate resources in the state that are potentially susceptible to alkali-silica reactivity, the way to prevent this problem in new construction is to use cementitious materials that minimize the potential for the reaction to occur. The Virginia Department of Transportation implemented specifications that require the use of pozzolans or ground slag in concretes made with cements with an alkali content greater than 0.40.

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# FINAL REPORT

## ALKALI-SILICA REACTIVITY IN VIRGINIA

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### INTRODUCTION

Alkali-silica reactivity (ASR) was first identified as a cause of the expansion and cracking of concrete in California by Stanton (1940). This reaction occurs in concrete when siliceous components in aggregates are attacked and dissolved by concrete pore solutions containing high concentrations of alkalies. Damage to the concrete results from cracking of the aggregate and paste, which apparently occur as a result of two mechanisms: (1) swelling of the silica as it is attacked by the alkaline solution and (2) swelling of the alkali-silica gel as it absorbs moisture (Helmuth and Stark, 1992). Damage is manifested on the concrete surface by distinctive cracking patterns (see Figures 1 and 2). Under certain conditions, the dissolving silica and resulting alkali-silica gel may not develop swelling pressures sufficient to crack the concrete. In such cases, internal evidence of the reaction can still be found but with little or no damage to the concrete.

The reactivity of an aggregate is related to the solubility of its siliceous components. The solubility of silica is dependent on its physical characteristics as well as the alkalinity (pH) of the solution to which it is exposed. The most important physical characteristic is the morphology or form in which the silica exists: amorphous (lacking crystalline structure) or crystalline. Silica occurs in a variety of different crystalline structures (minerals), depending on environmental conditions during and after crystallization. Amorphous forms, such as opal and volcanic glasses, are highly reactive. The reactivity of the crystalline forms is largely dependent on the stability of the particular mineral at normal atmospheric temperatures and pressures. Tridymite and cristobalite crystallize at high temperatures and occur in volcanic rocks. These minerals are metastable in normal atmospheric conditions and are highly reactive. The reactivity of quartz, the most common and the most stable form of silica, depends on the amount of surface area (specific surface) and the order/disorder of its crystalline structure (Ozol, 1975; Grattan-Bellew, 1986). The least stable variety of quartz is chalcedony. It has a microfibrinous, microporous morphology presenting a large surface area, which renders it highly reactive. Chalcedony is often present in chert, which is a rock composed of microcrystalline quartz.

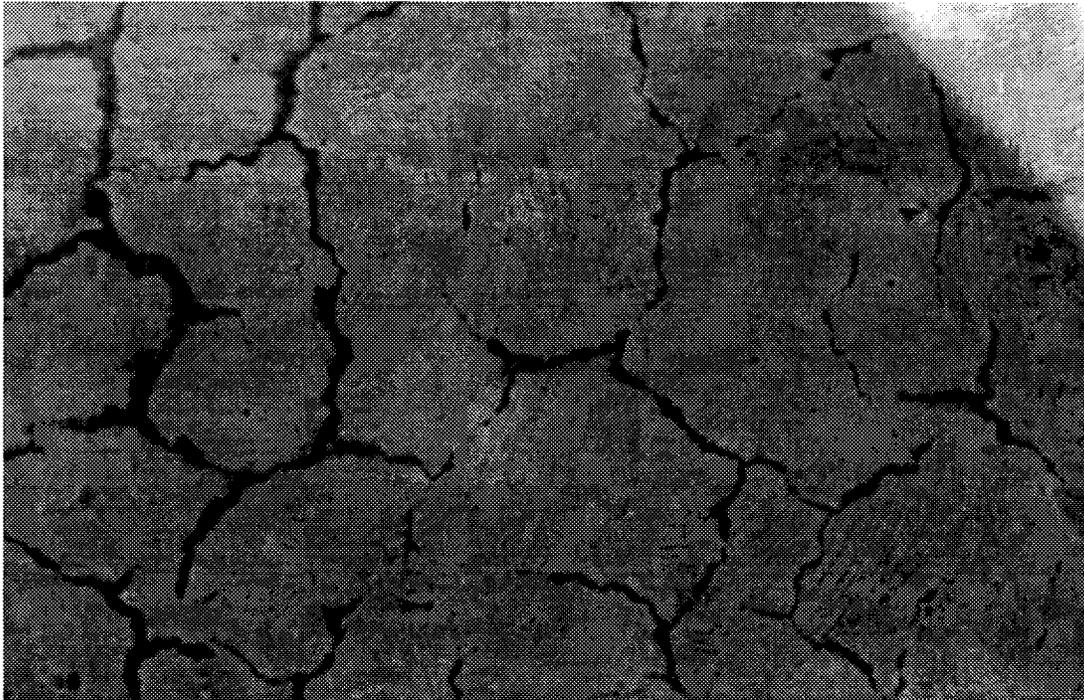


Figure 1. Map cracking on bridge wingwall.

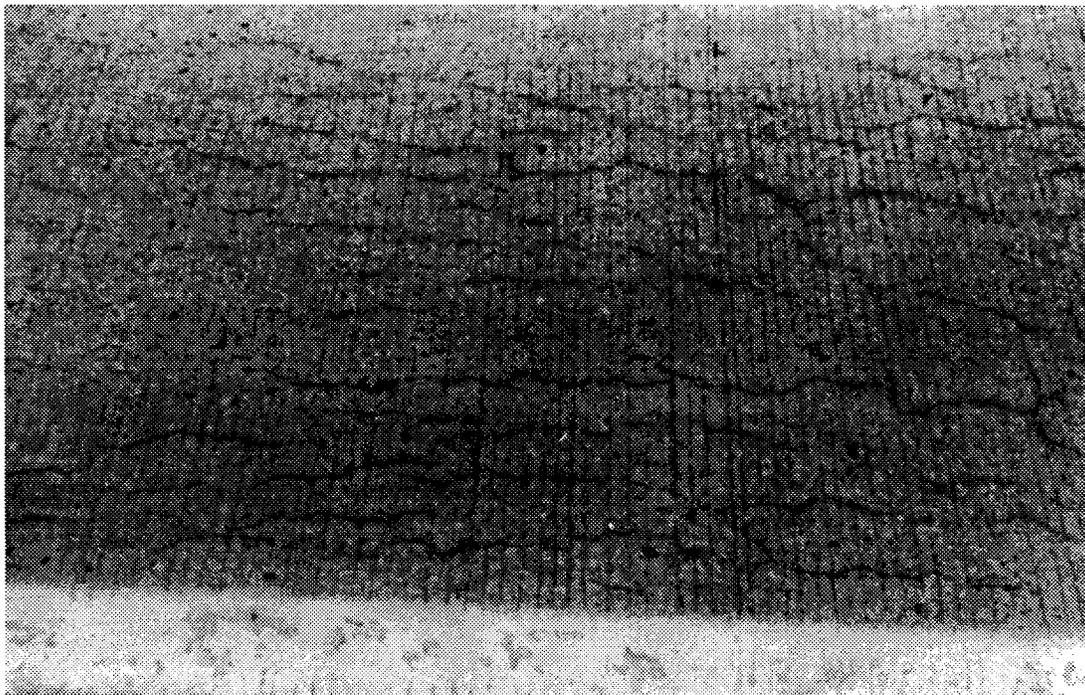


Figure 2. Longitudinal map cracking of continuously reinforced concrete pavement.

Microcrystalline quartz, intensely fractured or granulated quartz, and strained quartz are apparently less reactive than the previously mentioned forms of silica. The reactivity of microcrystalline and intensely fractured or granulated quartz is related primarily to the high specific surface of these forms; in strained quartz, the disorder (strain) of the crystalline structure is believed to be important. Because these forms apparently react more slowly than opal, volcanic glasses, and chalcedony, for a while, they were not widely recognized as being deleteriously reactive. It is now accepted that these forms of quartz can react with resulting damage to concrete (K. Mather, 1973; Buck, 1983; Buck and Mather, 1984; Grattan-Bellew, 1986). The accepted methods and criteria used to evaluate the reactivity of aggregates are not suitable when the reactive constituent is microcrystalline or strained quartz (Grattan-Bellew, 1978; Oberholster, 1986; Oberholster, Brandt, and Weston, 1978; Berra and Baronio, 1986; Hooton and Rogers, 1989). Even the most stable form, ordinary massive or vein quartz, can react sufficiently to cause damage, although it reacts at a slower rate than microcrystalline or strained quartz (Ozol and Dusenberry, 1992).

The solubility (and reactivity) of silica is also dependent on the alkalinity of its environment: it increases with an increase in pH. As a result of its chemistry, when portland cement is used as the sole cementitious material in concrete, it produces a highly alkaline medium (high pH).

Although there were indications to the contrary, the perception developed from the early work on ASR was that it was not a problem in Virginia. This perception remained until the mid 1980s, when a 6-mile section of I-64 pavement was removed and replaced because of ASR-related deterioration. The general consensus developed in the concrete industry after intensive study in the 1940s and 1950s was that ASR was predominately a problem in the western U. S. and that quartz-bearing aggregates of the eastern states were not deleteriously reactive. Isolated incidences of damage resulting from ASR in the east were apparently considered to be the exceptions that proved the rule.

As the I-64 deterioration was being investigated, similar cracking problems were being encountered elsewhere in Virginia and in other states. The growing recognition that microcrystalline or strained quartz can be reactive and the belief that these forms were present in many of Virginia's aggregate sources led to a project being initiated to study the problem.

## **PURPOSE AND SCOPE**

The objectives of this project were:

- to determine the extent to which ASR is affecting concrete in Virginia
- to determine which aggregates are deleteriously reactive
- to investigate laboratory test methods that may be effective in rapidly identifying the reactive aggregates and examine potential measures to prevent the reactivity.

## METHODS

### Occurrences of ASR and Identification of Reactive Aggregates

The identification of concrete structures and pavements affected by ASR was accomplished by investigating the occurrences of map and pattern cracking observed by field or research personnel. To assist in this identification, the Strategic Highway Research Program (SHRP) manual, *Handbook for the Identification of Alkali-Silica Reactivity in Highway Structures* (Stark, 1991), was distributed to VDOT district offices. In addition, reports of previously studied occurrences were reviewed.

When possible, concrete samples and construction records were obtained for structures and pavements exhibiting map and pattern cracking. Concrete samples were petrographically examined in the laboratory to determine the cause of the cracking and, if ASR had occurred, what aggregates were involved. A determination that concrete has been deleteriously affected by ASR is supported by the presence of alkali-silica gel, evidence that the aggregate has undergone chemical and physical alteration while in the concrete, and cracking of the aggregate particles and paste.

Petrographic examinations of concrete samples included reflected light microscopy of broken and polished surfaces (ASTM C 856); transmitted light microscopy of grain immersion mounts and thin sections (ASTM C 856); ultraviolet (UV) epi-fluorescence microscopy of thin sections (Walker and Marshall, 1979); and the uranyl acetate-UV light technique for identifying ASR gel (Natesaiyer and Hover, 1988; Stark, 1991).

### Aggregate Test Methods

Aggregates identified as being alkali-silica reactive in field concrete were tested according to ASTM P 214 "Proposed Test Method for Accelerated Detection of Potentially Deleterious Expansion of Mortar Bars Due to Alkali-Silica Reaction" (ASTM, 1990). Several aggregates believed to be nonreactive were

tested to serve as controls. This testing was performed to determine whether P 214 could be used as a rapid method to identify Virginia aggregates susceptible to ASR. ASTM P 214 is based on an adaptation by Hooton and Rogers (1989) of a method developed by Oberholster and Davies (1986). It was developed specifically to rapidly identify those reactive aggregates that contain microcrystalline or strained quartz as the reactive constituent and thus were not readily identified by ASTM C 227 "Standard Test Method for Potential Alkali Reactivity of Cement-Aggregate Combinations (Mortar-Bar Method)" (ASTM, 1990). In both methods, 1- by 1- by 11-in (25- by 25- by 254-mm) bars are fabricated from mortars containing a specified sand-sized (2.36 mm to 150  $\mu$ m) gradation of the aggregate being tested. In P 214, after an initial curing period of two days, the bars are placed in 1 N solution of NaOH at 80°C and periodically measured with a comparator for change of length. Expansions of P 214 bars measured at 14 or 28 days are believed to be indicative of an aggregate's susceptibility to ASR capable of resulting in damage to the concrete.

Additional but limited testing of aggregate was performed using C 227. In the C 227 tests, bars were fabricated from mortars made with selected aggregates and cements. After initial curing, the bars were placed over water in sealed containers at 38°C and measured periodically for change in length with a comparator. ASTM C 33 "Standard Specification for Concrete Aggregates" (ASTM, 1990) provides expansion limits at 3 and 6 months for evaluating aggregates tested by C 227. These limited tests were performed to confirm reports that the C 227 test and C 33 criteria were not effective for evaluating the reactivity of aggregates containing microcrystalline or strained quartz (Grattan-Bellew, 1978; Oberholster, 1986; Oberholster et al., 1978; Hooton, 1991).

## RESULTS

### **Buck Hydroelectric Plant in Carroll County**

Shortly after learning of Stanton's (1940, 1942) work identifying ASR, Kammer and Carlson (1941) reexamined the concrete expansion that had occurred at the Buck Hydroelectric Plant in Carroll Co. Virginia and concluded that ASR was its likely cause. The dam was constructed in 1912, and cracking was noticed in 1922. By 1929, it was evident that the concrete was progressively expanding. Phyllite, a fine-grained metamorphic rock, was used as the coarse aggregate and was identified as the source of the reactive silica. Parsons and Insley (1944) identified microcrystalline quartz and chalcedony as the siliceous components of the Buck phyllite. Recent occurrences of ASR have been reported from North Carolina involving meta-argillites (Hearne, Cowsert, and Cordle, 1992), which are probably similar to this aggregate.

## **Pentagon Road Network in Arlington Co.**

Map cracking of pavement was found to be caused by ASR in concrete produced with a natural quartzose sand and gravel (Woolf, 1958). The source of the aggregate was presumed to be deposits from the Potomac River. Sands and gravels from the Potomac River valley typically contain quartz and quartzite particles with strained and microcrystalline quartz as well as chert composed of microcrystalline quartz.

Walker (1968) also examined deteriorated concrete from the Pentagon network. She attributed the cracking of the pavement to the combined effects of freezing and thawing and ASR affecting cherts and quartzose metamorphic rocks (quartzites) contained in the Potomac River gravels used. In another section of pavement showing less distress, Walker found the deterioration primarily attributable to ASR of highly strained quartzose metamorphic rocks in the gravel. This aggregate contained little or no chert. Its source was reported to be deposits "outside the State of Virginia." In comparing the aggregates in these two concretes, Walker found the gravel containing chert to be more reactive than the gravel without chert. The natural sand used in both concretes was believed to be from the same source and showed no signs of deterioration from ASR.

## **R. E. Lee Bridge in Richmond**

A condition survey was made of the R. E. Lee bridge in 1967 to determine the extent of its deterioration and to provide a prognosis for the future (Whitlow, 1972). Whitlow concluded that the condition of the bridge in 1967 was a result of the combined effects of ASR, freezing and thawing, and loading and that the relative degree of responsibility of the individual factors could not be determined. However, he did conclude that the initial cracking of the concrete observed in 1942 was probably the result of ASR. Whitlow identified chert, presumably in James River sand and gravel, as the reactive constituent in the aggregate. Sand and gravel deposits in the Richmond area typically are composed of quartz, quartzite, and chert. This bridge was demolished in 1990 and 1991 (see Figure 3).

## **I-64 from Zion Crossroads to Shadwell**

The westbound lanes of I-64 from Zion Crossroads to Shadwell were constructed in 1970. In 1979, considerable longitudinal map cracking of the continuously reinforced concrete pavement (CRCP) was noted along with severe map cracking and deterioration of the bridge approach slabs (see Appendix 2). An investigation of this cracking found it to be the result of ASR involving the Catoctin greenstone (Shadwell metabasalt) coarse aggregate used in the con-

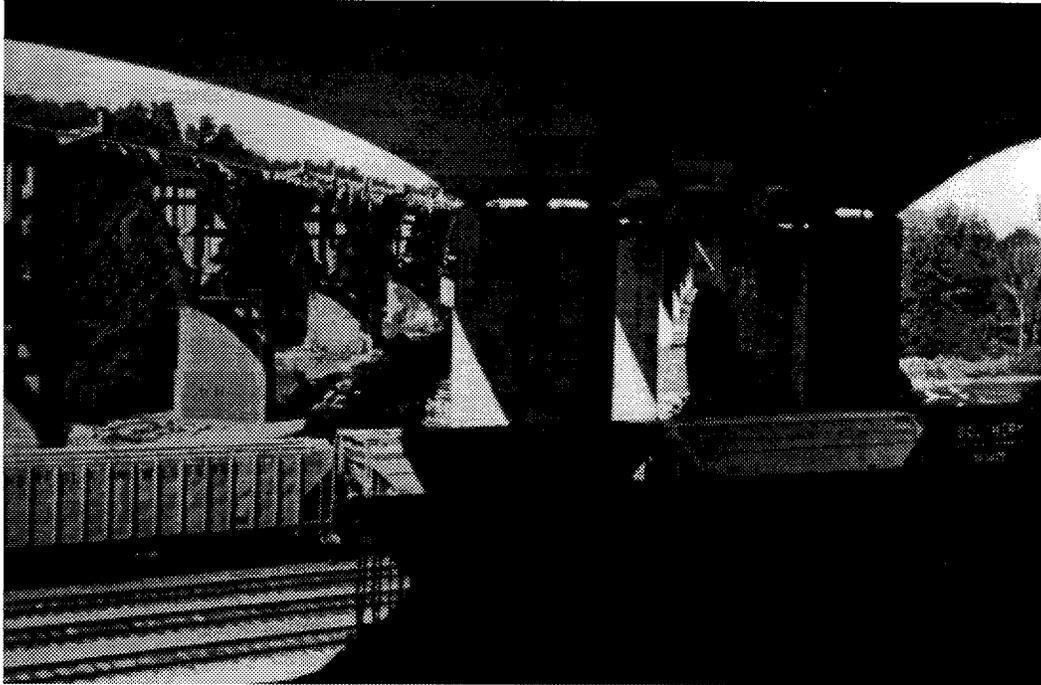


Figure 3. R. E. Lee Bridge during early stages of demolition in background. Vantage point is beneath new bridge.

crete (see Appendix 3). Progressive deterioration (see Figure 4) and mounting maintenance problems resulted in the removal and replacement in 1987 of 6 miles of pavement with new concrete containing a mineral admixture (ground granulated blast-furnace slag). It was concluded that the greenstone was reactive because of the darkened periphery of the greenstone particles and the presence of deposits of carbonated alkali-silica gel in microcracks in the aggregate and surrounding paste, which was observed on fractured surfaces (see Appendix 3) (see Figures 5-6).

Samples retained at the VTRC were examined during the course of this project. Figure 7 is a polished surface of a core showing cracks in aggregate particles partially extending into the paste. Deposits of ASR gel can be seen in cracks in the aggregate. In addition to confirming the observations of the previous study, it was observed that chert particles in the fine aggregate had also cracked as a result of ASR.

The greenstone (metabasalt) is a fine-grained schistose rock composed primarily of chlorite and epidote with small amounts of microcrystalline quartz. The fine aggregate used in this concrete is a natural sand from the Richmond area composed primarily of quartz, quartzite, and chert. This aggregate was also used in the construction of the eastbound sections of I-64 in this area. According to Stark (see Appendix 3), the cracking present in the eastbound



Figure 4. Longitudinal map cracking of CRCP on I-64 between Shadwell and Zion Crossroads.

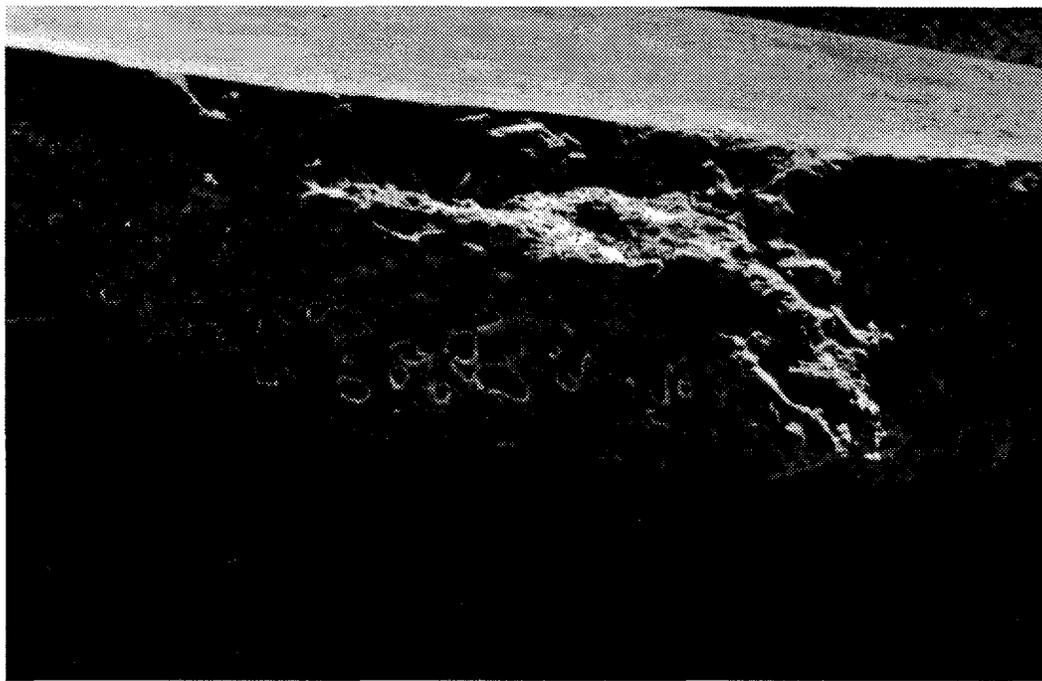


Figure 5. Alkali-silica gel rimming greenstone coarse aggregate particles in I-64 pavement.



Figure 6. Darkened periphery and collections of ASR gel around greenstone aggregates in I-64 concrete.

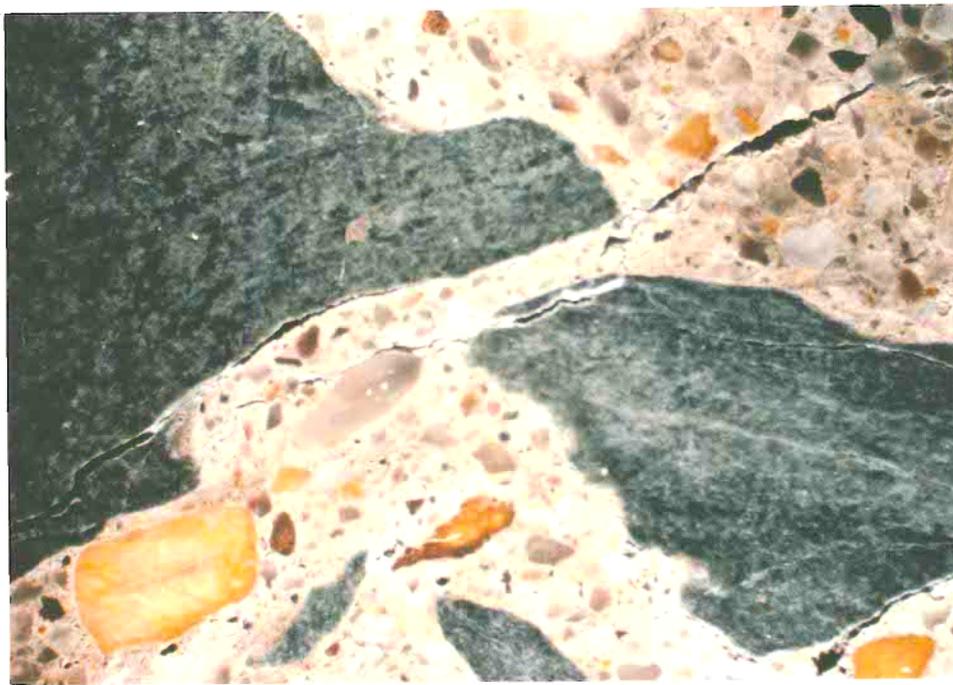


Figure 7. Cracks in greenstone aggregate extend into concrete paste. Cracks are partially filled with ASR gel.

lanes in 1979 was quite faint. In 1989, the longitudinal cracking in some sections of the eastbound lanes was more pronounced, and core samples were taken for inclusion in the SHRP study on ASR. The recently published SHRP report lists the greenstone as a slowly reactive aggregate (Stark et al., 1993).

### I-64 from Shadwell to Crozet

Closely spaced longitudinal map cracking has also developed in some areas of I-64 west of the pavement constructed with greenstone aggregate. Eastbound and westbound lanes of this section of pavement were constructed in 1969 and 1970 using a granite gneiss from Red Hill (Lovingston Fm.) as the coarse aggregate and natural sand from Richmond as the fine aggregate. Samples from this section were also removed for inclusion in the SHRP project and for study at the VTRC. As with the greenstone, the Red Hill granite gneiss was listed as a slowly reactive aggregate in the SHRP report (Stark et al., 1993).

From the east end of the Red Hill section west to Crozet, longitudinal map cracking occurs in locations in both the eastbound and westbound lanes with varying degrees of intensity (see Figure 8). Map cracking is evident in many approach slabs (see Figure 9) and on- and off-ramps (see Figure 10). Deterioration of these sections of pavement has progressed rapidly over the last several years. The most severe deterioration occurs as localized pavement punchouts,

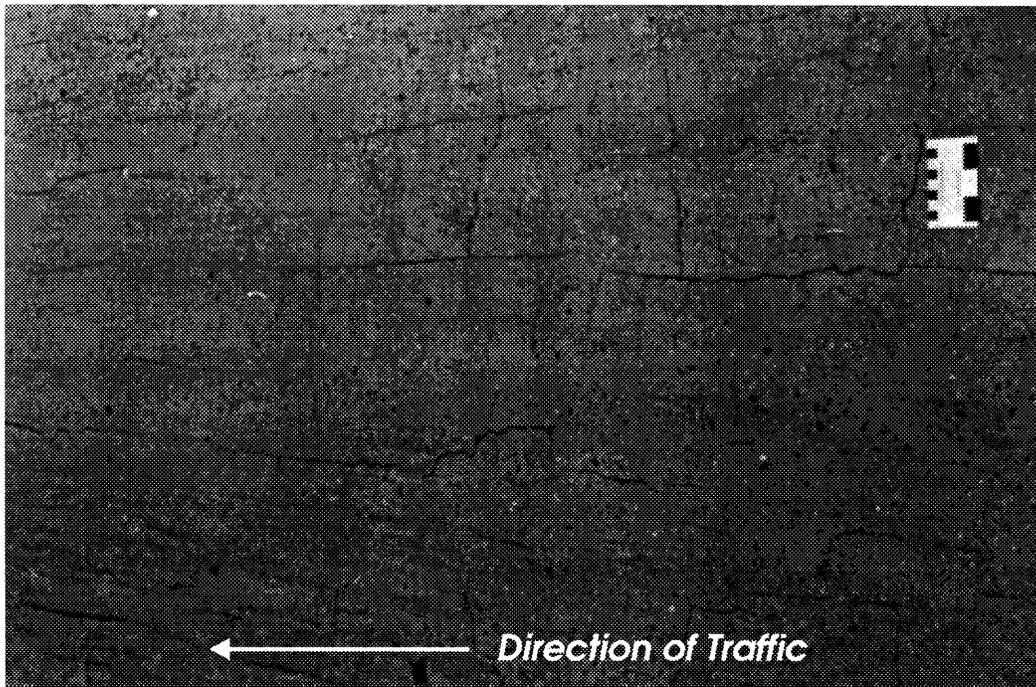


Figure 8. Closely-spaced longitudinal map cracking in I-64 pavement near Ivy. Coarse aggregate is Red Hill granite gneiss.

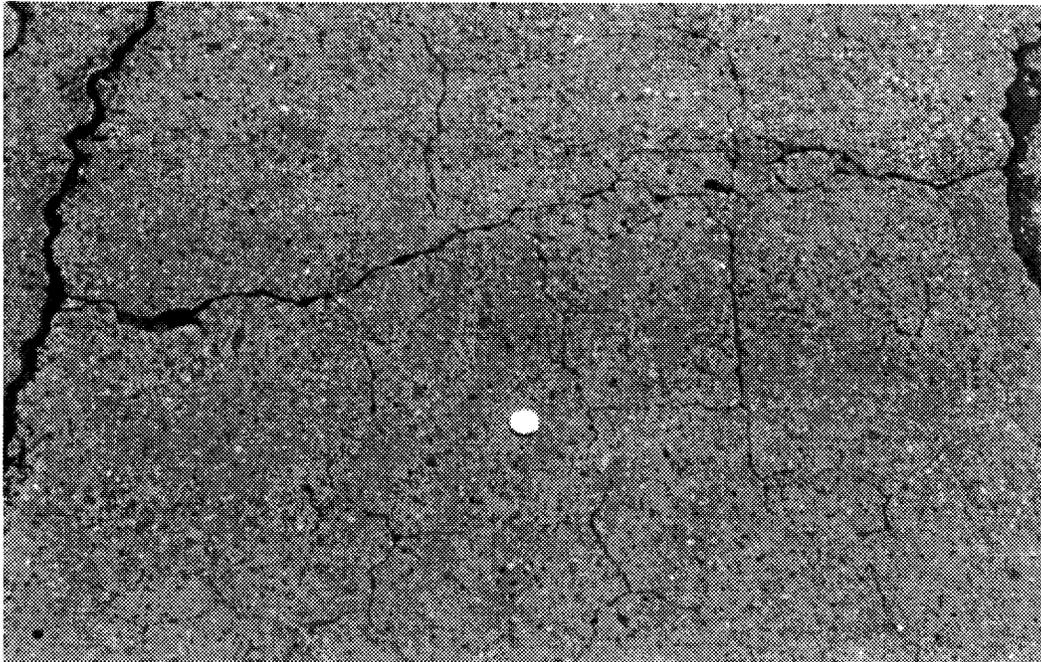


Figure 9. Map cracking in bridge approach slab on I-64 WB at Charlottesville.  
Red Hill granite gneiss.



Figure 10. Map cracking of plain-jointed off-ramp on I-64 EB to U.S. 29 NB at  
Charlottesville.

which occur at closely spaced transverse cracks (see Figure 11). Repair of these areas required full-depth slab removal and patching. In many of these areas, the slab had delaminated near the level of the reinforcement. After the punchouts were patched, edgedrains were installed, and the pavement was overlaid with asphalt concrete. The eastbound lane was patched in 1992 and overlaid in 1993, and the westbound lane was patched and overlaid in 1993.

Samples examined for this project include (1) a core (P2175) from the east end of the eastbound lanes where several closely spaced transverse cracks occur with little closely spaced longitudinal cracking evident (obtained in 1989 during SHRP coring); (2) pieces of concrete removed during repairs to a punchout from the westbound lanes near Ivy showing very faint longitudinal map cracking (P2073,4,8); and (3) four cores (P2164,5,6,7) from the approach slab (see Figure 9) and jointed pavement showing severe map cracking just west of structure 2071 in the westbound lanes.

On fractured surfaces, some Red Hill granite gneiss particles were rimmed by deposits of carbonated alkali-silica gel in the samples obtained from Ivy (see Figure 12). This feature is similar to that noted with the greenstone concrete (see Figure 6) and has been observed on samples of concrete removed from other structures during repairs in the Charlottesville area.



Figure 11. Punchout failure at transverse crack on I-64 WB near Ivy. Secondary products are exuding from cracks; map cracking is faint.

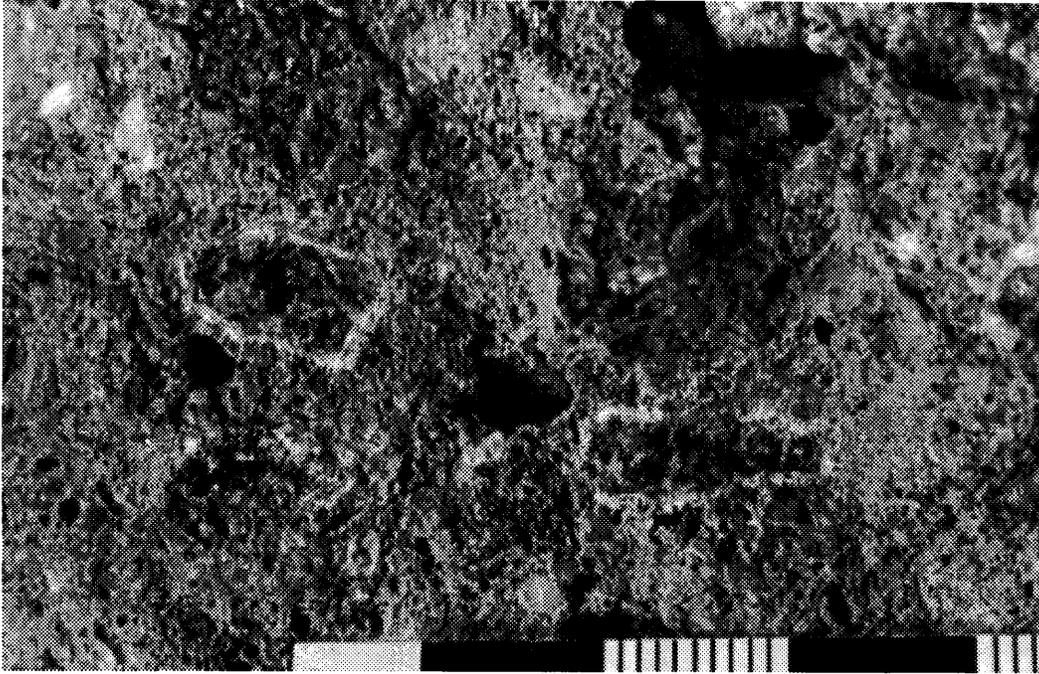


Figure 12. Deposits of ASR gel around granite gneiss aggregates in I-64 WB concrete near Ivy.

In sample P2175, the paste was gray in color and air entrained with a high number of large voids. Most voids were lined with calcium hydroxide or ettringite; a few contained milky white or blue gel. Darkened rims were apparent on some granite gneiss particles; a few were cracked, and in some instances, quartz grain boundaries were corroded (see Figures 13, 14). Milky white gel was observed in some cracks and grain boundaries. A few chert particles in the fine aggregate were cracked. In a few cases, cracks extended from aggregate particles into the paste.

In samples P2073 and P2074, the paste was tan colored and somewhat soft and granular in places. The paste was air entrained with deposits of ettringite and, in a few cases, gel. Granite gneiss particles often had darkened rims, but few were cracked. Some grain boundaries were corroded with occasional gel deposits. Of the fine aggregate, some quartzite particles had clarified rims and some chert particles were cracked. Little cracking of the paste was associated with particles of the aggregate.

In sample P2165, the paste was dark gray and air entrained. Clear to milky white and bluish gel lined some voids. Ettringite was present in some voids as well. Most granite gneiss particles had darkened rims, and many were cracked with the cracks extending into the paste. Quartz grain boundaries were corroded especially in fine-grained areas of the granite gneiss particles. In these locations, individual grains were loose and easily excavated with a small pick.



Figure 13. Cracks in granite gneiss aggregate extending into paste. White ASR gel filling crack in aggregate just below major crack.

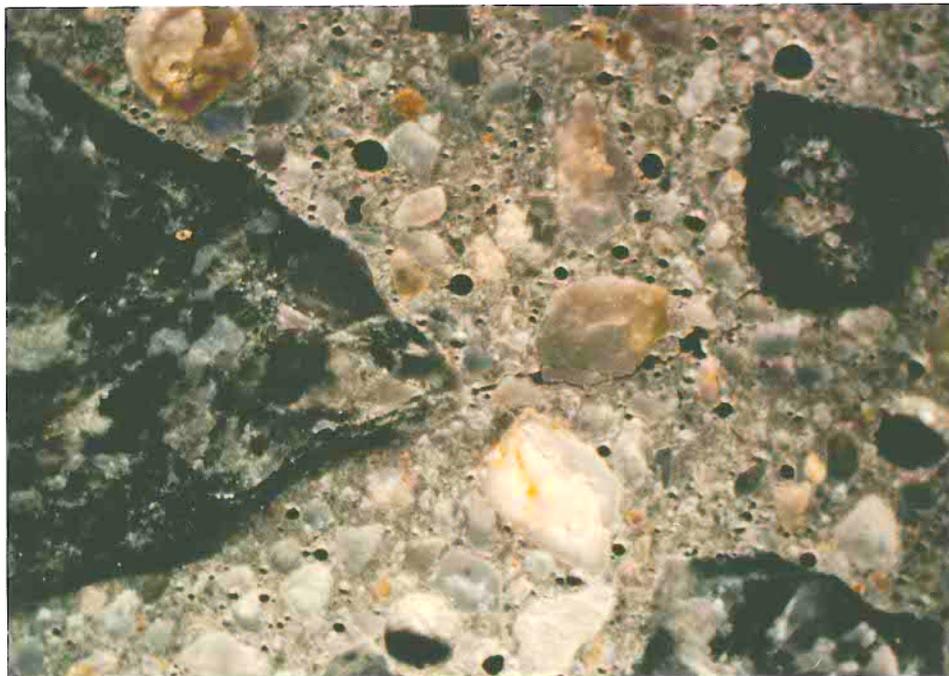


Figure 14. Cracking, corrosion, and darkened rims of granite gneiss particles in concrete from approach slab on I-64 at Charlottesville.

In the fine aggregate, some quartzite particles had clarified rims and were cracked. Many chert particles were also cracked (see Figure 15). Most cracks in the paste were associated with cracked particles of aggregate.

### **Retaining Walls, Shelburne Building, U.VA.**

Two retaining walls at this location are exhibiting progressive map cracking. The coarse aggregate used in this concrete was the Red Hill granite gneiss; the fine aggregate was a natural quartzose sand containing chert. During the SHRP workshop on alkali-silica reactivity in highway concrete pavements and structures held at the VTRC, the uranyl acetate-UV light method for detecting ASR (Natesaiyer and Hover, 1988; Stark, 1991) was demonstrated on the wall. The test yielded positive indication of ASR gel in granite gneiss particles. Subsequently, cores (P2152,3,4,5) were obtained from the wall for further study. The fractured surface of the end of one core was treated with uranyl acetate and is shown in Figure 16 illuminated with ordinary light. In Figure 17, the same specimen is illuminated with UV light. Areas where uranyl ions have replaced sodium ions fluoresce with a greenish-yellow color indicating the presence of a compound (i.e., ASR gel) in which the rapid exchange of ions can take place. A comparison of Figures 16 and 17 shows that the fluorescing areas are primarily coincident with fractured surfaces of granite gneiss particles, indicating the exchange of uranyl ions for alkalies at these sites.

In sample P2153, the paste is whitish in color and fairly soft. Calcium hydroxide and ettringite are present in some voids, and others contain deposits of clear to milky white gel. Granite gneiss particles exhibit darkened rims; many are cracked; and quartz grain boundaries are corroded. Whitish gel is sometimes observed in cracks or along grain boundaries. Quartzite particles in the fine aggregate have clarified rims, and some are cracked. Many chert particles are cracked. Most cracks in the paste are associated with particles of aggregate.

Figures 18 through 22 are photomicrographs of a thin section impregnated with a UV-fluorescent dye. The intergranular corrosion of a fine-grained area is illustrated in Figures 18, 19, and 20 viewed with plane polarized, crossed polarized, and UV light, respectively. Bright areas in Figure 20 indicate areas where dye was able to penetrate. Figures 21 and 22 show a granite gneiss particle and the surrounding paste under plane and UV light. Fluorescence of the paste indicates a high porosity. Cracking of the aggregate and paste are indicated by bright fluorescence as are corroded grain boundaries in the aggregate's interior. The dark zone at the aggregate's periphery where little dye penetrated corresponds to the darkened rim observed in reflected light.



Figure 15. Darkened rim of granite gneiss particle and cracking of chert particles in fine aggregate portion of concrete from I-64 approach slab at Charlottesville.



Figure 16. End of core from retaining wall at Shelburne Building treated with uranyl acetate and illuminated with white light.

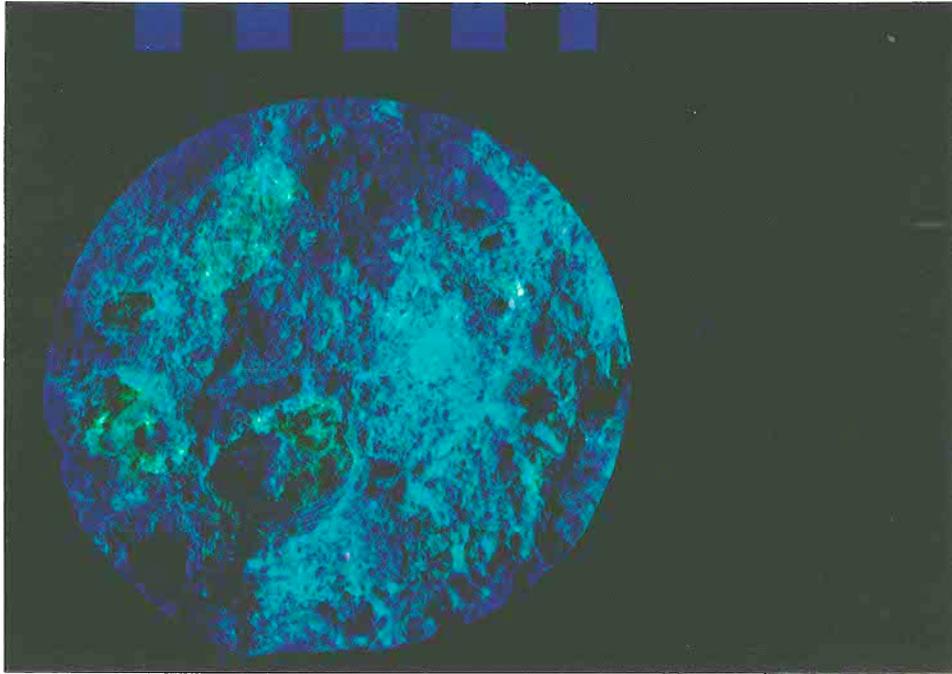


Figure 17. End of core from retaining wall at Shelburne Building treated with uranyl acetate and illuminated with shortwave ultraviolet light. Note greenish fluorescence of fractured surfaces of granite gneiss particles.

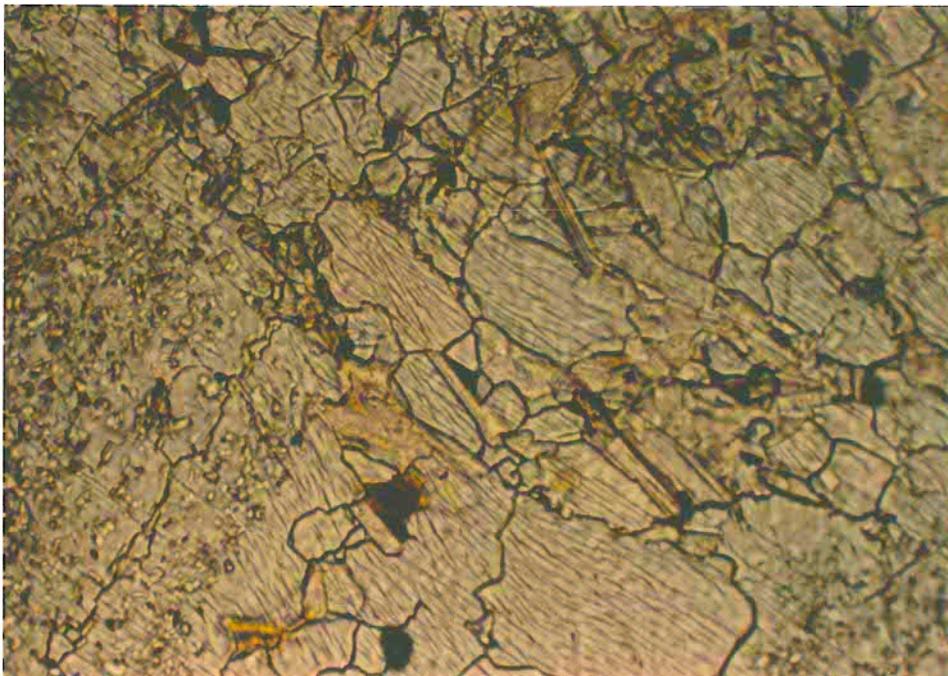


Figure 18. Photomicrograph of thin section of granite gneiss particle from retaining wall viewed with plane light. Central portion of view composed primarily of fine-grained strained quartz (100X).

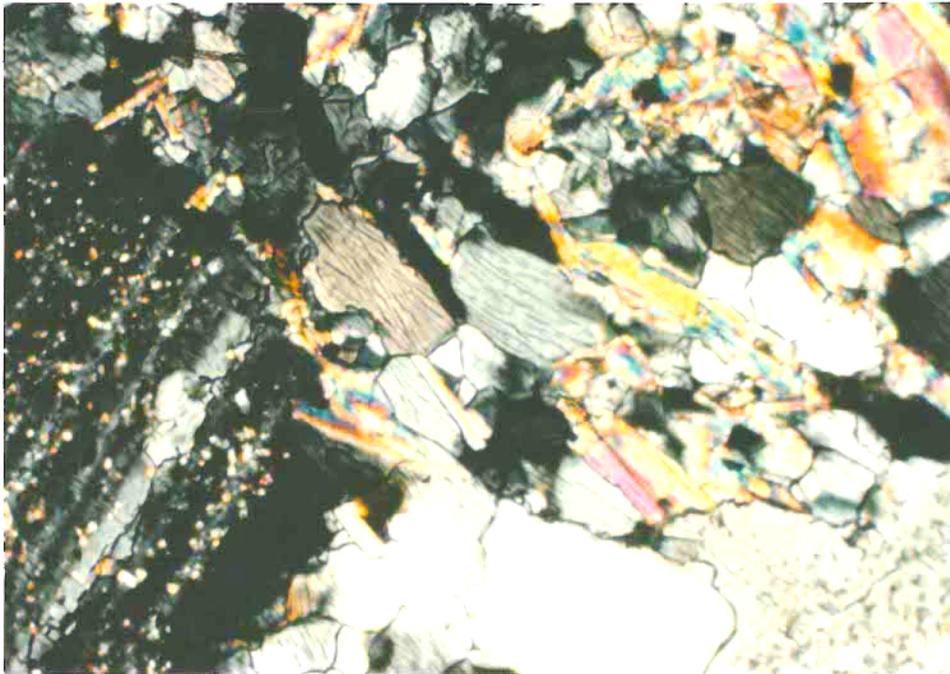


Figure 19. Same field as Figure 19 viewed with crossed-polarized light.

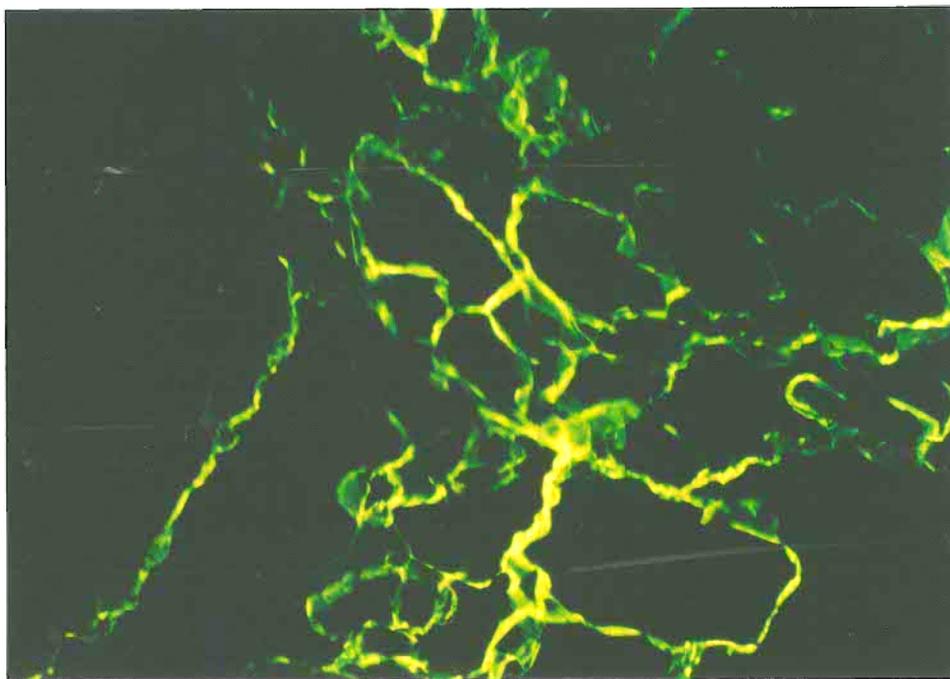


Figure 20. Same field as Figures 19 and 20 illuminated with ultraviolet light. Fluorescing dye indicates corroded intergranular areas.

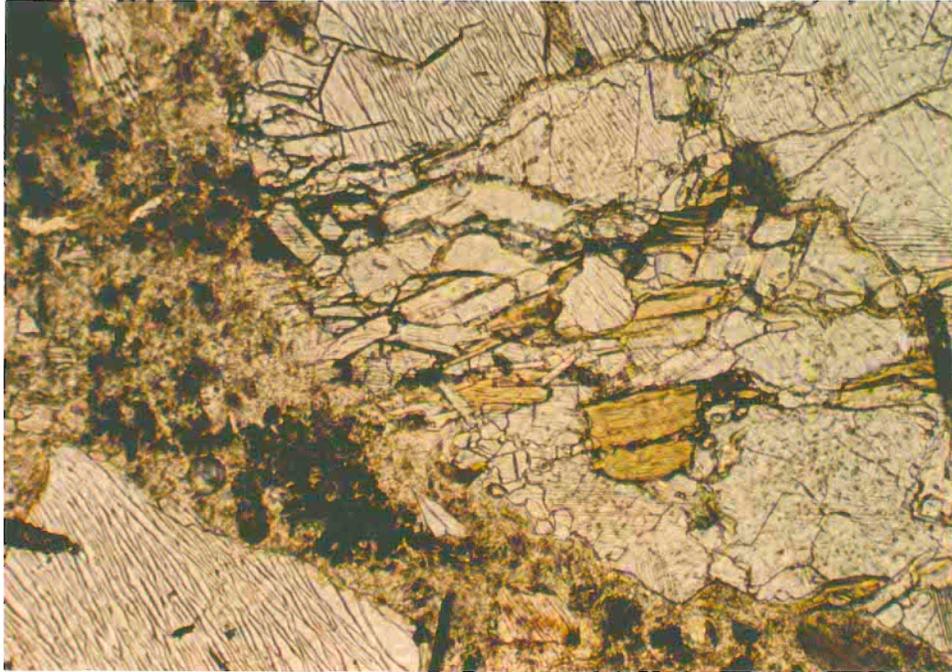


Figure 21. Thin section of concrete from retaining wall. Right side of field is a granite gneiss particle. Mottled brownish material is cement paste. Viewed with plane light (100X).

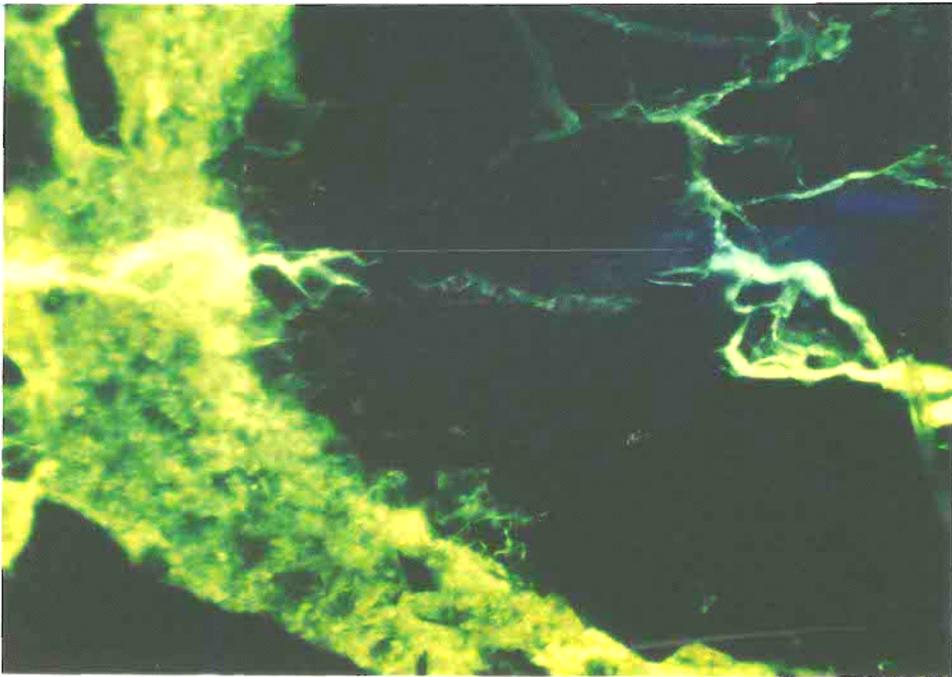


Figure 22. Same field as Figure 21 viewed with ultraviolet light. Bright fluorescence of area in the aggregate interior indicates intergranular corrosion. At periphery, crack extends into paste. Between interior and periphery, crack is partially filled with ASR gel. Fluorescence of paste indicates high porosity.

### **I-64 Eastbound Lanes in New Kent County**

In this section of CRCP, punchouts were developing in locations where transverse cracks were closely spaced (see Figure 23). No closely spaced longitudinal map cracking was observed. During full-depth removal of slabs for patching, it was noted that many slabs had delaminated near the reinforcement in a manner similar to the delaminations in the pavement of I-64 near Charlottesville (see Figure 24). An examination of cores showed the concrete contained a natural gravel consisting of quartz, quartzite, and chert as the coarse aggregate and a natural sand of similar composition as the fine aggregate. The paste was light tan in color and air entrained. Some quartzite particles had clarified rims, and a few were cracked as were some chert particles. Large deposits of white gel were found in a few voids. Very little cracking of paste associated with particles of aggregate was observed.

### **I-95 Median Barrier South of Falling Creek**

Approximately 1.5 miles of median barrier exhibited severe distress in the form of map cracking and spalls apparently resulting from crushing (see Figures 25 and 26). This median barrier is believed to have been constructed between 1982 and 1987. It was removed and replaced in 1993 because of concerns about its structural adequacy.

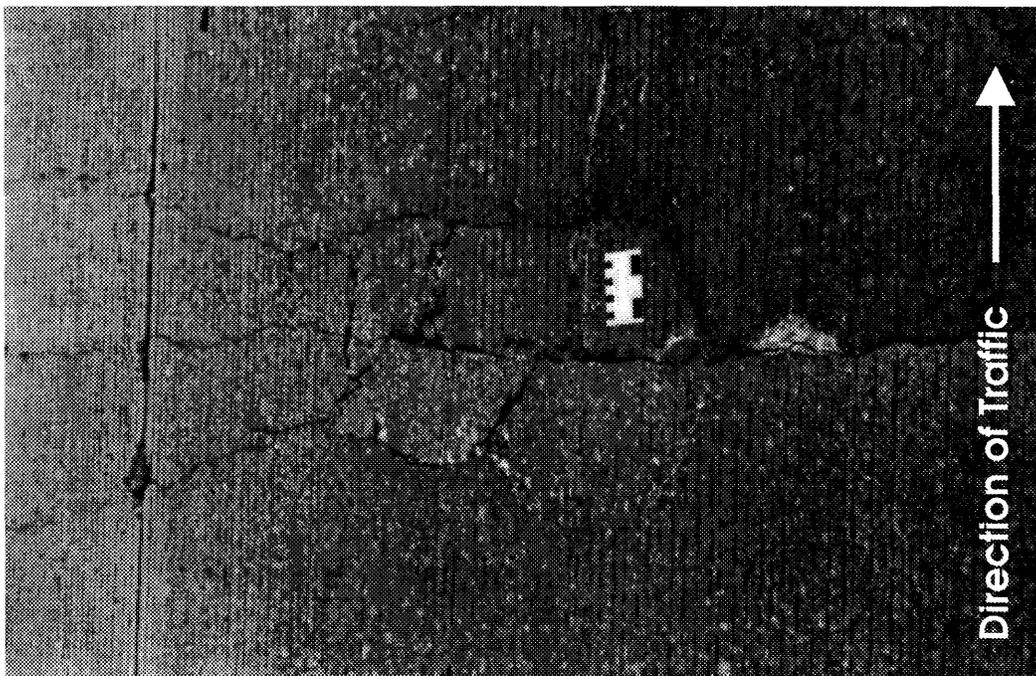


Figure 23. Punchout at transverse crack in CRCP on I-64 in New Kent Co.

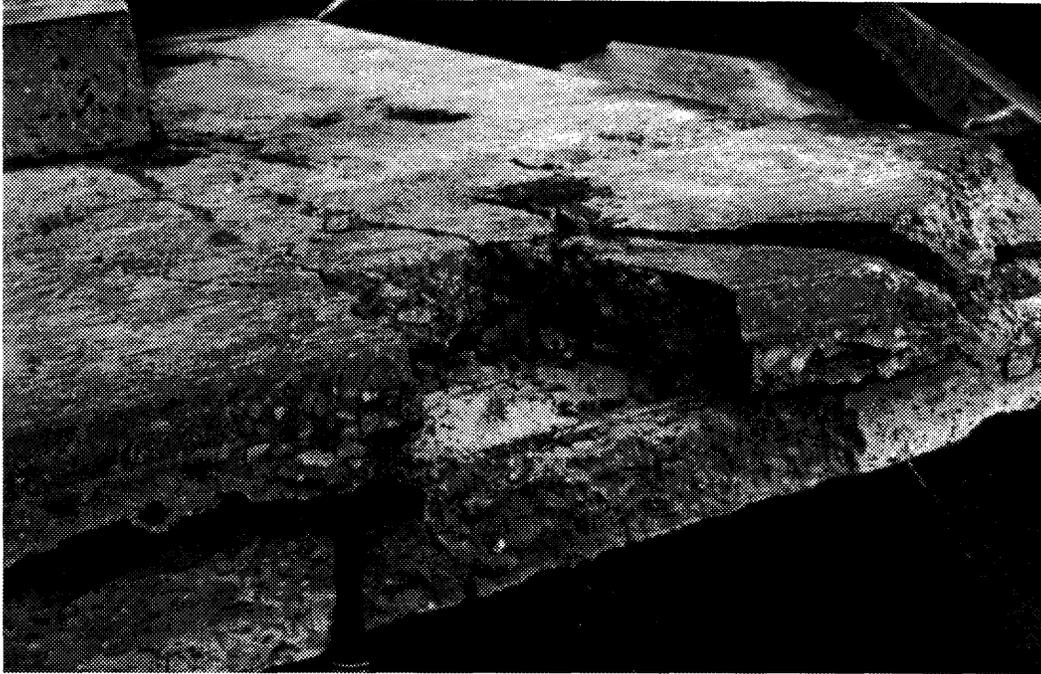


Figure 24. Full-depth pavement removed from distressed area of I-64 in New Kent Co. Pavement delaminated at reinforcement.

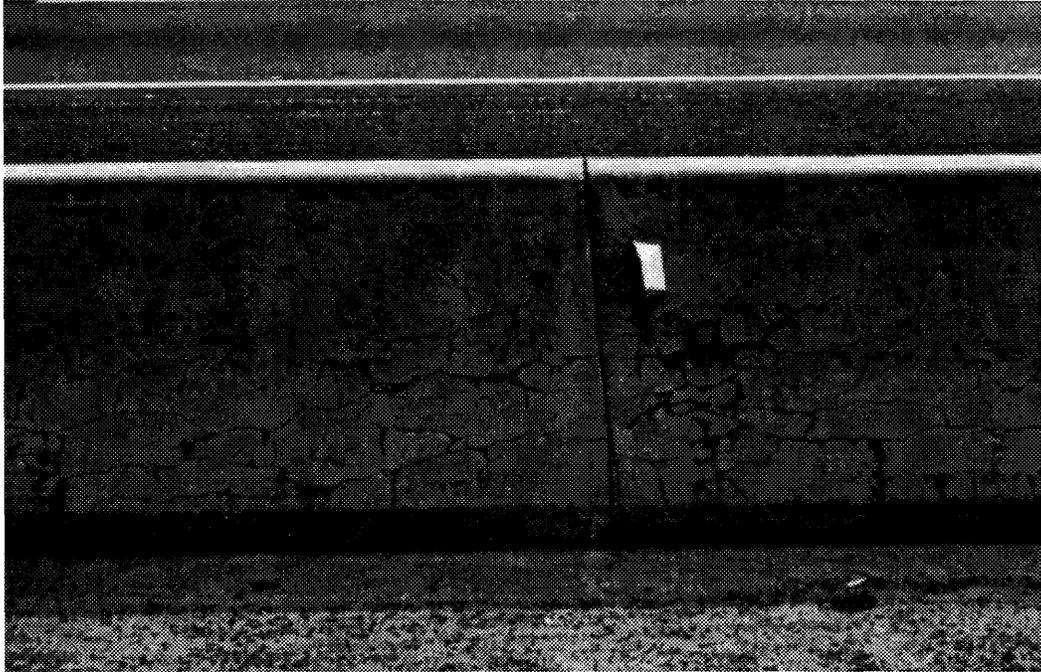


Figure 25. Median barrier on the Richmond-Petersburg Turnpike south of Falling Creek toll plaza.



Figure 26. Crushing of median barrier on the Richmond-Petersburg Turnpike south of Falling Creek toll plaza.

In sample 2114, the paste was medium gray in color and fairly hard. The voids were fairly coarse and irregular in shape as would be expected for stiff slipformed median barrier concrete. The coarse aggregate was a natural gravel composed primarily of quartz, quartzite, and chert. A natural sand of similar composition was used as the fine aggregate. Many quartzite particles had clarified rims and were cracked as were most chert particles. Deposits of clear to white gel were numerous in voids and cracks (see Figures 27 and 28). The paste was extensively cracked, and these cracks were associated with particles of aggregate.

### **I-295 From Short Pump to Sandston**

Constructed in the late 1970s and early 1980s, this section of interstate serves as the northern bypass around Richmond connecting I-64 and I-95. A visual survey of this project showed that at many locations, concrete has cracked in the distinctive patterns associated with ASR. Bridge approach slabs, parapets, and substructures are cracked in a closely spaced map pattern, and sections of CRCP display closely spaced longitudinal map cracking (see Figures 29 to 33). A summary of survey findings with locations identified is in Appendix 1.

The structure for which distress was most pronounced was No. 1038, which carries U.S. 301 over I-295. This structure was completed in 1978. The



Figure 27. Cracking and ASR gel deposits in quartzite aggregate from median barrier concrete on the Richmond-Petersburg Turnpike. Aggregate rim is somewhat clarified.



Figure 28. Cracking and ASR gel deposits in chert aggregate in the median barrier concrete on the Richmond-Petersburg Turnpike.

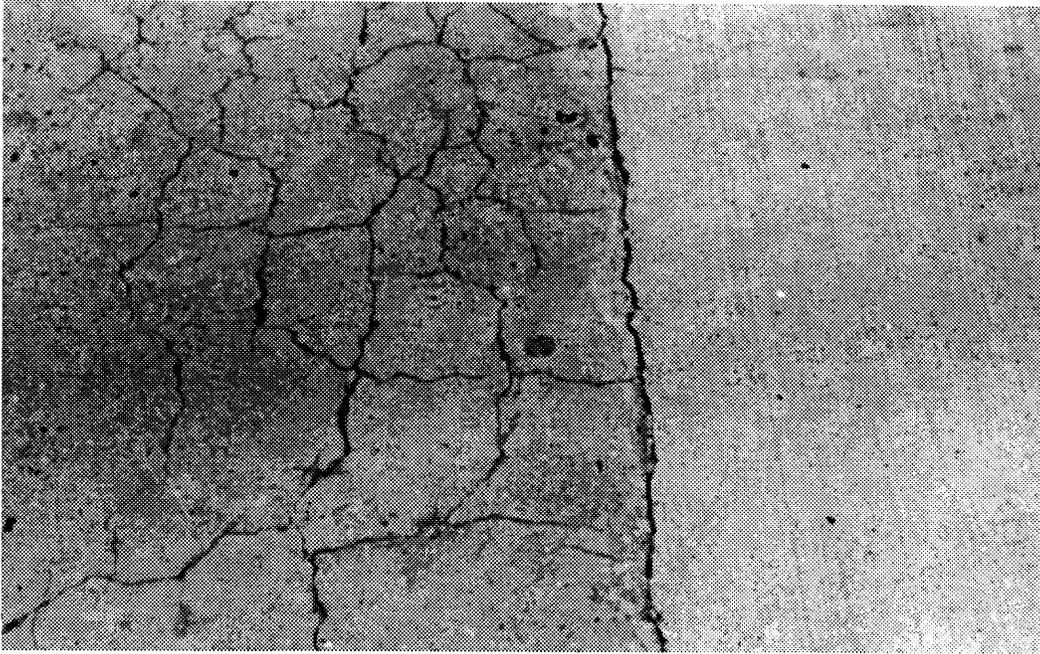


Figure 29. Map cracking of approach slab on U.S. 301 bridge over I-295. Joint was recently repaired.

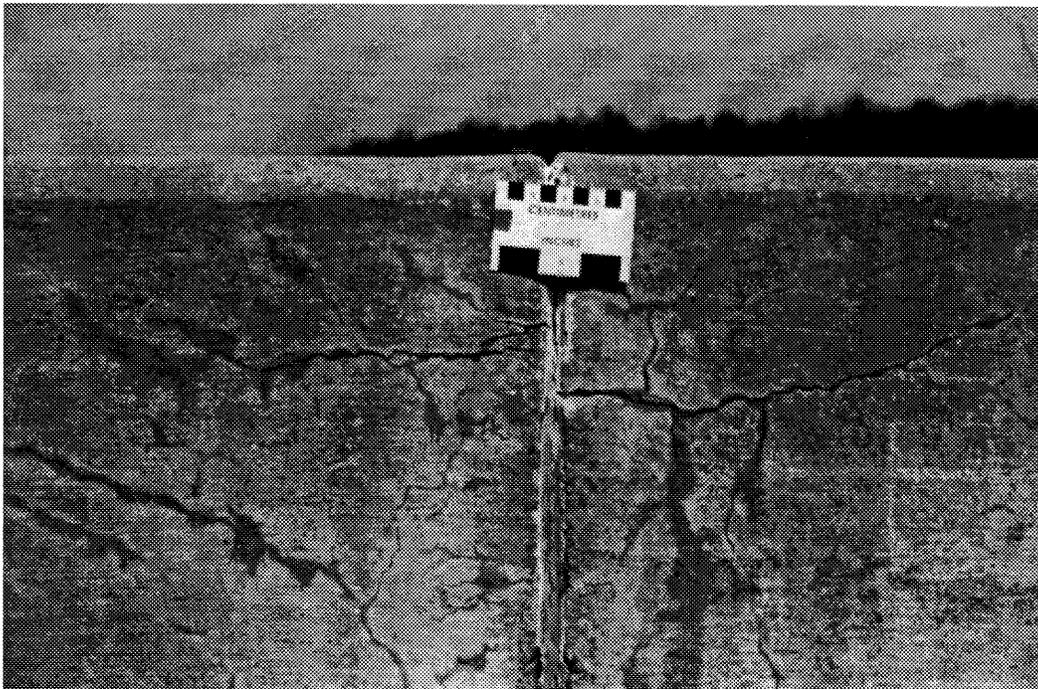


Figure 30. Parapet on U.S. 301 bridge over I-295.



Figure 31. Wingwall on U.S. 301 bridge over I-295.

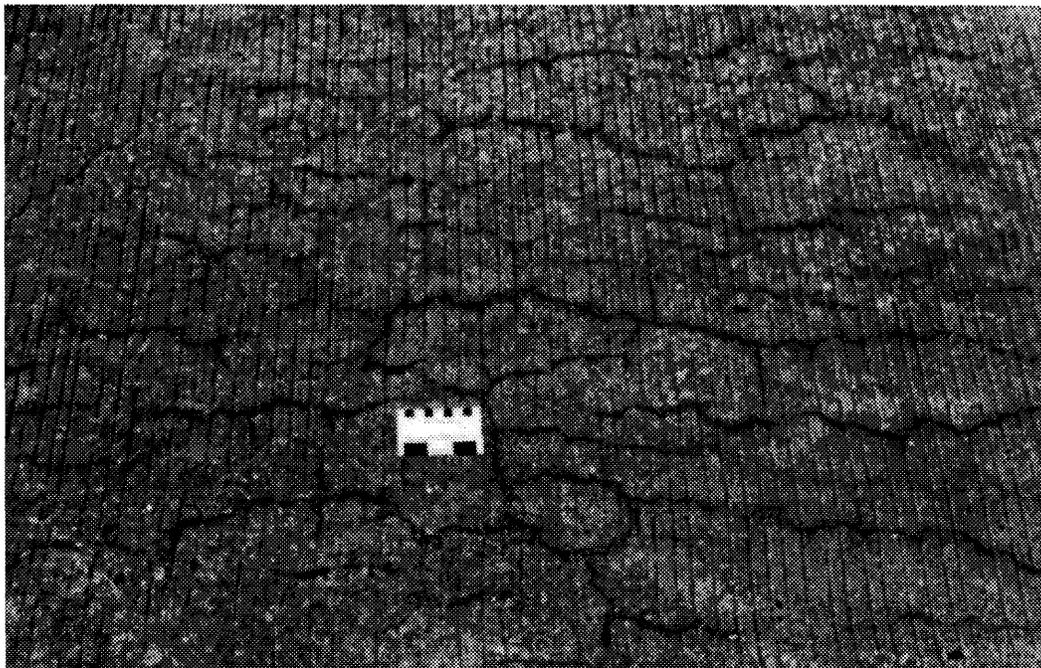


Figure 32. Longitudinal map cracking of CRCP on I-295 EB east of structure 2904.

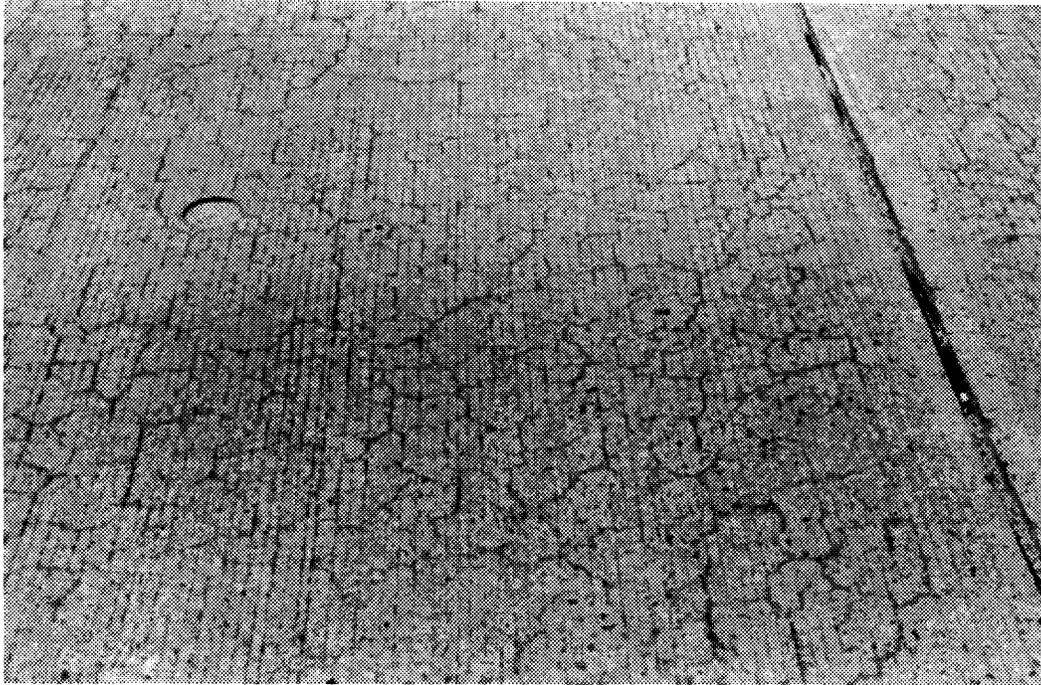


Figure 33. Approach slab at east end of structure 2904 on I-295 EB.

coarse aggregate was a natural gravel composed primarily of quartz, quartzite, and chert. The fine aggregate was a natural sand of similar composition. The approach slabs, parapets, and substructure have all been affected (see Figures 29 to 31). The parapets show signs of crushing with some spalling. Joints at the approach slab were repaired in 1990.

The CRCP in the eastbound lanes in the vicinity of the Chickahominy River bridge (structure No. 2904) exhibits closely spaced longitudinal map cracking (see Figure 32). The approach slabs for this structure also exhibit map cracking (see Figure 33) as does the substructure. A spalled piece of concrete from the joint of one approach slab was obtained and broken to produce a fresh fractured surface. This surface was treated with uranyl acetate, and when viewed under UV light, streaks of bright fluorescence were observed on a coarse aggregate particle. Cores (P2119-22) were obtained from the pavement and the approach slabs.

In sample 2120, the paste was gray in color, fairly hard, and air entrained. Some voids contained deposits of clear to white gel, and some ettringite was present. The paste was extensively cracked. The coarse aggregate was a metarhyolite from Hylas. The rock is foliated and predominately fine grained. It is composed primarily of feldspar (often as elongated augen), strained microcrystalline quartz, and mica. Many aggregate particles are cracked, often with white gel deposits lining cracks or along grain boundaries

(see Figure 34). The fine aggregate is a natural sand composed of quartz, quartzite, and chert. Some chert and quartzite particles are cracked. The cracking of the paste is associated with cracking of the aggregate particles.

### **Structure No. 1904 on U.S. 29 Northbound over Roanoke River**

The deck, parapets, backwall, and approach slabs exhibit map cracking (see Figure 35). Of these elements, the approach slabs show the most deterioration. This structure was constructed in 1973 and 1974. Cores were obtained from the approach slab and deck.

In samples P2136, P2137, P2138, and P2139, the paste is light gray, fairly hard, and air entrained. The coarse aggregate is a calc schist (Arch Marble) with microcrystalline quartz. The fine aggregate is a natural sand composed of quartz, quartzite, and some chert. The sample from the approach slab (P2136) exhibited a moderate amount of cracking of the paste associated with particles of coarse aggregate. Cracks in the aggregate were aligned with the schistosity (foliation, alignment of platy or elongated minerals) and were often filled with white gel (see Figure 35). Clear to white gel was present in some voids and cracks in the paste as well. Deck samples (P2137, P2138, and P2139) exhibited less cracking than the approach slab. Minor cracking of coarse aggregate and paste and the presence of small amounts of gel were observed in P2138 and P2139. There was little cracking of aggregate and paste in P2137. Very little coarse aggregate was present in the top 50 mm of P2139.

### **Laboratory Tests of Aggregates**

The results of the ASTM P 214 tests are given in Table 1. The result for each batch is the average expansion of three bars fabricated from the same batch of mortar. Results of the limited C 227 testing also appear in Table 1. The aggregates tested included materials believed to be similar to those associated with field occurrences of ASR; several sources not likely to be considered susceptible to ASR: Augusta limestone, Blacksburg dolomite, and Warrenton diabase; and several aggregates whose composition suggests a likelihood of being susceptible to ASR: Fredericksburg sand and gravel, and Sylvatus quartzite. A sample of a known alkali-carbonate reactive aggregate from Harrisonburg, "1-8", which has been discussed by Newlon and Sherwood (1964), was also tested.

Bars were immersed in 80°C NaOH solution at an age of 2 days according to the test procedure. Bars remained in this solution, except for periodic measurements, for a minimum of 14 days, however, in most cases, they remained for 28 days. Some bars were left in solution for up to 56 days to evaluate the effects of extended exposure to such a caustic solution.

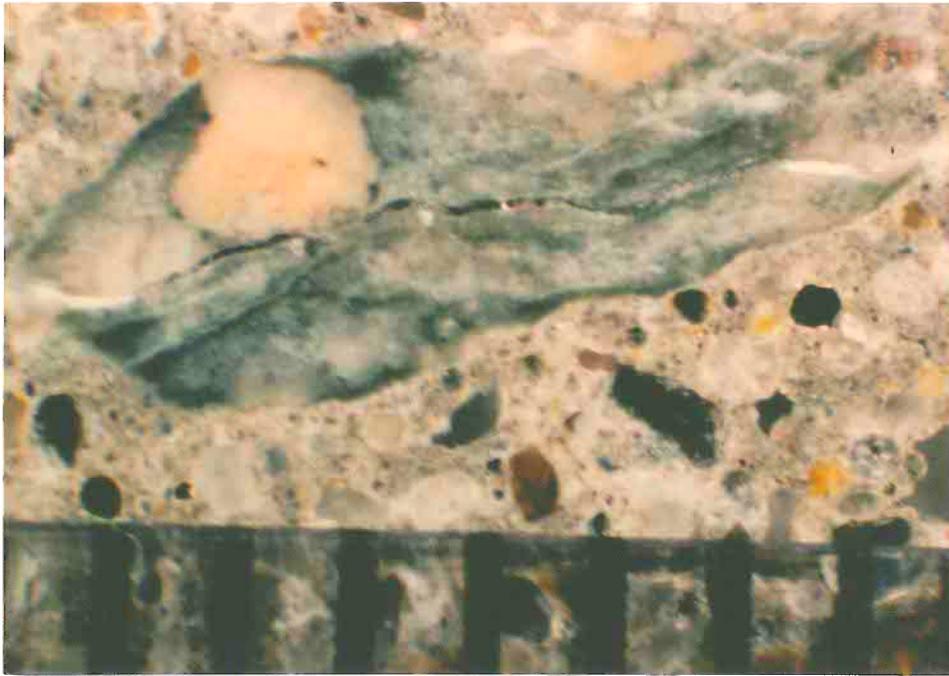


Figure 34. Cracking and ASR gel deposits in metarhyolite aggregate on I-295 pavement east of structure 2904.



Figure 35. Cracking and ASR gel deposits in Arch Marble aggregate in the approach slab on U.S. 29 over Roanoke (Staunton) River.

Table 1  
AGGREGATE SOURCE, TYPE, PERFORMANCE, AND P 214 RESULTS

Aggregate Source	Rock Type	Field Performance	C 227 Expansion	P 214 Expansion (%)			P 214 Classification
				Batch	14 d	28 d	
Augusta	Dolomitic Limestone	Undetermined	—	1	0.24	—	Reactive
				2	0.22	—	
				Avg	0.23	—	
Harrisonburg	Argillaceous Calcitic Dolomite	Alkali-carbonate reactive	—	1	0.24	—	Reactive
				2	0.22	—	
				Avg	0.23	—	
Blacksburg	Argillaceous Dolomite	Good	—	1	0.09	—	Innocuous
				2	0.08	—	
				Avg	0.09	—	
Warrenton	Diabase	Good	—	1	0.15	0.36	Inconclusive
				2	0.11	—	
				Avg	0.13	0.36	
Fredericksburg	Quartzose Sand	Undetermined	—	1	0.10	0.19	Innocuous
				2	0.08	0.21	
				Avg	0.09	0.20	
Fredericksburg	Quartzose Gravel	Undetermined	—	1	0.13	0.28	Inconclusive
				2	0.08	0.28	
				Avg	0.12	0.28	
Richmond	Quartzose Sand	Alkali-silica reactive	0.045% <sup>a</sup> @ 27 mon	1	0.18	0.38	Inconclusive
				2	0.19	0.36	
				Avg	0.19	0.37	
Richmond	Quartzose Gravel	Alkali-silica reactive	0.016% <sup>b</sup> @ 6 mon	1	0.31	0.50	Reactive
				2	0.32	0.48	
				Avg	0.32	0.49	
Rockville Hylas	Metarhyolite	Alkali-silica reactive	0.014% <sup>b</sup> @ 6 mon	1	0.40	0.59	Reactive
				2	0.38	—	
				Avg	0.39	0.59	
Sylvatus	Quartzite	Undetermined	0.021% <sup>b</sup> @ 6 mon	1	0.27	0.42	Reactive
				2	0.30	0.43	
				Avg	0.29	0.43	
Mt. Athos	Arch Marble Calc schist	Alkali-silica reactive	0.012% <sup>b</sup> @ 6 mon	1	0.18	0.32	Inconclusive
				2	0.16	0.28	
				Avg	0.17	0.30	
Shelton	Granite gneiss	Suspected alkali-silica reactive	—	1	0.18	0.30	Inconclusive
				2	0.16	0.26	
				Avg	0.17	0.28	
Red Hill Lovington	Granite gneiss	Alkali-silica reactive	0.049% <sup>a</sup> @ 27 mon	1	0.07	0.14	Innocuous
				2	0.06	—	
				Avg	0.07	0.14	
Shadwell	Greenstone Metabasalt	Alkali-silica reactive	0.038% <sup>a</sup> @ 27 mon	1	0.08	0.14	Innocuous
				2	0.09	0.16	
				Avg	0.09	0.15	

a. Personal communication, D. Stark. Tests conducted by CTL, Inc. under SHRP contract using cement with 1% Na<sub>2</sub>O equivalent.

b. Tests conducted by Virginia Transportation Research Council using cement with 1% Na<sub>2</sub>O equivalent.

After the bars were removed from the solution, they were cut open, and an interior surface was polished. ASR gel was apparent on polished slabs of tested bars made with all aggregates except the Augusta, Harrisonburg, and Blacksburg aggregates. Cracked particles were observed with all aggregates except the Blacksburg dolomite. Corrosion of fine-grained areas was evident in many particles except for the Augusta, Harrisonburg, and Blacksburg aggregates. In some cases, particles, particularly of chert and metaryholite, were almost completely dissolved except for a peripheral rim, especially when the bars remained in NaOH for longer than 28 days. Cracking and corrosion (except for Augusta and Harrisonburg aggregates) of particles were qualitatively proportional to the percentage of expansion of the specimen. An examination of thin sections of the Augusta aggregate showed that some particles exhibited the classical alkali-carbonate reactive rock texture and revealed the presence of some discrete microcrystalline quartz.

Broken surfaces of bars made with these aggregates were treated with uranyl acetate and examined under UV light. Some small areas of fluorescence were observed on the bar containing Augusta aggregate but not on the bars containing the Harrisonburg or Blacksburg aggregate.

## DISCUSSION

Previous occurrences of ASR have been reported in Virginia with a phyllite aggregate (Kammer and Carlson, 1941), chert and quartzite in gravels from the Potomac and James River valleys (Woolf, 1958; Walker, 1968; and Whitlow, 1972), and quartzite in a gravel bearing little or no chert of unknown origin (Walker, 1968). The reactive siliceous components in the phyllite and cherts are microcrystalline quartz and chalcedony, and in the quartzites, they are microcrystalline quartz, strained quartz, and ordinary quartz.

Quartzose gravels of eastern Virginia and southern Maryland are locally important sources of concrete aggregate. Even more important are the natural sands, which are used much more extensively. The primary constituents of these natural sands and gravels are quartz and quartzite composed of ordinary quartz, metamorphically strained quartz, and microcrystalline quartz. The presence of chert is dependent on the source of the gravel or sand. The cherts originate in the carbonate rocks west of the Blue Ridge and thus are present in the deposits of rivers that breach it. Chert is generally absent in the deposits of rivers that originate on the east flank of the Blue Ridge. Sands and gravels of the Potomac and James Rivers, which cross the Blue Ridge, contain chert, whereas those of the Rappahannock River do not.

Walker (1968) noted that the concretes she examined could be differentiated by whether the gravel contained chert or not. Quartzites in both concretes

were reactive, but deterioration was more extensive in the concretes containing chert. She concluded that the chert-bearing gravels are more reactive than the non-chert-bearing gravels.

Whitlow (1972) reports of ASR-related damage involving a gravel in the Richmond area bearing quartzite and chert. An examination of concrete from the I-95 median barrier at Falling Creek shows an association between the cracking of quartzite particles, chert particles, and alkali-silica gel and the extensive cracking of the concrete. The reacting quartzite and chert particles are present in both the sand and gravel used to produce this concrete. Thus, although Walker (1968) considered the sand in the Pentagon pavements to be innocuous, in this case, quartzite and chert in the sand reacted and caused damage to the concrete. A similar situation is occurring in the U.S. Highway 301 bridge over I-295.

Evidence of the reactivity of quartzite and chert in sand was also found during the examination of concretes from the Charlottesville area. Cracked chert sand particles were observed in the I-64 pavement that contained the greenstone coarse aggregate, and cracked quartzite and chert sand particles were found in concretes made with the Red Hill coarse aggregate (P2165, P2153). However, in both cases, the reactivity of the coarse aggregates played a larger role in the damage to the concrete.

If the only reacting particles in these sands and gravels associated with damage were chert, then one could conclude that sands and gravels lacking chert would not be deleteriously reactive. However, quartzite particles have also been associated with concrete damage. Buck and Mather (1969) report of damage to concrete caused by ASR of quartzite in a non-chert-bearing gravel and sand in the Charleston, S. C., area. Furthermore, Buck (1983) and Buck and Mather (1984) included samples of a similar gravel from Fredericksburg in their studies of the reactivity of strained quartz. They concluded that gravels containing quartzite composed of strained quartz were reactive. Although Buck (1983, 1986) considers strained quartz to be reactive, Grattan-Bellew (1986) believes microcrystalline quartz associated with the strained quartz is the actual reactive constituent. Regardless, it would appear that strained quartz is probably a good indicator of reactivity because it is easily recognized, exhibiting undulatory extinction when viewed with crossed polarized light (see Figures 36 and 37). Consequently, sands and gravels that lack chert but do contain quartzite composed of strained or microcrystalline quartz, such as those in Rapahannock River deposits near Fredericksburg, should be considered to be potentially reactive.

The I-64 pavement in New Kent Co. was also produced with chert-bearing sands and gravels as the fine and coarse aggregates. In this case, examination of the concrete revealed some evidence of reactivity of chert and quartzite particles in the form of cracking and the presence of ASR gel. However, there was no

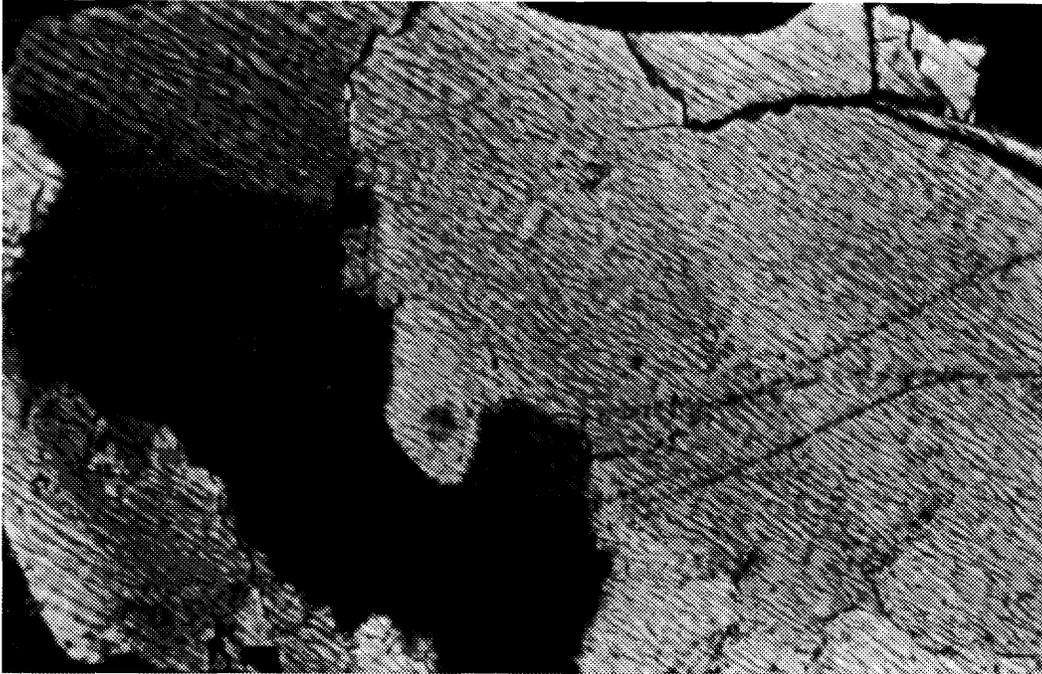


Figure 36. Quartz grains in Shelton aggregate exhibit undulatory extinction when viewed with crossed-polarized light indicating strain.



Figure 37. Same field as Figure 38, stage rotated 30 degrees.

apparent internal damage to the concrete resulting from the reactivity, and there was no closely spaced map or longitudinal map cracking on the pavement surface. The form of deterioration of the concrete in this case was punchout of the pavement at closely spaced transverse cracks in the CRCP coupled with slab delamination. Zollinger and Barenberg (1990) have reported that closely spaced transverse cracks and delaminations may occur when concrete shrinks excessively given the amount of reinforcement in the pavement. They correlate excessive shrinkage to a high water demand when concrete is placed during hot weather. The loss of load-carrying capability at closely spaced transverse cracks results in the punchout failure.

An association of closely spaced map or longitudinal map cracking with cracked and corroded coarse aggregate particles, deposits of alkali-silica gel, and internal cracking was observed (1) in the concrete from I-64 containing the greenstone aggregate; (2) in a bridge approach slab and pavement from I-64 and in a retaining wall all containing Red Hill granite gneiss; (3) in an approach slab and pavement from I-295 containing Hylas metarhyolite; and (4) in an approach slab and bridge deck on U.S. 29 containing Arch Marble schist. The presence of ettringite was noted in voids in many of the samples examined. Such deposits of ettringite are common in concretes affected by alkali-silica reactivity and may indicate the progress of the deterioration (Mielenz and Witte, 1948). The presence of such deposits does not indicate that the alkali-silica reaction was benign.

Most of the internal cracking in these cases appeared to be related to damaged coarse aggregate particles; consequently, the primary cause of damage resulting in the closely spaced cracking was ASR of coarse (and, to a lesser degree, fine) aggregate particles in these concretes. The corrosion of grain boundaries of microcrystalline and strained quartz indicates that they are the reactive constituents in these aggregates. Mather (1973) has reported cases of ASR in bridges involving a granite gneiss from Georgia.

Samples of concrete from the sections of I-64 pavement containing Red Hill granite gneiss that did not exhibit any significant closely spaced map or longitudinal map cracking were also examined. At one location, several transverse cracks were spaced at approximately 0.5-m intervals; at the other, pavement punchouts and slab delaminations had occurred near closely spaced transverse cracks. Although there was evidence of ASR involving both the granite gneiss and the sand in these concretes, it was minimal and produced little apparent internal or external damage to the concrete. The primary cause of damage at these locations is believed to be similar to that described above for the New Kent County section of I-64.

The greenstone, Red Hill granite gneiss, Hylas metarhyolite, and the Arch Marble calc schist are from quarries in the Piedmont. The Piedmont is a geologic province consisting primarily of metamorphic rocks of igneous and sedimentary origin. Most Piedmont rocks contain microcrystalline and strained

quartz that are the product of various episodes of metamorphism and deformation; consequently, they may be susceptible to ASR. For instance, the Shelton granite gneiss from the Danville area contains microcrystalline and highly strained quartz and has been used in concrete that exhibits closely spaced map cracking. Some aggregates from the Piedmont, in particular the diabases and basalts (traprocks) in Northern Virginia would be considered unlikely to be reactive because of their low quartz content, and they do seem to provide good field performance.

In the western part of the state, sedimentary rocks predominate. Carbonate rocks have traditionally been the primary source of concrete aggregates there, and some dolomitic limestones have been found to be susceptible to alkali-carbonate reactivity, a distinct phenomenon that produces similar results (Newlon and Sherwood, 1964; Sherwood and Newlon, 1964). With new requirements for nonpolishing aggregates in pavements and bridge decks, some local quartzites are now being used in addition to importing aggregates from the Piedmont. One such aggregate, a quartzite (Erwin Fm.) from Sylvatus, is composed primarily of fine-grained to microcrystalline strained quartz with siliceous cement. Based on composition, this aggregate is likely to be susceptible to ASR.

Although the presence of certain types of silica in aggregates has been associated with damaging ASR, the results of laboratory tests have long been considered to provide the definitive answer to whether an aggregate will react with damaging results when used in concrete having a high alkali content. The most widely relied upon method, C 227, when used with the evaluation criteria in C 33, has been reported to be ineffective for evaluating aggregates that contain microcrystalline or strained quartz (Grattan-Bellew, 1978; Oberholster, et al., 1978; Oberholster, 1986; Hooton, 1991). Six aggregates associated with ASR in field structures (natural sand and natural gravel from Richmond, Hylas metarhyolite, greenstone, Red Hill granite gneiss, and Arch Marble calc schist) and one suspected of being potentially reactive based on its composition (Sylvatus quartzite) have been tested by C 227. In no case, have expansions of bars reached the 3-month expansion limit of 0.05 percent listed in C 33, even in tests that have been extended for over 2 years. These results support the findings of others that the C 33 criteria cannot be used to evaluate aggregates containing microcrystalline or strained quartz when tested according to C 227.

P 214, which is a new method, has been proposed as being better suited for rapidly evaluating such aggregates. The criteria suggested for evaluating test results listed in P 214 (ASTM, 1990) are:

- Mean expansion of test specimens exceeding 0.20 percent after 14 days of exposure to NaOH solution is indicative of potentially deleterious expansions with respect to ASR.
- Mean expansion of test specimens of less than 0.10 percent after 14 days is indicative of innocuous behavior with respect to ASR.

- Mean expansion of test specimens of 0.10 to 0.20 percent after 14 days is not yet conclusive with respect to ASR.

Hooton (1991) has suggested further that expansions in excess of 0.33 percent after 28 days is indicative of reactive behavior regardless of the 14-day expansion. The Mid-Atlantic Technical Committee (1993) has suggested a single limit of 0.10 percent expansion at 14 days as indicative of damaging reactivity.

The results of P 214 tests conducted on a variety of aggregates for this project are shown in Table 1. Results for the six aggregates associated with damaging ASR in field concretes range from expansions of 0.07 to 0.39 percent after 14 days in NaOH and from 0.14 to 0.59 percent at 28 days. An examination of bars indicated that ASR had occurred in these samples; therefore, P 214 expansions may be reflective of the relative reactivity of these aggregates.

Based on these results, one could arrange these aggregates from most to least reactive, keeping in mind that they all have been associated with damaged concrete: Hylas metarhyolite, Richmond gravel, Richmond sand, Arch Marble, Shadwell greenstone, and Red Hill granite gneiss. The Sylvatus quartzite would appear to fall between the Richmond gravel and sand and the Shelton granite gneiss and alongside the Arch Marble. The gravel and sand from Fredericksburg would fall between the Arch Marble and the Shadwell greenstone. This placement for the Fredericksburg aggregate is in keeping with the observation that gravels and sands containing chert (i.e., Richmond) are more reactive than those that do not contain chert.

Although it appears that P 214 expansions may permit a relative ranking of reactivity for aggregates suspected of being susceptible to ASR, the results obtained with other aggregates confound the issue. The Warrenton diabase, which reportedly has good field performance and is considered unlikely to be susceptible, yields expansions slightly higher than the Fredericksburg gravel. This diabase does contain small amounts of quartz, and a further investigation of field concretes made with this aggregate is suggested. When the Augusta limestone was first tested, it also was thought to be nonreactive. Examinations of thin sections revealed not only the presence of small amounts of authigenic, microcrystalline quartz, but more significantly, a texture similar to that indicative of rocks susceptible to alkali-carbonate reactivity. This prompted testing of samples of the classical Virginia alkali-carbonate reactive rock from Harrisonburg. Expansions of the Harrisonburg dolomite were similar to those of the Augusta limestone. A dolomite from Blacksburg with good field performance was also tested and yielded expansions equivalent to the Shadwell greenstone and the Fredericksburg sand.

Comparing these expansion results to the various criteria suggested for use with P 214 indicates that none would be adequate for specification purposes with Virginia aggregates. The 14-day expansions of the Red Hill granite gneiss

(0.07 percent) and Shadwell greenstone (0.09 percent) in the tests conducted for this project compare with 14-day expansions of 0.096 and 0.082 percent, respectively, obtained in the SHRP study (Stark et al., 1993). They suggested a limit of 0.08 percent expansion to delineate between nonreactive and reactive aggregates. However, given the 0.07 percent expansion of the Red Hill aggregate in these tests, a limit of 0.05 percent after 14 days would seem necessary to allow for interlaboratory testing variations and to ensure that aggregates susceptible to ASR would be so classified. Setting the limit this low would undoubtedly misclassify some nonreactive aggregates as reactive, but this is considered preferable to the converse. However, because these results are from a limited sampling of Virginia aggregate, no basis was developed for using P 214 expansions to distinguish between aggregates susceptible and not susceptible to ASR, and no such criteria are suggested.

The sections of I-64 constructed with the gravel from New Kent Co. and with the Red Hill granite gneiss from the Charlottesville area that exhibited little or no closely spaced longitudinal cracking serve to illustrate that the use of reactive aggregates in concrete does not always result in damage, even if some reactivity occurs. This is because in addition to the inherent reactivity of the aggregate as a result of the nature of its siliceous components, the degree to which reaction occurs is dependent on the pH of the pore solution in the concrete and the availability of water to catalyze the dissolution of silica and cause the expansion of the resulting gel. Stark and DePuy (1987) indicate that an internal relative humidity in excess of 80 to 85 percent is necessary for damaging ASR to occur.

It is likely that concrete in contact with the ground in Virginia maintains a relative humidity sufficient to promote damaging ASR. The higher frequency with which ASR affects bridge approach slabs and substructure elements in contact with the ground as compared with elevated decks (apparently produced with the same concrete) seems to bear this out. Variations in moisture content in different sections of pavement may explain some of the differences in the intensity of ASR. Efforts to provide and maintain good drainage around pavements and structures are encouraged because water is the catalyst for most chemical and physical durability problems affecting concrete. However, such efforts cannot be relied on to provide primary protection against ASR in concretes exposed to the elements.

When a concrete containing susceptible aggregates is exposed to moisture, the primary factor that governs the extent to which reactivity occurs is the pH of the pore solution of the concrete. Although not as apparent as the difference between approach slabs and bridge decks, the cracking of approach slabs does seem more pronounced than that of adjacent sections of pavement. The concrete of approach slabs has a higher cement content than paving concrete; thus, it would have a higher alkali content and pH if the alkali content of the cement used is the same in both. This may also explain the extremely pro-

nounced map cracking that has been observed in some concrete patches that presumably contain very high portland cement content.

From his work in California with opaline shales, Stanton (1942) concluded that damage from ASR did not occur when the total alkali content (by weight) of the portland cement used did not exceed 0.60 percent  $\text{Na}_2\text{O}$  equivalent ( $\text{Na}_2\text{O}$  equiv. =  $\text{Na}_2\text{O} + 0.658 \text{K}_2\text{O}$ ). However, an interlaboratory test program conducted by ASTM Committee C-1 on Cement (1946) found that excessive expansions occurred in mortar bars containing reactive aggregates with cements having an alkali content of 0.58 percent or greater; whereas, with an alkali content of 0.40 percent or less, excessive expansion did not occur. Woolf (1952) also reported on laboratory tests which indicated that damage from ASR could occur with cements having an alkali content lower than 0.60 percent. Lerch (1959) describes damage that occurred despite the use of cements with an alkali content below 0.60 percent. Although Lerch suspected that there might be some other cause, Hadley (1968) confirmed that the damage had resulted from ASR. In 1959, following 18 years of study and deliberation, a limit of 0.60 percent was adopted by ASTM in C 150-59 Standard Specification for Portland Cement (Frohnsdorff, Clifton, and Brown, 1978) as the maximum alkali content for low-alkali cement (those cements that could be used safely with reactive aggregates).

More recently, others have reported that using the 0.60 percent limit on cement alkalis has not prevented damaging ASR (Hadley, 1968; Stark, 1980; Tuthill, 1980, 1982; Ozol and Dusenberry, 1992). Tuthill suggested that an alkali limit of 0.40 percent  $\text{Na}_2\text{O}$  is more appropriate (1980). The aggregates with which Tuthill was working contained opal as the reactive constituent, whereas Stark was working with volcanic glasses. Hadley (1968) suggested that the ASR occurring in Kansas and Nebraska with cements under the 0.60 percent limit was the result of a concentration of alkalis within the pavements resulting from extreme wetting and drying. This results in a localized elevation of the pore solution pH to a level sufficient to cause ASR. Stark and Bhatti (1985) suggest that aggregates composed of volcanic rocks may contribute alkalis to the system, thereby increasing the amount of damage. The reactive constituents in these cases, opal and volcanic glasses, differ in morphology and are more reactive than the microcrystalline and strained quartz encountered in aggregates from Virginia. Ozol and Dusenberry (1992), however, describe a case of ASR involving ordinary quartz with a portland cement apparently below the 0.60 percent limit. The reactive constituent in this aggregate is similar to the microcrystalline and strained quartz found in many Virginia aggregates, but it is probably less reactive.

The preceding discussion indicates that the simple placement of a limit on the alkali content of cement may not be effective in preventing damaging ASR unless that limit is lower than the currently accepted 0.60 percent (ASTM C 150, 1990). Several factors apparently account for this. Higher cement content

in the concrete results in higher alkali content in the concrete with a given cement alkali content. Portland cement concretes are permeable enough to permit migration and localized concentration of alkalis as suggested by Hadley (1968) and Ozol (1990) and demonstrated by Xu and Hooton (1993). Xu and Hooton show that freezing and thawing, constant humidity gradients, and electrical currents can concentrate alkalis in concrete just as wetting and drying do. The permeability of portland cement concrete also permits the ingress of alkalis from external sources such as deicing salts and seawater. Finally, as indicated by the reports of ASTM Committee C-1 (1946), Woolf (1952), and Lerch (1959), the 0.60 percent limit was not low enough to begin with.

Concretes used for transportation structures and pavements in Virginia are subjected to wetting and drying cycles, freezing and thawing cycles, and deicing salts. Consequently, the reliance on the use of low-alkali portland cement to prevent ASR requires that the alkali content be low enough that high cement content and external sources of alkalis do not result in an alkali content in the concrete sufficiently high to promote reactivity. Although further work is needed to determine what the tolerable alkali content of concrete is, Tuthill's (1980) suggestion of a limit of 0.40 percent on the alkali content of cement seems prudent at this time. Stark et al. (1993) suggest that the P 214 test can be modified slightly to determine the limit on the cement alkali content that can safely be used with a particular aggregate. The modification suggested is to vary the normality of the storage solution to simulate various cement alkali contents. By testing the aggregate in different solutions, one finds the maximum normality that does not produce excessive expansions. The solution normality corresponds to a cement alkali content dependent on the water-cement ratio; thus, if the water-cement ratio is proposed for a concrete, a safe cement alkali content can be determined. Interestingly, one of the aggregates used by Stark et al. was the greenstone from Shadwell. The safe cement alkali content with this aggregate would be 0.40 percent based on a water-cement ratio of 0.4 to 0.5 as commonly used in highway concretes. A higher water-cement ratio would increase the safe alkali content, whereas a lower water-cement ratio would decrease it; however, the negative effect of a higher water-cement ratio on a concrete's strength and durability must be remembered.

An alternate means of preventing ASR in concrete when using susceptible aggregates is to use pozzolans or ground-granulated, blast-furnace slag as part of the cementitious material rather than limiting the cement alkali content. These materials are composed primarily of glassy silica or silicates that react in highly alkaline environments in a manner analogous to the reactive silica in aggregates. Because pozzolans and slag are extremely fine compared to aggregates and present a large surface area for reaction, they react much more quickly and apparently reduce the pH below that necessary to sustain damaging ASR. The product of the reaction of pozzolans and slag is similar to the hydration products of portland cement; consequently, it increases strength and reduces the permeability of concrete. The reduction in permeability provides an

added benefit by impeding the ingress of moisture and alkalis into the concrete and by impeding the migration of moisture and alkalis within the concrete.

The pozzolans commonly available in Virginia are ASTM C 618 Class F fly ash and silica fume. According to Buck (1987), silica fume is most effective in controlling expansions resulting from ASR because of its extreme fineness and high silica content. Typical Class F fly ashes generally provide adequate protection when they comprise 15 to 20 percent of the cementitious material (Kosmatka and Fiorato, 1991). Because of their high lime and alkali content, Class C fly ashes generally require much higher percentages to prevent excessive expansions (Farbiarz and Carrasquillo, 1987). At a content of 40 percent or higher, slag is also effective in preventing expansions caused by ASR (Pepper and Mather, 1959; Hogan and Meusel, 1981; Buck, 1987).

Pozzolans and slag can be incorporated into concrete in two ways: either in the production of the cement (blended cement) or as a mineral admixture in the production of the concrete. It is reported that fly ash interground with portland cement in the production of blended cement is more effective in preventing expansions than an equivalent amount of fly ash simply blended with cement (Farbiarz, Schuman, Carrasquillo, and Snow, 1989). The effectiveness of pozzolans and slag depend on their fineness, their reactivity, their alkali content, and the amount of the cement with which they are used. Because these factors vary for materials from different sources and within sources as well, research is needed to establish criteria for evaluating their effectiveness (Lane and Ozyildirim, 1992).

## CONCLUSIONS

Investigations of occurrences of closely spaced map and longitudinal map cracking of concrete in Virginia indicate that the cause of this cracking in the cases studied is ASR involving sands and gravels from the Richmond area: Hylas metarhyolite, Shadwell greenstone (metabasalt), Red Hill granite gneiss, and Arch Marble calc schist. The reactive constituents in these aggregates are microcrystalline and strained quartz. Microcrystalline and strained quartz are primary constituents of most aggregates east of the Blue Ridge and nearly all nonpolishing aggregates statewide. Thus, the potential for ASR-related problems is quite extensive.

Limited aggregate testing by C 227 confirmed that the use of this test method with C 33 evaluation criteria is not effective in identifying reactive aggregates containing microcrystalline and strained quartz as the reactive constituents.

P 214 provides an indication of the relative reactivity of aggregates susceptible to ASR as well as those susceptible to alkali carbonate reactivity; however, the results obtained do not permit the establishment of criteria to distinguish between aggregates that are susceptible to ASR and those that are not.

The purpose of this project was to complete a statewide survey to determine whether ASR was affecting concrete and which aggregates were susceptible. As the study progressed, it became apparent that the size of the state and its numerous aggregate resources would not allow for the completion of these tasks in the allotted time. Once it became apparent that a significant portion of the state's aggregate resources may be susceptible to ASR, it was decided that preliminary precautions should be taken to protect against its occurrence in new concrete construction. A review of the mechanisms involved in ASR suggest that the best assurance of minimizing ASR would be obtained through the use of cementitious materials that minimize or control the alkalis introduced. Consequently, the specifications for concrete have been modified to require the use of Class F fly ash, ground-granulated, blast-furnace slag, or silica fume in concrete when the alkali content of the portland cement exceeds 0.40 percent (Appendix 4). These guidelines were culled from existing literature to provide what is considered at this time to be acceptable protection; however, new research has been started to better define the relative effectiveness of various cementitious materials (portland cement, pozzolans, and slag) in controlling the alkalis in concrete to prevent damaging ASR.

## RECOMMENDATIONS

It is recommended that investigations of cases of closely spaced map and longitudinal map cracking be continued to determine their cause. If the cause is determined to be ASR, then a determination of what aggregates are involved needs to be made. The cases focused on in this study were located in the Culpeper, Richmond, and Lynchburg Districts. Surveys of structures in the future should target other districts, particularly Northern Virginia, Fredericksburg, and Suffolk. Evaluations of aggregates should continue coupling petrographic examinations with field performance and P 214 testing to better define the nature of aggregates susceptible to ASR.

Investigations should also continue to attempt to determine the alkali content of concrete necessary to drive damaging ASR. This will permit the development of more exacting measures to prevent ASR, thus promoting more efficient and economical use of materials.

Additional research should focus on the mitigation of damage to existing structures and pavements. The use of sealers to prevent the ingress of moisture and the use of lithium compounds to alter the physical characteristics of ASR gel show promise in this regard.

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## **APPENDIX 1**

### **Survey Results of Structures and Pavements on I-295 from Short Pump to Sandston**

I-295, Short Pump to Sandston, Structures and Pavements  
Exhibiting Map And Longitudinal Map Cracking

Location 1

SN 5063 - 1980

5064 Approach slabs: map cracking at ends  
Parapets: cracking, but signs of shrinkage  
Deck: some longitudinal cracks, center  
FA: natural sand  
CA: crushed stone

Location 2

SN 2114 - 1981

2115 Approach slabs: map cracking  
Substructure: map cracking  
Parapets: cracking w/ some crushing  
Deck: some cracking, mid-span

Location 3

Pavement: west of 2114; 10/80

Longitudinal cracking off transverse joints

Location 4

SN 5062 - 1980

Approach slabs: variable map cracking major to none  
Deck: Cracking developing in N end  
FA: natural sand, white  
CA: crushed stone

Location 5

SN 2092 - 1979

No cracking  
FA: natural sand  
CA: natural gravel

Location 6

SN 5065 - 1980

Approach slabs: map cracking at ends  
Parapets: minor cracking  
Cem: Plant 1  
FA: JR sand  
CA: JR gravel

Location 7

SN 2108 - 1980

No cracking  
FA: natural sand  
CA: natural gravel

Location 8

SN 1095 - 1981

Approach slabs: map cracking  
Parapets: cracking  
Substructure: some cracking

Location 9

SN 2118 - 1981

Approach slabs: joints at deck repaired  
Parapets: cracking  
Deck: faint cracking visible on sides

Location 10

Pavement - 7/80

Map cracking  
Cem: Plant 2, 3  
FA: JR sand, Mpi sand  
CA: JR gravel; crushed stone, Hylas confirmed asr gel assoc. w/ crushed stone

Location 11

Pavement - W of 2904

Map cracking  
FA: natural sand  
CA: crushed stone

Location 12

SN 2904

Substructure: map cracking  
FA: natural sand  
CA: crushed stone

Location 13

Pavement - E of 2904

Map cracking  
FA: natural sand  
CA: Crushed stone

Location 14

SN 1038 - 1978

Approach slabs: map cracking pronounced  
Parapets: cracking pronounced, crushing

Substructure: map cracking pronounced  
Cem: Plant 1,2  
FA: JR sand  
CA: JR gravel

Location 15

SN 2030 - 1979

Approach slabs: map cracking  
Cem: Plant 2  
FA: JR sand  
CA: JR gravel (deck); crushed stone (AS), Hylas & Doswell

Location 16

Pavement - 9/79 E and W of 2030

Map cracking  
FA: natural sand  
CA: crushed stone

Location 17

SN 1048 - 1978

Approach slabs: map cracking; one w/ A3  
Parapets: cracking  
Substructure: Map cracking, N end  
Deck: widely spaced map cracking  
Cem: Plant 1  
FA: JR sand  
CA: JR gravel

Location 18

SN 2022 - 1979

Substructure: some faint map cracking

Location 19

Pavement - 7/80 E of 2022

Longitudinal cracks developing

Location 20

SN 2906 - 1980

Substructure: map cracking, top of backwall; wingwall  
Cem: Plant 1, 3(?)  
FA: JR sand  
CA: crushed stone, Doswell

Location 21

Pavement - 7/80 E & W of 2906

Map cracking

Location 22

SN 1094 - 1980

Approach slabs: map cracking

Parapets: some cracking

Substructure: map cracking

Deck: cracking, SB lane

Cem: Plant 1, 3

FA: JR sand

CA: crushed stone, Doswell

### I-295 MATERIALS

CONSTRUCTION: I-295 N of Richmond between I-64 W and E of town was constructed between approximately 1976 and 1981. The following information was obtained from records for this construction. However, not all records have been examined.

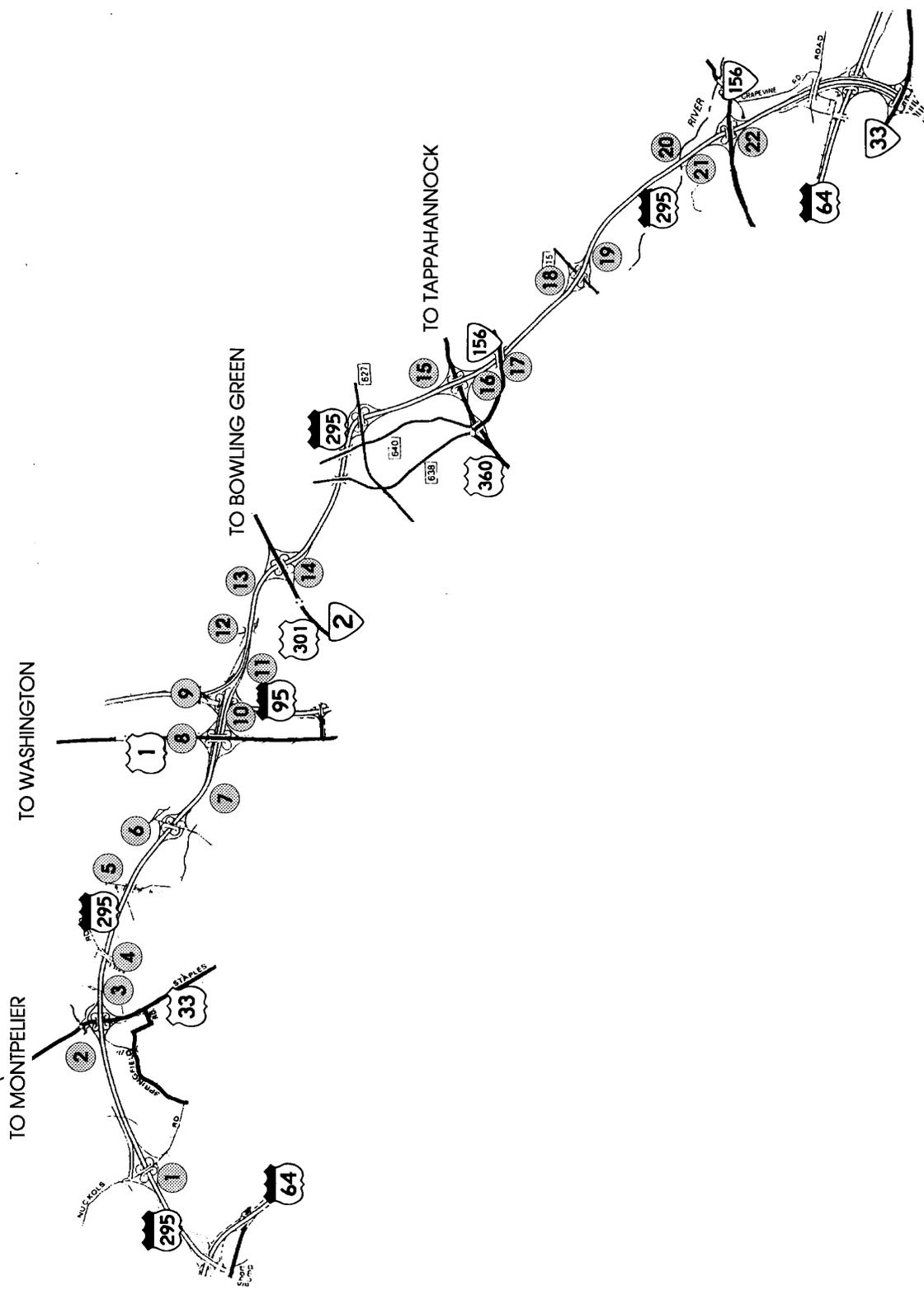
	DATE	Na <sub>2</sub> O equiv.	
CEMENTS:	Plant 1	5/76	0.64
		5/76	0.59
		7/77	0.69
	Plant 2	3/78	0.41
		3/78	0.42
		6/78	0.46
	Plant 3	7/78	0.53
		10/78	0.54
		3/79	0.56
7/79		—	

#### FINE AGGREGATES:

Natural sands—James River (JR)  
Mattaponi River (Mpi)

#### COARSE AGGREGATES:

Natural gravels—James River (JR)  
  
Doswell: diabase, amphibolite gneiss, granite



I-295, Short Pump to Sandston.

## **APPENDIX 2**



# COMMONWEALTH of VIRGINIA

## HIGHWAY & TRANSPORTATION RESEARCH COUNCIL

August 31, 1979

JACK H. DILLARD, HEAD  
VIRGINIA HIGHWAY & TRANSPORTATION RESEARCH COUNCIL

BOX 2817 UNIVERSITY STATION  
CHARLOTTESVILLE, VIRGINIA 22903

IN REPLY PLEASE REFER TO FILE NO. 26.4.4.3

Mr. David Stark  
Portland Cement Association  
Old Orchard Road  
Skokie, ILL 60077

Dear Dave:

This letter is attached to a parcel of core pieces taken from a deteriorating continuously reinforced section of I-64 just east of Charlottesville. By now Bill Alcock should have contacted you to say that he suggested I send them to you for your impute on this curious situation.

This kind of deterioration can be found only in the west bound lane. The east bound lane was placed with similar aggregates and cement in November and December of 1969 and only shows a little surface scaling probably due to surface freezing of freshly placed concrete. Ken McGhee remembers having seen ice under the polyethylene sheeting. The deteriorating section was placed in April 1970.

The continuously reinforced pavement is showing groups of longitudinal cracks. The spacing within each group is about 3/4 inch. The cracks are six inches to several yards long. The groups seem to bear no correlation to the reinforcement but seem to be spaced across the roadway at about the spacing of the spud vibrators. The cracks seem to be more prevalent in sections where the screed was, or may have been traveling at faster speeds. A small portion of this six mile stretch of pavement was used for a study of the parameters of consolidation (attached papers: "Vibrator Test" by Foster and Bruce, April 1970, and "Void Parameters of 24 Cores of Concrete Removed from a Consolidation Test Study Section of I-64", H. N. Walker, 1972), thus the screed speed is known in some short portions. If you assume that the screed traveled down hill faster than up hill you definitely get the feeling that the cracks are more prevalent in high speed areas. It is well known that it was considered politically expedient to get the highway open to traffic "yesterday if not sooner". Two specimens of the deteriorating reinforced pavement are being sent to you.

The bridge approach slabs are not reinforced and are showing severe deterioration. At the surface there is a deep pattern cracking of hexagonal nature on 2 six inch centers. In the worst areas the central portion of the pavement is nothing but rubble with a relatively solid two inch top and bottom. One core half, and one rubble fragment are being sent.

The coarse aggregate is Catoctin greenstone with a poor particle shape and a tendency to split along the schistosity. This aggregate is no longer in use in Virginia highway portland cement concrete.

You will note white rims exterior to many of the particles in the approach slab concrete and occasionally in the reinforced concrete. These rims are apparently composed of  $\text{Ca}(\text{OH})_2$  and some kind of gel. Certain of the cracked particles have a minor interior rim of the same material.

I hesitate to label this mess alkali aggregate reaction because there seems to be no evidence of expansion. Joints are not squeezed etc.

As there is a possibility that the chloritic coarse aggregate was stockpiled and exposed to the weather during the '69-'70 winter the mechanisms of chlorite degeneration mentioned in the attached paper by G. H. Rowe may be applicable here. I have written to Dr. Rowe asking what failures of portland cement concrete have been attributed to weathered chloritic aggregate. I will send a copy of his reply when received.

For comparison purposes we are hoping to core the east bound lane which shows none of this deterioration. It will be interesting to see if better consolidation of the bottom of the pavement was obtained and if the surface void structure correlates with vibrator spacing.

At present we are considering checking the drainage in some of the most deteriorated reinforced pavement; replacing areas gone to rubble; temporary filling of open cracks and overall linseed oil treatment.

I will be very interested to talk to you about this situation and see if you have ideas similar to ours.

Sincerely yours,

HNW/mam

attachment

cc: Mr. J. H. Dillard  
Mr. H. H. Newlon  
Mr. H. E. Brown  
Mr. K. H. McGhee

Hollis N. Walker  
Materials Research Petrography

## **APPENDIX 3**



August 5, 1980

William Alcoke

Eastern Region

Enclosed is a report on the deterioration of continuously reinforced pavement in I64 near Charlottesville, Virginia. As you will note, C227 tests are under way on coarse aggregate from the same source as that used in the pavement. Although the test calls for a 6-month storage period, it is probable that a longer period, perhaps 1-2 years, will be required to develop significant results. In the meantime, interim results will be made available periodically.

*David Stark*

DAVID STARK  
Concrete Materials Research Department

Encl.

HR-1070

Copy to-  
Paul Klieger, w/encl.  
Ray Gordon, "

INVESTIGATION OF PAVEMENT DISTRESS,

I64 - VIRGINIA

By David Stark

Mr. William Alcoke of the Portland Cement Association Eastern Region has brought to our attention the development of abnormal cracking in a section of continuously reinforced concrete pavement in I64 near Charlottesville, Virginia. Subsequent arrangements were made through Mrs. Hollis Walker of the Commonwealth of Virginia Highway and Transportation Research Council to inspect the pavement, examine cores taken from the pavement, and evaluate coarse aggregate from the same source as that used in the pavement. Following are the results of this work.

The pavement in question was built using fine aggregate from Southern Materials, Richmond, and coarse aggregate, identified as Catoctin greenstone, from a quarry near Charlottesville. Lehigh cement from Union Bridge, Maryland was used in the westbound lanes, which were built in the spring of 1970, while cement of uncertain origin was used in the eastbound lanes built in the fall of 1969. The pavement inspection was conducted on November 1, 1979 by Mrs. Walker and Mr. Kenneth McGhee of the Research Council, and the writer.

Inspection of the westbound lanes revealed the presence of numerous, fine, closely spaced cracks with a prevailing longitudinal orientation. Individual cracks normally were less than several feet long but occasionally extended up to lengths

of 15 to 20 ft. Adjacent cracks were usually no more than a few inches apart and eventually intersected to produce an overall braidlike pattern. Few, if any, cracks had a generally transverse orientation. In contrast, the eastbound lanes displayed little or no cracking of this type, and that which was present was very faint.

The type of cracking observed in the westbound lanes is similar to that seen by the writer in numerous pavements affected by alkali aggregate reactivity. The cracking is initiated by expansive reactions and accentuated at the wearing surface by shrinkage, abrasion of crack edges, and secondary deposits in the cracks. The generally prevailing longitudinal crack pattern results from the lesser transverse restraint on the concrete compared with that in the longitudinal direction, wherein, the continuous steel reinforcement serves to resist expansions induced by reactivity.

Prior to the inspection, cores were submitted to the Portland Cement Association Laboratories for petrographic examination to determine the causes of the observed cracking. Microscopic examination of lapped surfaces of core 6-2, taken from "Ballenger Test Section #6" which displays faint traces of longitudinal cracking, revealed the presence of fine dark reaction rims on numerous greenstone coarse aggregate particles, and microcracking within these particles that extends into surrounding mortar. Many of these cracks are located just inside the paste-aggregate interface, while others extend entirely through the center portion of the particles and

into the surrounding mortar. Essentially no gel reaction products were observed on these surfaces. Examination of lapped and fractured surfaces of cores 9-1 and 9-4, both taken from bridge approach slabs displaying pattern cracking, revealed features similar to those in core 6-2.

Examination of fractured surfaces of mortar and coarse aggregate in a concrete fragment from core 8-1, taken from a section of severely cracked continuously reinforced pavement, revealed well defined reaction rims in the aggregate and secondary reaction products in microcracks in these particles. These deposits consist primarily of partially carbonated alkali silica gel, which is indicative of alkali silica reactivity involving the greenstone particles. These cracks and, to a lesser extent, aggregate surfaces separated from the paste, were the only locations where gel deposits were observed.

The conclusion reached is that the observed cracking in the pavement was initiated through expansive alkali silica reactivity involving a fraction of the greenstone coarse aggregate particles. To help verify this finding ASTM C227 mortar bar tests are being run in which aggregate from the same source as the greenstone is being tested in combination with five cements with alkali levels of 0.36, 0.48, 0.57, 0.75, and 0.92 percent alkali as sodium oxide. Meaningful results will be forwarded as they become available.

## **APPENDIX 4**

VIRGINIA DEPARTMENT OF TRANSPORTATION  
SPECIAL PROVISION FOR  
HYDRAULIC CEMENT CONCRETE

December 10, 1991c

SECTION 217 of the Specifications is amended as follows:

Section 217.02 (a) is replaced with the following:

Cement shall conform to Section 214 and shall be Type II with a maximum alkali content of 0.40% or Type I-P, unless otherwise permitted herein or otherwise specified in the contract. Fly ash or granulated iron blast-furnace slag shall not be added to concrete when Type I-P cement is used. Fly ash, granulated iron blast-furnace slag, silica fume, or other approved mineral admixtures shall be used with Types I, II (if above 0.40% alkali content) or III cements as specified herein.

Types I, II or III cements may be used with latex modified portland cement concrete.

Fly ash, Type F, shall replace 15% by weight of the design cement, and have an additional 5% by weight of the design cement content added which will be considered cementitious material. Additional fly ash will be considered aggregate.

Granulated iron blast-furnace slag shall replace from 35% to 50% by weight of the design cement content.

Silica fume shall replace a minimum of 7% by weight of the design cement content.

Other mineral admixtures shall be used in accordance with the requirements shown on the approved list of mineral admixtures.

Section 217.02 is amended to replace (h) and (i) with the following:

- (h) Fly ash shall conform to the requirements of Section 241.
- (i) Granulated iron blast-furnace slag shall conform to the requirements of Section 215.

Section 217.02 is amended to add the following:

- (k) Silica fume shall conform to the requirements of Section 215.