Causation of Near-Surface ASR at Concrete Slabs-on-Grade

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ABSTRACT

Alkali-silica reaction (ASR) in concrete structures is a well-known damage mechanism. The mechanism of near-surface ASR (NSASR) differs from traditional ASR in that the reaction occurs relatively quickly, occurs only near the top surface of a concrete slab, extrudes gel onto the surface of the slab, and does not result in widespread cracking of the slab. Evaluations of residential and commercial structures in Central Texas have determined the presence of this mechanism.

Through recent case studies, this paper will discuss factors that cause and/or exacerbate NSASR and the patterns of NSASR distress. These case studies involve slab-on-grade foundation systems with many similar conditions, but with some important variation in the factors which contribute to NSASR. This paper will also discuss in-situ testing and material testing performed for the case studies and how the results of these tests correlate with some common theories related to the causation of NSASR in slab-on-grade foundation systems.

Finally, the paper will discuss potential future laboratory testing to study the NSASR mechanism and the effects of specific causation factors.

MECHANISMS OF ASR

ASR is a well-researched deleterious mechanism in concrete that involves a chemical reaction between alkalis and certain siliceous rocks or minerals present in some aggregates that are susceptible to degradation by the alkalis. The alkalis primarily consist of sodium and potassium cations, which originate from the materials used to make cement, and are present in the pore solution of concrete. Other sources of the alkalis can contribute to the total alkalis in the concrete, including supplementary cementitious materials (SCMs), aggregates, admixtures, and floor preparation materials. Also in the pore solution are hydroxyl anions that exist in equilibrium with the cations. As the concrete hydrates, the hydroxyl content increases, resulting in a very high pH environment. High pH causes a degradation of the aggregates, which introduces silica into the pore solution that combines with the alkalis to form a hydrophilic gel. This gel absorbs moisture from the surrounding paste, causing the gel to expand and impart internal tensile stresses on the paste, ultimately causing it to crack.

Three main components are necessary for ASR to occur in concrete: elevated relative humidity (RH) (typically greater than 80%), elevated pH (typically greater than 13.1) in the pore solution, and susceptible aggregates. The RH and pH thresholds necessary to cause ASR vary with each susceptible aggregate (Farny and Kerkhoff 2007) (Stark 1991).

When the proper conditions are present in a concrete mixture, ASR will occur throughout the entire concrete member and takes several years to initiate, typically on the order of 10 or more years. Map cracking (i.e., widespread cracking throughout the concrete member, including at the surface) will occur, resulting in loss of strength, as well as unsightliness and serviceability concerns. This particular mechanism will be referred to herein as "traditional ASR." **Figure 1** depicts map cracking on a concrete member affected by traditional ASR (Thomas, et al. 2011).

Another type of ASR encountered in concrete slab-on-grade foundation systems in the central Texas region is near-surface ASR (NSASR). NSASR differs from traditional ASR in that the reaction occurs relatively quickly in comparison to traditional ASR, occurs only near the top (exposed) surface of the concrete slab, gel is extruded at the top surface of the slab, and it does not result in map cracking. **Figure 2** depicts gel exudations and white residue resulting from NSASR at the top surface of a concrete slab.

Figure 1: Traditional ASR map cracking.

Figure 2: Gel exudations and white residue from NSASR at concrete slab surface.

Other forms of ASR occurring in the near-surface region of concrete foundations have been previously reported in other parts of the USA (South Dakota, Iowa, and Minnesota) with the primary difference being the distress manifestation, which includes concrete popouts in addition to gel exudations (Landgren and Hadley 2002). Other reported forms of distress related to ASR at the near-surface region of concrete foundations include blistering to epoxy floor coverings in which osmotic effects are the primary cause of distress with some contribution from ASR (Ignoul, et al. 2004).

The data and analyses regarding NSASR in this paper are based on three recent case studies involving concrete slab-on-grade foundation systems for residential and commercial structures in Central Texas.

INVESTIGATIONS AND TESTING

The investigations of the case study buildings were prompted due to the complaints of the building occupants about the manifestation of gel and residue at the surfaces of the slabs. After preliminary observations and data collection, a testing protocol was developed by the authors to determine the cause(s) of the gel and residue. The in-situ testing performed at the structures utilized a variety of methods, including concrete coring, soil borings, concrete RH testing, pH level testing of the concrete surface, gel removal and subsequent monitoring, and plumbing testing. Petrographic analyses were performed on concrete cores extracted from one of the structures. Gel samples were also obtained for analytical testing from two of the structures.

Case Study 1 – Residential Structure in Central Texas

The building foundation consisted of a post-tensioned concrete slab-on-grade with a specified 28-day compressive strength of 3000 psi and a continuous vapor barrier below the slab portions of the foundation. The vapor barrier was specified to be terminated at the sides of the grade beams (i.e., no vapor barrier present below the grade beams). The cement used for the concrete foundation had an equivalent alkali content (Na_2O_{eq}) of 0.48. The concrete was specified to be normal weight with no addition of SCMs or air-entrainment. The concrete mix design per cubic yard (yd^3) consisted of 425 lbs of cement. The specified water-to-cement (w/c) ratio was 0.49. The aggregates were specified to comply with ASTM International (ASTM) standard, C33 *Standard Specification for Concrete Aggregates*, which sets limits for the amount of deleterious substances in fine and coarse aggregates. The requirements for fine aggregates include a limit of 3.0% for deleterious clay lumps or friable particles (ASTM 2016).

The intended flooring at the building was exposed concrete (i.e., no floor finishes) and gel exudations reportedly began appearing at the top surface of the foundation approximately 17 months after the slab was poured. During the investigation, gel exudations and white residue were observed at the top surface of the slab in a checkered pattern (**Figure 3**) at the interior of the building, and at the back patio (**Figure 4**), which was exposed to the elements. The gel was opaque and brown in color, surrounded by white residue (**Figure 5** and **Figure 6**). The texture of the gel varied between viscous/deformable to hard/brittle.

Figure 3: Gel exudations at concrete slab surface at interior – note the checkered pattern.

Figure 4: Gel exudations at concrete slab surface at back patio – note the checkered pattern.

Figure 5: Close-up view of gel exudations and surrounding white residue.

Figure 6: Close-up view of gel exudations and surrounding white residue.

Concrete Coring. Concrete coring was performed to determine the depth of concrete at the NSASR areas, to determine if a vapor barrier was present at the slab-to-subgrade interface, and to obtain cores for the performance of petrographic analyses. The results of the petrographic analyses will be discussed later in this section. Based on the coring and a review of the construction drawings, it was determined that the NSASR was occurring in the vicinity of the grade beams, which correlated with the checkered patterns of gel formation at the surface of the foundation as depicted in **Figure 3**. It was also verified that a vapor barrier was present at the slab-to-subgrade interface within the fields of the slab.

Soil Borings. Soil borings were obtained at locations of the concrete coring to be analyzed for moisture content of the underlying soils and to determine the presence and depth of groundwater, if any. The analysis determined that the moisture content of the fill material ranged between 6% and 9%, and the moisture content of the clay soils below the fill ranged between 14% and 18%. Groundwater was observed to be sixteen feet below the ground surface at the boring taken outside of the footprint of the structure. There was no indication of elevated moisture at the subgrade soils from groundwater or another water source.

Concrete RH Testing. The RH of the concrete was determined by the use of in-situ probes performed in general accordance with ASTM standard, F2170 *Standard Test Method for Determining Relative Humidity in Concrete Floor Slabs Using in situ Probes* (ASTM 2018). Probes were placed in the vicinity of the grade beams and within the fields of the slab. The results of the RH testing revealed that the RH of the concrete at the areas of NSASR in the vicinity of the grade beams was elevated to levels of 99% at each location. The results also revealed that the RH of the concrete at areas not exhibiting NSASR within the fields of the slab were lower and ranged between 76% and 86%.

Gel Removal and Monitoring. Two locations exhibiting NSASR were chosen for gel removal in which a 12" by 12" area with gel was wiped clean. Seven days later, the areas were evaluated for the presence of new gel formation. At each of the locations, new gel formation had occurred and had not yet formed a hard outer layer. **Figure 7** and **Figure 8** depict the new gel formation within these areas.

Figure 7: New gel formation after seven days. Note that the slab was wiped clean of gel seven days prior.

Figure 8: Close-up view of new gel formation with no hard outer layer.

Plumbing Testing. The testing performed included static and flow testing on the wastewater plumbing and hydrostatic testing of the domestic water supply plumbing. The testing revealed no leaks present in the plumbing. Therefore, there was no plumbing-related water source beneath the slab.

Petrographic Analyses and Gel Testing. Petrographic analyses were performed on concrete cores extracted from the foundation. Samples of the gel exudations were also analyzed. The analyses revealed the following:

- The gel deposits at the top surface of the concrete were alkali-silica gel as determined by SEM/EDS and were caused by ASR.
- Expansion cracking and microcracking related to ASR was confined to the near surface areas. The maximum depth of deterioration related to ASR was 5 to 8 mm.
- The reactive components of the ASR were chert, chalcedonic chert, and quartzite, which were a part of the fine aggregate and distributed throughout the mixture. The percentage of reactive aggregates was 3% to 4%.
- Cracks were filled with ASR gel at the chert particles.
- Deposits of ettringite were observed in some voids indicating the presence of elevated moisture.
- Cores extracted from within the vicinity of the grade beams with NSASR exhibited little-to-no carbonation, indicative of elevated RH in the concrete.
- Cores extracted from within the fields of the slab at areas with no NSASR did not show signs of ASR or ettringite. These cores also exhibited carbonation at a greater depth than cores extracted from in the vicinity of the grade beams. These findings indicate that the concrete was relatively dry.
- The mixture was comprised of straight portland cement (no SCMs) and the estimated w/c ratio was 0.55.

Analytical elemental and pH testing on gel samples were also performed. The analyses revealed that the gel contained elevated levels of sodium and potassium cations, consistent with alkalis present in ASR. The silica cation contents within the gel were relatively low; however, it was stated that the method used to digest the samples would not have dissolved all of the silica

cations bound within other molecules. The pH of the samples was 10.80. The relatively low pH of the samples is likely related to carbonation of the samples prior to testing.

Case Study 1 Key Observations

- Distress at the surface of the slab consisted of gel exudations and white residue.
- The distress reportedly began appearing approximately 17 months after the slab was poured.
- The distress was present within the vicinity of the grade beams, and not within the fields of the slab.
- A vapor barrier was present within the fields of the slab, and was specified to be terminated at the sides of the grade beams.
- In-situ RH testing revealed a correlation between elevated concrete RH and the distress manifestation.
- Petrographic analyses determined that the gel exudations were caused by ASR confined to the near-surface region of the slab.

Case Study 2 – Commercial Structure in Central Texas

The building foundation consisted of a conventionally reinforced concrete slab-on-grade with a specified 28-day compressive strength of 3000 psi and a continuous vapor barrier below the slab portions of the foundation. The concrete was specified to be normal weight with no addition of SCMs or air-entrainment. The aggregates were specified to comply with ASTM standard, C33. The concrete mix design and composition of the cement was requested for review by the authors, but was not made available. As in Case Study 1, the vapor barrier was specified to be terminated at sides of the grade beams.

The intended flooring at the building was exposed concrete. It was reported by the owners that gel exudations began appearing at the top surface of the foundation in a checkered pattern approximately 6 months after the foundation was poured. Due to the presence of the gel, vinyl composition tile (VCT) was placed on the concrete throughout the building with the exception of isolated rooms where the concrete remained exposed. During the investigation, gel exudations were observed at the top surface of the slab in a checkered pattern (**Figure 9**) at the exposed portions of the foundation. The gel was opaque and brown in color, surrounded by white residue (**Figure 10**). The texture of the gel varied between viscous/deformable to hard/brittle. Distress to the VCT in the form of cracking, pitting, and/or ridging (i.e., raised portions) were also observed in a checkered pattern (**Figure 11**). Upon removal of the VCT, the tiles exhibiting distress were debonded from the slab and were brittle (**Figure 12**). The surrounding tiles with no distress present were bonded well to the slab, and were flexible and sound upon removal.

Due to budgetary constraints, the scope of testing was limited and did not include soil borings and petrographic analysis as in Case Study 1.

Figure 9: Gel exudations at concrete slab surface – note the checkered pattern.

Figure 10: Close-up view of gel exudations and surrounding white residue.

Figure 11: Pitting at VCT.

Figure 12: Brittleness of VCT.

Concrete Coring. Concrete coring was performed to determine the depth of concrete at the NSASR areas and to determine if a vapor barrier was present at the slab-to-subgrade interface. Based on the coring and a review of the construction drawings, it was determined that the NSASR was occurring in the vicinity of the grade beams, which correlated with the checkered patterns of distress to the VCT flooring and the gel formation at the surface of the foundation. It was also verified that a vapor barrier was present at the slab-to-subgrade interface within the fields of the slab.

Concrete RH Testing. The RH of the concrete was determined by the use of in-situ probes performed in general accordance with ASTM standard, F2170. Probes were placed in the vicinity of the grade beams and within the fields of the slab at areas with exposed concrete and VCT floor covering. The results of the RH testing revealed that the RH of the concrete at the areas of NSASR in the vicinity of the grade beams was elevated to levels of 99% at each location. The results also revealed that the RH of the concrete at areas not exhibiting NSASR within the fields of the slab at exposed concrete were typically lower and ranged between 66% and 67%, with the exception of one location that had a concrete RH of 99%. The RH of the concrete at areas not exhibiting distress to the VCT within the fields of the slab ranged between

97% and 98%; the likely cause of the elevated concrete RH at these locations is due to the near-impermeable nature of the VCT flooring that does not allow water vapor to escape the concrete.

pH Level Testing. pH level testing was performed at the exposed concrete surface in general accordance with ASTM standard, F710 *Standard Practice for Preparing Concrete Floors to Receive Resilient Flooring* (ASTM 2017). Testing was performed at areas exhibiting gel/residue and areas with no gel/residue. Distilled water was placed on the concrete surface for 60 seconds prior to absorption of the test fluid onto pH paper strips. The color of the strips changes based on the level of pH and is compared to a pH color chart. The levels of the fluid pH obtained at areas exhibiting gel/residue ranged between 10 and 12, indicating an elevated level of pH of the fluid (**Figure 13**). The levels of the fluid pH obtained at areas with no gel/residue ranged between 4 and 5, indicating a minimal level of pH of the fluid (**Figure 14**).

Figure 13: Elevated level of fluid pH at area exhibiting gel/residue.

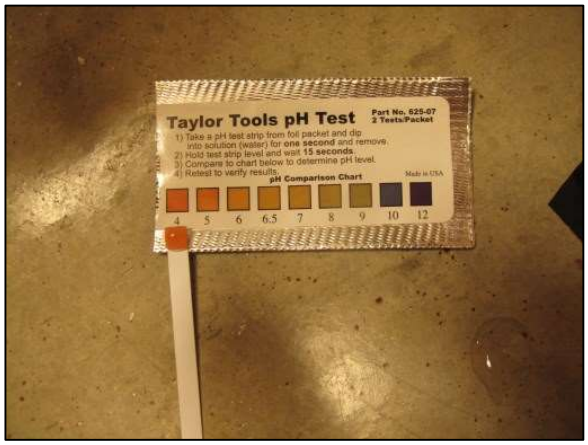

Figure 14: Minimal level of fluid pH at area with no gel/residue.

Gel Testing. Analytical elemental and pH testing on gel samples were performed. The analyses revealed that the gel contained elevated levels of sodium and potassium cations, consistent with alkalis present in ASR. The silica cation contents within the gel were relatively low; however, it was stated that the method used to digest the samples would not have dissolved all of the silica cations bound within other molecules. The pH of the samples was 10.65. The relatively low pH of the samples is likely related to carbonation of the samples prior to testing.

Plumbing Testing. The testing performed included static and flow testing on the wastewater plumbing and hydrostatic testing of the domestic water supply plumbing. The testing revealed no leaks present in the plumbing. Therefore, there was no plumbing-related water source beneath the slab.

Case Study 2 Key Observations

- Distress at the surface of the slab consisted of gel exudations and white residue.
- The distress reportedly began appearing approximately 6 months after the slab was poured.

- VCT flooring was installed throughout most of the building as a result of the presence of gel/residue, and distress then manifested at the VCT in the form of cracking, pitting, ridging, and debonding.
- The distress was present within the vicinity of the grade beams, and not within the fields of the slab.
- A vapor barrier was present within the fields of the slab, and was specified to be terminated at the sides of the grade beams.
- In-situ RH testing revealed a correlation between elevated concrete RH and the distress manifestation.
- Analytical elemental testing on gel samples revealed that the gel contained elevated levels of sodium and potassium cations, consistent with alkalis present in ASR.
- The levels of the fluid pH at areas exhibiting gel/residue was elevated, indicating that the pore solution within the concrete at the near-surface region was also elevated.

Case Study 3 – Residential Structure in Central Texas

The main differentiator for Case Study 3 versus the prior two case studies is the presence of a continuous vapor barrier below the grade beams (**Figure 15** and **Figure 16**), which was not present at the buildings in Case Studies 1 and 2. Information regarding construction/design documentation and photographs were provided to the authors by the structural engineer of record for the project.

The building foundation consisted of a post-tensioned concrete slab-on-grade with a specified 28-day compressive strength of 3000 psi and a maximum w/c ratio of 0.5. The concrete was specified to be normal weight with no addition of air-entrainment. The aggregates were specified to comply with ASTM standard, C33. The concrete mix design and composition of the cement was requested for review by the authors, but was not made available.

The intended flooring at the building was a polyurethane coating at the interior and exposed concrete in the garage. It was reported that pitting of the coating, and gel exudations, white residue, and discoloration began appearing at the top surface of the foundation in the garage in a checkered pattern (**Figure 17** and **Figure 18**) approximately 12 months after the foundation was poured.

Case Study 3 Key Observations

- Distress at the surface of the slab consisted of gel exudations, white residue, and discoloration.
- Distress at the coating at the interior of the building consisted of pitting.
- The distress reportedly began appearing approximately 12 months after the slab was poured.
- The distress was present within the vicinity of the grade beams, and not within the fields of the slab.
- A vapor barrier was present within the fields of the slab and below the grade beams.

Figure 15: Vapor barrier at the slab portions of the foundation (image included with permission).

Figure 16: Vapor barrier at the slab portions and grade beams of the foundation (image included with permission).

Figure 17: White residue and discoloration at concrete slab surface – note the checkered pattern (image included with permission).

Figure 18: Close-up view of white residue at concrete slab surface (image included with permission).

ANALYSIS

Many similarities existed among the subject cases for this paper. All of the concrete slabs-on-grade were designed for one-story structures and consisted of normal weight concrete with design compressive strengths of 3000 psi, and no addition of SCMs or air-entrainment. Also, all of the concrete slabs were intended and prepared to be exposed, with the exception of the interior at Case Study 3, which consisted of a polyurethane coating. Case Studies 1 and 3 consisted of post-tensioned foundations, while Case Study 2 consisted of conventional reinforcement.

The distress at areas of exposed concrete consisted of gel exudations, white residue, and/or discolorations that were present within the vicinity of the grade beams and did not occur within the fields of the slab. At the buildings with floor finishes, Case Studies 2 and 3, pitting of the finishes was present in the vicinity of the grade beams. Based on reported information and documentation by others, the NSASR occurred within 6 months to 17 months after construction of the slabs.

As previously discussed, the three main components necessary for ASR to occur in concrete are:

1. Elevated concrete RH,
2. Elevated pH in the pore solution, and
3. Susceptible aggregates.

Testing performed as part of this study confirmed the presence of these conditions in each case.

Elevated Concrete RH. The amount of moisture in concrete is greatest when the concrete is still in its fresh, plastic state. As the concrete cures, chemical hydration reactions cause an increase in the ratio of chemically bound water (unavailable to the concrete surface) to free water. This ratio continues to increase asymptotically with the age of the concrete, unless the concrete is exposed to an external source of free moisture in the form of a wetting event.

Free moisture will migrate through concrete as the relative humidity of the concrete equilibrates with that of ambient conditions. The vapor pressure differential caused by temperature and relative humidity differences between the concrete and the ambient conditions results in a driving force for moisture. Given that fresh concrete is effectively 100% RH, and a drying gradient develops toward the concrete surface, fresh concrete with a surface exposed to air equilibrates with its surroundings by desorbing, or emitting, moisture.

In order for the concrete RH to be elevated, a water source must be present. There are many sources of water for concrete structures, including internal water from mixing, water sources at the subgrade (i.e., plumbing leaks, standing water prior to construction, ingress from improper drainage, etc.), and water sources at the exposed surfaces. Popular hypotheses for the cause(s) of elevated concrete RH include elevated subgrade RH due to improper fill material in conjunction with improper site drainage, and the lack of a vapor barrier beneath the grade beams. The lack of a vapor barrier makes concrete elements susceptible to a continuous moisture vapor drive.

The analysis of the soil borings in Case Study 1 determined that the moisture content of the fill material and the clay soils below the fill were not significantly elevated. Based on the lack of a subsurface moisture source and the presence of a continuous vapor barrier below grade beams at the building in Case Study 3, it is the opinion of the authors that a primary source of moisture for the elevated concrete RH in the vicinity of the grade beams is the internal water from mixing. The larger volume of concrete within the grade beams in comparison to the fields of the slab would provide a significant source of moisture as vapor drive would cause moisture in the pore solution to migrate towards the top surface where the RH of the ambient air is less than the RH of the concrete. This continual movement of moisture to the top surface would cause the concrete RH to be near 100%, as the testing confirmed. The thinner concrete elements within the fields of the slab have significantly less internal moisture in comparison to the grade beams, and therefore exhaust sufficient moisture through vapor drive to have a lower RH, also confirmed by the testing.

Elevated Pore Solution pH. The pH levels in concrete are a function of the hydroxyl anion content present in the pore solution of concrete. As the concrete hydrates, the hydroxyl content increases, resulting in a very high pH environment. The typical pH levels of fresh concrete range

between 12 and 13. The surface of a concrete slab will react with carbon dioxide in air when the relative humidity of the concrete is typically between 40% and 90%, resulting in carbonation of the concrete. Concrete surfaces unable to carbonate due to excess moisture will retain a high pH.

Results of the petrographic analyses indicated that the concrete cores obtained from within the fields of the slab with no distress at the building in Case Study 1 exhibited a greater depth of carbonation in comparison to the cores obtained from the vicinity of the grade beams. pH level testing at the building in Case Study 2 revealed that the levels of fluid pH at the surface of the concrete were elevated at areas in the vicinity of the grade beams, indicating that the pore solution within the near-surface region of the slab had an elevated pH level. Conversely, the levels of fluid pH at the surface of the concrete within the fields of the slab were minimal, indicating that the pore solution within the near-surface region of the slab was not elevated. These results correlate with the depth of carbonation results obtained in Case Study 1 in that the areas in the vicinity of the grade beams had elevated levels of concrete RH and pore solution pH, and the areas within the fields of the slab had lower levels of concrete RH and pore solution pH.

Similar to the areas in the vicinity of the grade beams having higher concrete RH due to the higher volume of internal water in the grade beams, the grade beams also have a higher volume of alkalis available to migrate to the top surface and contribute to the elevated pH levels of the pore solution at the near-surface region of the slab in comparison to the thinner concrete elements within the fields of the slabs.

In addition to the alkalis available in the grade beams, the authors hypothesize that the inclusion of outside sources of alkalis likely contributed to the elevated levels of pore solution pH in the near-surface region of the concrete. Concrete slabs intended to be the finished flooring system are typically prepared with the application of densifiers and sealers that commonly include sodium and/or potassium, which are the alkalis present in the pore solution that contribute to elevated pH levels and ASR. The concentrated inclusion of alkalis to the top surface would significantly increase the pH levels in the pore solution in the near-surface region.

ASR Susceptible Aggregates. Petrographic analyses performed on concrete cores obtained from the building in Case Study 1 indicated that the fine aggregate contained susceptible aggregates that included chert, chalcedonic chert, and quartzite, and were distributed throughout the mixture. The analyses also estimated that the percentage of the susceptible aggregates was 3% to 4%. ASTM standard, C33 limits the amount of deleterious substances in fine aggregates to 3.0% (ASTM 2016). Therefore, the amount of susceptible aggregates within the concrete for Case Study 1 likely exceeded this limit, creating an environment for ASR to occur in conjunction with elevated concrete RH and elevated pore solution pH.

Alkali Loading of Concrete. Traditional ASR typically occurs in concrete structures that are designed for high compressive strengths, which include a higher cement content, and subsequently, the presence of more alkalis in the pore solution. This is referred to as a higher alkali loading (Farny and Kerkhoff 2007). Based on industry research, ASTM standard, C1778 *Standard Guide for Reducing the Risk of Deleterious Alkali-Aggregate Reaction in Concrete* recommends a maximum alkali loading of 3 to 5 lb/yd^3 (based on risk level) to prevent ASR from occurring (ASTM 2016). The specified compressive strengths for the buildings included in

this study would typically not include enough cement to create an alkali loading sufficient to initiate ASR. For the building in Case Study 1, based on the stated alkali content of the cement and the cement content in the concrete provided by the mix design, the alkali loading of the concrete would be approximately 2 lb/yd^3. Hence, the authors hypothesize that an alkali catalyst may have been present to initiate the ASR in the studied cases.

Mechanism of Observed Distress. The elemental analyses of the gel determined that the gel contained elevated levels of sodium and potassium, which are the alkalis present in ASR. The petrographic analyses determined that the gel exudations at the surface of the concrete were alkali-silica gel caused by ASR, and that the deterioration related to ASR was limited to the near-surface region of the concrete. The petrographic analyses also determined that expansion cracking related to ASR was limited to the near-surface region of the concrete, which did not manifest to the top surface. As previously discussed, traditional ASR typically occurs throughout the entire concrete member and results in map cracking, including at the surfaces of the concrete. The reported timelines of distress manifestation at the buildings included in this study ranged between 6 months and 17 months, which is significantly less than the timeline for traditional ASR, which is typically on the order of 10 or more years. Therefore, based on the reported information, observations, and testing performed, it is the opinion of the authors that the distress observed at the surface of the concrete and floor finishes at the buildings included in this study are the result of near-surface alkali-silica reaction (NSASR), which is a different mechanism than traditional ASR.

The authors hypothesize that the inclusion of outside sources of alkalis, such as the application of densifiers and sealers containing sodium and/or potassium during the preparation process for exposed concrete floors, likely contributed to the occurrence of NSASR. The primary reasons for this hypothesis is that the alkali contents of the concrete were not sufficient for the initiation of ASR as recommended within ASTM C1778 and that the ASR was confined to the near-surface region of the concrete where the application of products containing alkalis would be effected. Additionally, the accelerated timeline for the initiation of NSASR is consistent with the inclusion of a high concentration of outside alkalis at the top surface of the concrete.

Further, the distress to the finished flooring installed in the buildings in Case Studies 2 and 3 are the result of the occurrence of NSASR. Excess moisture at the surface of the concrete and elevated levels of pH can cause distress to flooring and degradation of the adhesive (Anders and Lars 2008). Both of these conditions were present at the surface of the concrete in the vicinity of the grade beams where NSASR occurred.

CONCLUSIONS AND RECOMMENDATIONS

Based on the patterns of distress and the testing performed at the buildings included in this study, the presence of gel exudations, white residue, and/or discolorations that were present within the vicinity of the grade beams at the top surfaces of the concrete slabs are the result of NSASR due to the following conditions:

- Elevated concrete RH at the near-surface region due to migration of the significant amount of internal mix water within the grade beams through vapor drive of moisture to the top surface of the concrete.

- Elevated pH levels in the pore solution at the near-surface region due to migration of the significant amount of alkalis within the grade beams through vapor drive of moisture in the pore solution containing alkalis.

- Presence of fine aggregates susceptible to ASR near the top surface of the concrete.

The authors hypothesize that the inclusion of outside sources of alkalis, such as the application of densifiers and sealers containing sodium and/or potassium during the preparation process for exposed concrete floors, likely contributed to the occurrence of NSASR. For concrete slabs intended to be exposed in the Central Texas region on projects with no available data on fine aggregates to be used, the authors recommend the use of densifiers and sealers that include lithium in lieu of sodium and/or potassium. It is commonly known in the concrete research community that lithium ceases the expansion of ASR gels (Farny and Kerkhoff 2007) (Thomas, et al. 2012). The downside to the widespread use of lithium-based products for the preparation of exposed concrete slabs is the significant increase in cost in comparison to products with sodium and/or potassium. Other measures to be taken include the use of SCMs such as Class F fly ash or natural pozzolans, which lower the pH in the pore solution and controls the expansion of ASR gel (Farny and Kerkhoff 2007) (Thomas et al. 2012).

FUTURE TESTING

Future testing is planned to be conducted in which concrete slabs with grade beams will be constructed and include various surface preparations in an attempt to initiate NSASR on a timeline similar to those encountered in the case studies. The sides and bottoms of the systems will be coated with a sealer to prevent the escape of moisture through those surfaces, similar to field conditions. Three systems will be cast and will consist of a control slab with only a trowel finish; a slab with a top surface preparation including the application of a densifier and sealer with sodium and/or potassium; and a slab with a top surface preparation including the application of a densifier and sealer with lithium. The slabs will be cast with normal weight concrete and a mix design with an intended compressive strength of 3000 psi. A fine aggregate containing reactive components similar to those present in Case Study 1 will be used in the mixture, with a percentage of approximately 3%. If initiation of NSASR occurs, additional testing will be performed, including petrographic analyses of cores, elemental analysis of gel exudations, and alkali content gradients through the depths of the systems.

Additionally, the alkali content gradients of the concrete cores extracted from the buildings in Case Studies 1 and 2 will be performed.

REFERENCES

Anders, Anderberg, and Wadso Lars. "Degradation of floor adhesives as a function of pH." *Polymer Degradation and Stability*, 2008: 329-334.

ASTM. *ASTM F710 Standard Practice for Preparing Concrete Floors to Receive Resiliant Flooring.* ASTM International, 2017.

ASTM. *C1778 Standard Guide for Reducing the Risk of Deleterious Alkali-Aggregate Reaction in Concrete.* ASTM International, 2016.

ASTM. *C33 Standard Specification for Concrete Aggregates.* ASTM International, 2016.

ASTM. *F2170 Standard Test Method for Determining Relative Humidity in Concrete Floor Slabs Using in situ Probes.* ASTM International, 2018.

Farny, James, and Beatrix Kerkhoff. *Diagnosis and Control of Alkali-Aggregte Reactions in Concrete.* Portland Cement Association, 2007.

Ignoul, S., F. Van Rickstal, and D. Van Gemert. "Blistering of epoxy industrial floor on concrete substrate: phenomena and case study." *11th International Congress on Polymers in Concrete*, June 2-4, 2004: 393-400.

Landgren, Robert, and David W. Hadley. *Surface Popouts Caused by Alkali-Aggregate Reaction.* Portland Cement Association, 2002.

Stark, David. *Handbook for the Identification of Alkali-Silica Reactivity in Highway Structures.* 1991.

Thomas, M.D.A., B. Fournier, and K.J. Folliard. *Selecting Measures to Prevent Deleterious Alkali-Silica Reaction in Concrete.* Washington DC: Federal Highway Administration, 2012.

Thomas, M.D.A., B. Fournier, K.J. Folliard, and Y.A. Resendez. *Alkali-Silica Reactivity Field Identification Handbook.* Final Report, Washington DC: Fedeal Highway Administration, 2011.