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SEVERE PAVEMENT DAMAGE CAUSED BY ALKALI-SILICA REACTION IN LIMESTONE COARSE AGGREGATE CONTAINING VERY FINE QUARTZ PARTICLES

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ABSTRACT

Portions of U.S. Interstate Highway I-20 across northern Louisiana, constructed in 1987 and 1992, developed cracking and loss of wearing surface sufficient to require its replacement by 1996.

The coarse aggregate incorporated five varieties of limestone all of which, in the most severely distressed concrete, might be transected by cracks. By examining samples exhibiting varying degrees of distress, from mild to severe, the particular expansive, crack-generating, lithology can be isolated. It is an aphanitic, silty, microporous, variably dolomitic, micrite, which comprises about 20% of the coarse aggregate.

The expansion is caused by ASR which produces a peripheral separation around the limestone particle and internal cracks extending into the matrix. ASR product in the reactive rock is identified by its characteristic microscopical features, its characteristic fluorescence in UV light after treatment with uranyl acetate solution, and by its chemical composition using Energy Dispersive Spectrometry (EDS). And, using SEM and EDS, the reactive silica in the crack-generating lithology is identified as very small detrital and authigenic quartz particles (0.002 - 0.010 mm) in the groundmass of the limestone.

Keywords: Alkali-silica reaction, quartz, limestone, highway pavement.

INTRODUCTION

United States Interstate Highway I-20 is a heavily traveled main route across northern Louisiana connecting the principal cities, from east to west, of Jackson, Mississippi, Shreveport, Louisiana, and Dallas, Texas.

Portions of I-20 east and west of Monroe, LA (midway between Jackson and Shreveport) were placed in 1987 and 1992, respectively. More particularly, 14.5 km (9 miles) of pavement concrete was poured between July 1986 and May 1987 in the east project, and 10.6 km (6.6 miles) was poured between September 1991 and July 1992 in the west project.

The same crushed limestone coarse aggregate from a quarry in the central U.S. was used in both projects and the same local natural sand fine aggregate was used in both projects. Different portland cements were used in the east and west projects but both had Na_2O equivalent alkali contents varying between 0.4 to 0.5 percent, according to available mill analysis. Class C fly ash, which in addition to having pozzolanic and cementitious properties may also have a high lime content, was used in the west of Monroe project, but no fly ash was used in the east project. However, there is no significant difference in the severity of the cracking in the east and west projects.

CONDITION OF ROADWAY AND SHOULDER CONCRETE

Both projects exhibited early distress and by December 1996 the appearance of a badly distressed portion in the west project was as shown in Figure 1, with extensive map cracking and shallow holes in the pavement a few inches deep and up to one foot (30 cm) in diameter. Where the pavement is not as badly distressed as in Fig. 1 it exhibits severe pattern cracking and the presence of one, or more, horizontal crack planes which develop below the wearing surface at typical depths between 25 to 75 mm (1 to 3 inches). Figure 2. The combination of the vertical and horizontal cracks in the wheel paths isolates chunks of concrete which are then excavated by the traffic.

The concrete in the shoulder, of presumably the same composition as in the traffic lanes, exhibits little to no apparent cracking Figure 3. On the assumption that the pavement cracking is related to an expansive cement/aggregate reaction, a core was taken for the particular purpose of addressing the question of why the concrete in the shoulder is in so much better condition than in the adjacent severely cracked roadway if the concrete in the shoulder and the roadway is the same material.

Coincident with the inspection of the roadway and the taking of core samples (December 1996) portions of severely distressed roadway were in process of excavation. The excavated concrete was stored temporarily in piles near the highway. The rubble piles provided large areas of broken-across vertical and horizontal interior section for examination. These broken-across sections revealed numerous interior paste/mortar surfaces coated with white powdery material, which also occurred around coarse aggregate particles exhibiting reaction rims, Figure 4. The appearance and occurrence of the white material was strongly suggestive of it being an alkali-silica reaction product.

Figure 1. Appearance of badly distressed roadway surface in the West project in December 1996. Note extensive pattern cracking, and shallow holes in the pavement near the joint where chunks of concrete have been excavated by traffic. Some asphalt patching has been attempted.

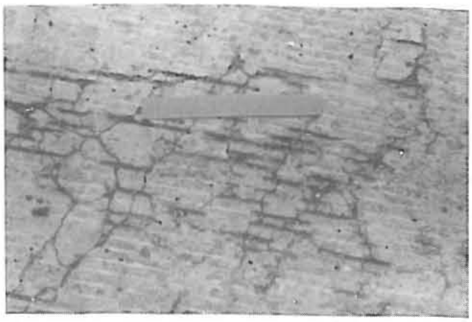

Figure 2. Distressed roadway surface, West Project, December 1996, scale is 6" (150 mm). Note pattern cracking. The cracks penetrate 1-2" (25-50 mm) vertically, and pieces of concrete isolated by cracks may be pried loose along a horizontal crack plane present at a depth of 1-2".

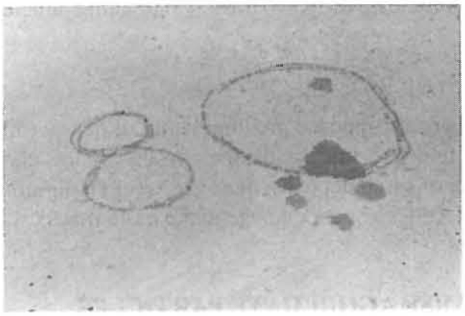

Figure 3. Shoulder surface, West Project, December 1996, circle is approximately 6" (150 mm) in diameter. Note absence of visible cracking as compared to Figure 2 which is taken in the adjacent traffic lane at the same scale.

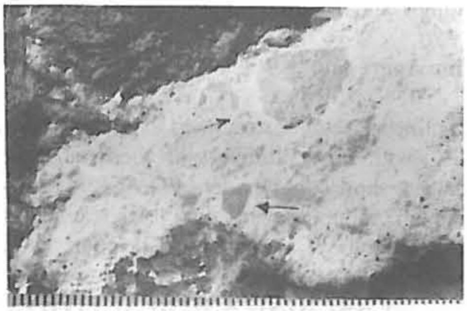

Figure 4. Broken interior surface of excavated concrete. Note white material around coarse aggregate particles (arrows).

PETROGRAPHIC EXAMINATIONS

Samples used for this investigation were eight 150 mm (6 inch)diameter, full depth, approximately 305 mm (12 inch) cores taken in December 1996. Six cores were from the traffic lanes of the west project; one core from a shoulder in the west project; and one core from a traffic lane in the east project.

Coarse Aggregate

The coarse aggregate in all of the cores, is crushed limestone with maximum particle dimension up to 6.3 cm (2 ½ inch). The material is composed of five limestone types, deriving from different beds comprising the portion of the stratigraphic section used to produce the crushed stone for these projects.

The limestone lithologies include: oolitic limestone (or rounded biospartite); calcitic and dolomitic microcrystalline limestone with little to no micrite or clay; and three micritic limestones distinguished by differences in fossil content, dolomitization, micrite volume, porosity, and amount of quartz silt.

One of the three micritic limestones is the crack-generating lithology and is shown in thin-section in Figures 5 and 6 and in macroscopic views in Figures 7 and 8. It is a dark, greenish-gray, aphanitic, silty, microporous, slightly dolomitic, micrite composed of a ground mass of microcrystalline carbonate mud in which are quartz silt grains, sparsely distributed dolomite rhombs, and irregular pores ranging in size from minute up to approximately 0.08 mm diameter.

Fine Aggregate

The fine aggregate is rounded to angular natural sand composed predominantly of quartz (50 - 60%) with lesser amounts of chert, quartzite, feldspar, and sandstone. Many of the chert particles show some evidence of ASR in the form of small deposits, or coatings, of alkali-silica reaction product, but show no particle cracking. And, no crack damage to the paste matrix was observed to be associated with the chert particles.

CRACKING AND REACTIVE COARSE AGGREGATE PARTICLES

Samples from the Roadway Surface

Severely cracked samples from the roadway surface typically display several vertically trending cracks, penetrating from 25 to 75 mm (1 to 3 inches), to intersect one or more horizontally trending cracks at slightly varying depths.

Vertical sections through the upper, severely cracked, regions of the core samples therefore reveal numerous cracks through the matrix and transecting coarse aggregate particles of more than one lithology. Such crack patterns will not provide conclusive evidence regarding the origin of the cracks since it is apparent that the horizontal cracks, particularly, originated outside of the core and now transect coarse aggregate particles of several lithologies as they pass through the core sample.

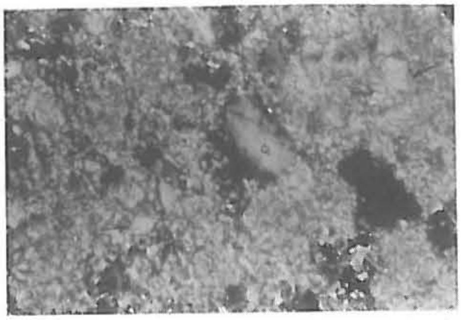

Figure 5. Thin-section, crack-generating lithology, XPL, field is 0.19 mm across. Ground mass of microcyrstalline calcite with triangular sharp edged quartz grains (Q) and some dolomite rhombs (arrows).

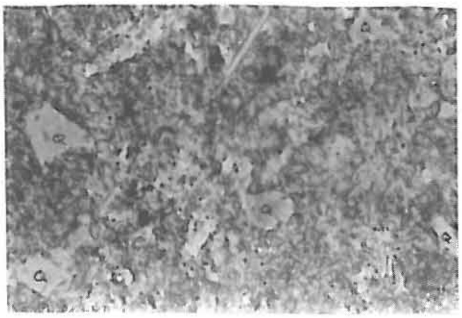

Figure 6. Thin-section, crack-generating lithology, partial XPL, field is 0.19 mm across. Groundmass of microcrystalline calcite with squarish, equant, quartz grains (Q) in left of field, and a grain with irregular curved boundary in lower right, and one with scalloped, or crenulated, edges in upper right.

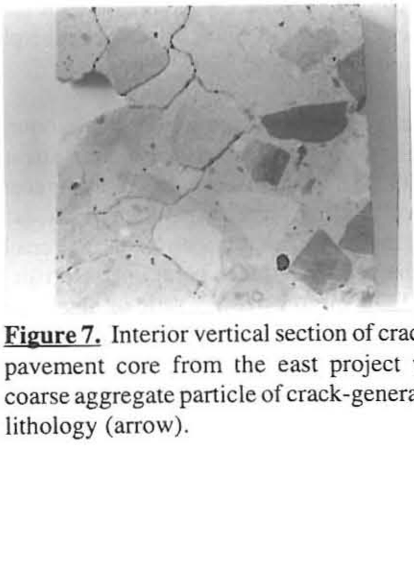

Figure 7. Interior vertical section of cracked pavement core from the east project with coarse aggregate particle of crack-generating lithology (arrow).

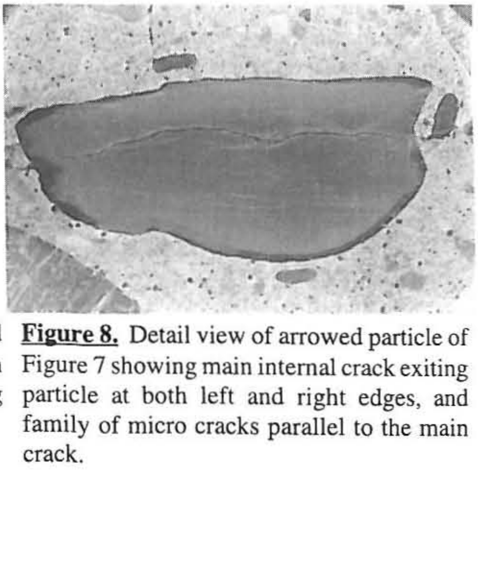

Figure 8. Detail view of arrowed particle of Figure 7 showing main internal crack exiting particle at both left and right edges, and family of micro cracks parallel to the main crack.

Cracks through the concrete that originate from the expansion and cracking of particles of a particular lithology must be studied at the early stage of crack development and extension into the mortar, so that by comparison and correlation of several study slabs the particular crack-generating lithology can be identified.

Using study slabs from regions of the cores with fewer cracks going through both the matrix and the coarse aggregate particles the required information can be obtained. An example is shown in Figure 7 in which cracks propagate through the matrix but around all coarse aggregate particles in the field except for one, in which there is a full width crack extending into the matrix on both sides of the particle. Figure 8 shows a detail view of the cracked particle with reaction rim, and the crack, wider in the particle mid-region and with parallel microcracks, extending into the matrix on both sides.

Reaction Features of Crack Generating Particles

The crack-generating coarse aggregate particles exhibit one or more of the following features indicating internal alkali-silica reaction.

- Peripheral cracks separating the particle margin from the enclosing matrix. Figure 9.
- Cracks from the particle interior into the matrix, often with alkali-silica gel filling in the crack, Figure 10.
- Alkali-silica reaction product inward of the particle perimeter extending into the paste to form exterior margins around the particles. Figure 11. Such features are the plan views of the crack planes seen in cross section in e.g., Figure 10.
- Alkali-silica reaction product within, and adjacent to, micro-cracks in the interior of particles of the crack-forming limestone lithology, as identified on uranyl acetate treated surfaces in UV light and by SEM and EDS. The treatment of the reactive coarse aggregate particle cross-section in concrete with the uranyl acetate solution produces the exudation of a soft, shiny, jelly-like, material in, and around, the interior particle cracks. The material is strongly fluorescent, with the yellowish-green color characteristic of alkali-silica gel in UV light, and produces EDS spectra characteristic of alkali-silica reaction product, Figure 12.

All of the coarse aggregate particles which exhibit the above reaction features are of the same silty, micritic, lithology. [But, not every particle of this lithology exhibits the reaction features.] No particles of the four other limestone lithologies exhibit any of the reaction features.

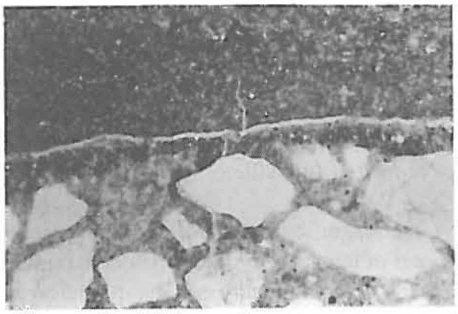

Figure 9. Thin-section, coarse aggregate particle of crack-generating lithology above (CA), and concrete matrix below, PPL, field is 2.7 mm width. Note peripheral separation between CA and matrix, and radially oriented crack across CA/matrix interface and into matrix.

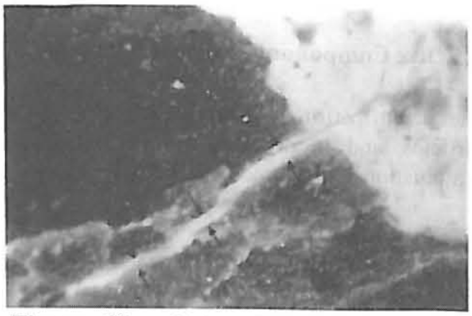

Figure 10. Cut and polished section, shoulder concrete core, field is 1.9 mm across. The white crack-filling material (arrows) extends into the paste, and the micro-crack extends into the paste a greater distance. The crack-filling material is ASR product as identified optically and which fluoresces in UV light on the uranyl acetate treated surface.

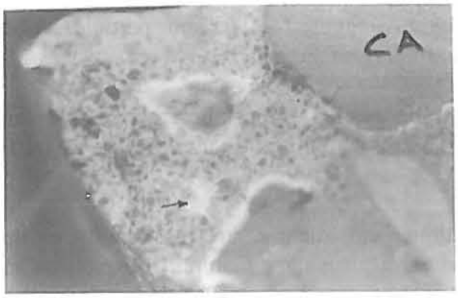

Figure 11. Partially saw-cut and broken section, shoulder concrete core, parallel to pavement surface at 127 mm (5 in) depth, field is approximately 30 mm across. Surface treated with uranyl acetate solution and photographed in UV light. The ASR product around the central and lower coarse aggregate particles fluoresces brightly. The interior of the central particle is lightly coated with ASR product and fluoresces weakly. The arrow indicates a void with reaction product.

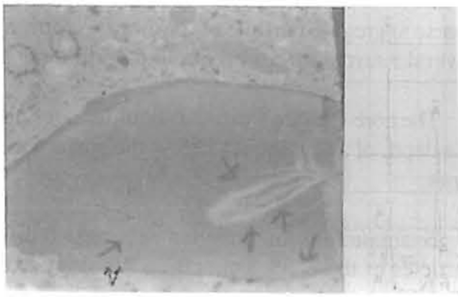

Figure 12. Saw-cut vertical section treated with uranyl acetate solution and photographed in UV light. Fluorescent envelopes of ASR product are present around internal cracks in coarse aggregate particle (arrows). An EDS spectrum of the fluorescing material is shown.

Reactive Component in the Crack Generating Particles

The identification of alkali-silica reaction product within the crack-generating limestone particles, and in cracks from the particles into the enclosing paste, suggested detailed examination of the limestone matrix for the source of the reacting silica.

Examination by optical microscope at 400x to 600x magnification establishes the presence of numerous quartz particles in the matrix on the order of ten to thirty micrometers maximum dimension — sometimes several at a time in fields 0.19 mm across. The particles are predominantly sharp edged and triangular or squarish in shape, indicating that those are detrital in origin, Figures 5 and 6. But, many are more delicate and irregular, with curved or crenulated edges suggesting that they may be authigenic, or that they may be embayed grains as a result of replacement by calcite, Figure 6.

The presence of numerous quartz particles in the limestone matrix still smaller than ten micrometers was also noted under the optical microscope. Those were more conveniently studied and identified by means of scanning electron microscopy and EDS, which established the presence of quartz particles in the two micrometer size range. Figure 13 shows an approximately 5 micron quartz particle with its EDS spectrum.

Sample from the Road Shoulder

The core sample from the road shoulder, which shows no readily apparent cracks, Figure 3, does in fact have a surface crack which extends to a depth of 114 mm (4 ½ inch) where it enters a coarse aggregate particle of the crack — forming lithology Figure 14. The same particle exhibits several internal micro-cracks and peripheral separation from the matrix.

The core sample from the shoulder does not exhibit a well developed horizontal crack plane at a depth of a few inches below the surface as is the case with the core samples from the traffic lanes.

Examinations of polished sections, thin-sections, and fracture surfaces, establishes that particles of the crack-generating lithology exhibit exactly the same features of expansion and cracking as in the cores from the traffic lanes — but to a lesser degree. That is, cracks into the paste are fewer, thinner, and shorter, and peripheral separations are thinner and more discontinuous around the particle margins. For those particles that exhibit internal cracks extending into the paste, the same association of alkali-silica reaction product with the cracks is present, Figures 10 and 11.

DISCUSSION

It is evident from the examination of all of the cores that the sample from the shoulder is the same concrete as the samples from the roadway and that it exhibits the same types of distress present in the samples from the roadway. But, at a less advanced stage of the development of the coarse aggregate and concrete cracking.

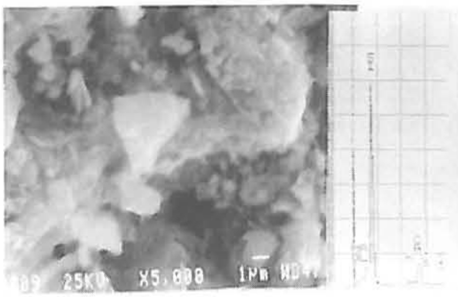

Figure 13. SEM micrograph of area of limestone matrix with quartz particle (lighter gray, triangular, in center of field) and its EDS spectrum.

Figure 14. Core from road shoulder, top to right, showing surface crack extending to dark coarse aggregate particle of crack-generating lithology (right arrows). The upper left arrows indicate cracks near the core bottom.

It is most probable that the reason for the absence of the same profuse cracking in the shoulder as is present in the adjacent traffic lanes is the absence of the stress due to the heavy traffic. The traffic extends and widens the cracks by two interacting, and additive, mechanisms:

1) Direct mechanical pounding and stress on the roadway surface opens and extends the initially formed short, thin, cracks, which are present in the shoulder concrete, and

2) The now more open and extended cracks allow more rain water to penetrate into the concrete, feeding the alkali-silica reaction, which, in turn, produces more expansion and cracking to be exacerbated by 1).

CONCLUSIONS

The cracking in the pavement and shoulder concrete is due to the expansion and crack generation of one particular lithology, of several, in the crushed limestone coarse aggregate.

The expansion producing mechanism in the crack-generating coarse aggregate particles is alkali-silica reaction. The ASR produces a peripheral separation around the coarse aggregate particle, and internal cracks, both radial to the particle perimeter and parallel to the bedding planes of the limestone, which extend into the matrix and which can extend through coarse aggregate particles of the (four) other limestone types.

The ASR product has been identified in the reactive rock by its characteristic microscopic features and spatial relationship to the cracks; by its characteristic fluorescence in ultraviolet light on surfaces treated with uranyl acetate solution; and by its elemental composition using x-ray micro analysis.

The results of scanning election microscopy and x-ray micro analyses studies indicate that the reactive silica in the crack-generating lithology is very fine-grained quartz, on the order of two to ten microns diameter, in the groundmass of the limestone.