Suppressing Alkali-Silica Expansion

Using ECC for extended infrastructure service life

by Mustafa Şahmaran and Victor C. Li

The term "durability" does not stand for a special attribute of a concrete material in general but it rather signifies a conclusion reached after the material has been exposed to certain environmental conditions in which the structure serves. The material itself is called "durable" if, in its environment, it survives a desired service life without necessitating excessive costs for repair and/or maintenance applications caused by degradation or deterioration. The reason durability is being perceived vitally important for different infrastructure types is that it has a close intimacy with the basic mechanical properties—the lacking of which could result in structural breakdown at exorbitant deterioration levels.

Alkali-silica reaction (ASR)—one of the most commonly encountered problems contributing to the rapid loss in overall durability of concrete—is particularly important because the deteriorating effects of the mechanism may not be traceable for a very long time (10 to 30 years). This is a significant issue for critical infrastructure components such as highway bridges, pavements, and barriers[1]; airport pavements[2]; and railway ties.[3]

ASR is a deterioration mechanism that takes place between the individual components (cementitious paste and aggregates) of concrete. To be more precise, reactions occur when the siliceous constituents of reactive aggregates come in contact with alkali ions released into pore solution as a result of hydration reactions and/or provided externally into the cementitious system. The final product of ASR is the alkali-silica gel (Fig. 1(a)) surrounding the aggregate particles and/or propagating through cementitious paste. In cases where the reactive aggregates happen to be porous, ASR gels may form inside as well as on the surfaces of the aggregates. This gelatinous material, which might have variable composition and characteristics, is hygroscopic and swells as it imbibes water. The resulting pressures can produce internal stress levels of typically 3 to 4 MPa (440 to 580 psi). In some cases, the hygroscopically induced pressure has been reported to reach 8 MPa (1160 psi),[4] sufficient to cause cracking in most concrete structures.

When ASR damage takes place, concrete, as a characteristic feature, displays a network of cracks commonly labeled as "map cracking" (Fig. 1(b)). Alkali-silica gel can also emanate from the cracks and be seen as white residue on the surface of concrete.

For ASR to take place in a hardened concrete element, alkalis of cementitious paste, reactive siliceous aggregates, and water must be present simultaneously. Absence of one of these contributing factors would terminate ASR. Likewise, anything amplifying any of the three factors would lead to acceleration of ASR-originated deterioration. Cracks create preferential pathways where extra moisture and alkalis can be transported into concrete and therefore have very high potential for worsening ASR-based damage. Although, as of yet, it seems unrealistic to manufacture crack-free concrete, it is apparent that a material that possesses self-control of

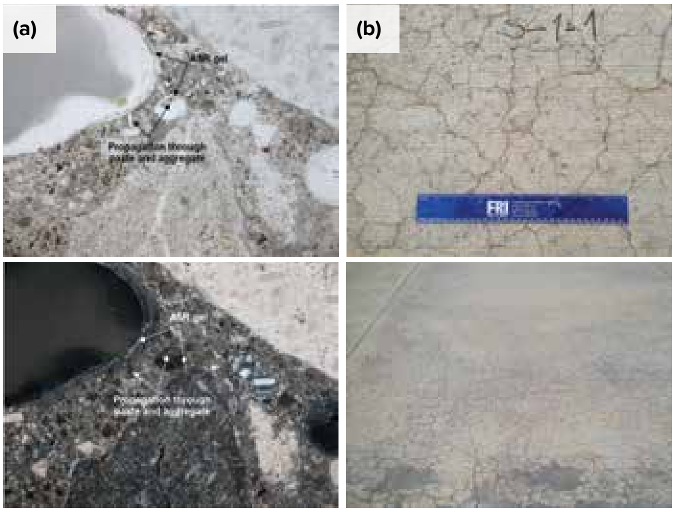

Fig. 1: ASR deterioration: (a) petrographic examination of 10-year-old ASR-damaged airport pavement (plane-polarized light image [top] and crossed-polarized light image [bottom]; and (b) typical severe map cracking as a result of progressive ASR in 10-year-old airport pavement

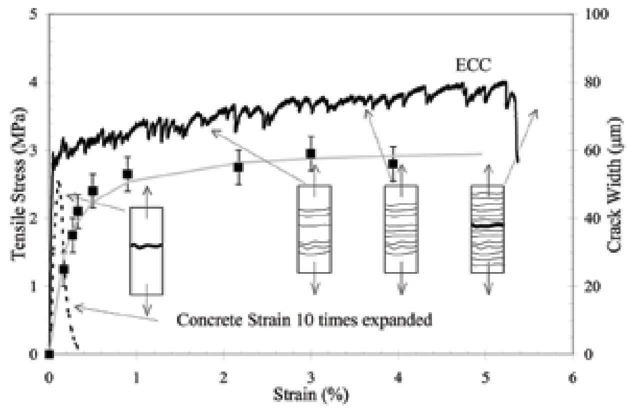

Fig. 2: Crack width in ECC self-controls to less than 60 μm (Note: 1 MPa = 145 psi; 1 μm = 0.00004 in.)

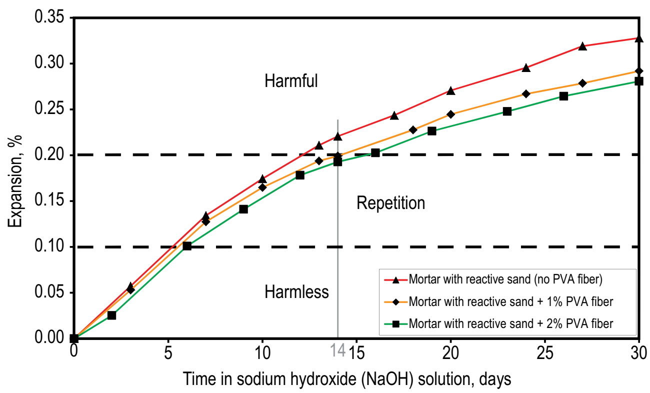

Fig. 3: Microfibers help to restrain ASR-based expansion of mortar specimens

Fig. 4: Typical formation of map cracking due to ASR damage in mortars without PVA fibers after 30 days of high alkaline exposure

cracking will have reduced risk of ongoing and accelerating ASR deterioration. In addition, cracks initiated by ASR will be more difficult to grow in length and width in such a material, resulting in space confinement for the gel, and slowing the continuing deterioration.[5]

Engineered Cementitious Composites

As one of a special kind of materials having controlled cracking behavior, engineered cementitious composites (ECCs) have been under development at the University of Michigan, Ann Arbor, MI, over the last two decades.[6] In contrast to conventional concrete, ECCs exhibit superior tensile ductility—several hundred times that of conventional concrete as well as exceptional energy absorption capacity that is similar to that of some metals.[7] Also, the average crack width for ECCs is self-maintained to less than about 60 μm (0.002 in.) under imposed strain of up to several percent. Figure 2 shows a typical tensile stress-strain relationship and associated crack width development for an ECC.

The exceptional ductile behavior and crack control of an ECC is grounded on the synergistic interactions among its individual components, namely fibers, cementitious paste, and the interface between the two. Even with multiple microcracks, ECC has been reported to remain durable under severe environmental exposures; this behavior has been attributed to the fact that the material has an intrinsic ability to keep crack width tight.[8] Intrinsic microcracking behavior of ECC could also be the key for enhanced durability in terms of ASR. The outcomes of an experimental study on ASR performance of ECC are reviewed in this article, in light of field experiences.

ASR Testing

Mortars with different amounts of PVA fibers

While ECC can be produced with different fiber types (for example, polyethylene or polypropylene), in the present study, the focus was placed on ECCs with polyvinyl alcohol (PVA) fibers. The influence of PVA fiber content on ASR performance of mortar mixtures (not ECC) including reactive silica sand with maximum aggregate size (MAS) of 4 mm (0.2 in.) was evaluated for mixtures with fiber volumes of 0, 1, and 2%. The PVA fibers were 8 mm (0.3 in.) long and 39 μm (0.002 in.) in diameter and had nominal tensile strength of 1320 MPa (190 ksi) and a Young's modulus of 42.8 GPa (6210 ksi). Mortars were prepared and tested according to ASTM C1260, "Standard Test Method for Potential Alkali Reactivity of Aggregates (Mortar-Bar Method)." Results obtained after exposure to sodium hydroxide (NaOH) solution at 80°C (176°F) for 30 days are shown in Fig. 3 in terms of percent length changes of prism-shaped specimens.

The horizontal reference lines included in the figure indicate the standard's nonmandatory ASR expansion limits at 14 days after immersion in the solution. Expansions less than 0.10% (labeled "Harmless") are indicative of innocuous behavior in most cases; expansions of more than 0.20% (labeled "Harmful") are indicative of potentially deleterious expansion; and expansions between 0.10 and 0.20% (labeled "Repetition") include both aggregates that are known to be innocuous and deleterious in field performance. In the latter case, additional testing is recommended.

ASR-induced expansion is observed immediately, regardless of the amount of PVA fibers. The resultant damage after 30 days reveals the typical map cracking in specimens without PVA fibers (Fig. 4).

However, it appears that incorporation of PVA fibers in mortar bars with reactive aggregates has a positive influence on the ASR resistance. The specimen without PVA fibers had expansion in the "Harmful" zone at 14 days after immersion, while the specimens with 1 and 2% PVA fibers had expansion in the "Repetition" zone at 14 days. These findings are in line with several studies showing reduced cracking intensity, narrower crack widths, and lower maximum crack depths of ASR-susceptible mortars reinforced with fibers.[5,9-11]

Mortars with different aggregate types

For ECC mixtures to exhibit superior tensile ductility and multiple microcracking behaviors, they are typically produced using powdery silica sand (microsilica sand), although aggregates with different types and sizes can also be used.[12] To better understand the effect of this component on ECC mixtures, mortar specimens produced with microsilica sand with MAS of 400 μm (0.02 in.) and mortar specimens produced with reactive silica sand with MAS of 4 mm (0.2 in.) were tested per ASTM C1260. No PVA fibers were used in the mortars. Mortar specimens produced using reactive sand had expansions within the "Harmful" zone at 14 days of exposure, while mortar specimens produced with microsilica sand exhibited low levels of expansion, even after 30 days of NaOH solution exposure (Fig. 5).

Mortars with different fly ash types

Incorporation of supplementary cementitious materials such as fly ash, slag cement, and limestone powder in ECCs will lower the cement content and thus reduce the cost and environmental impact of ECC production. Two fly ash types were evaluated for their effects on ASR expansion in ECCs. Class C fly ash with high lime content (FA-C) was used to produce C-ECC mixtures, and Class F fly ash with low lime content (FA-F) was used to produce F-ECC mixtures. The composition and physical properties of the portland cement and fly ashes used in the study are shown in Table 1. Two different amounts of each fly ash type were used in the mixtures. The fly ash-portland cement ratio (*FA*/*PC*) in the ECC mixtures was either 1.2 (55% fly ash by weight of total cementitious material) or 2.2 (70% fly ash by weight of the total cementitious material); refer to Table 2. All ECC mixtures were prepared with a water-cementitious materials

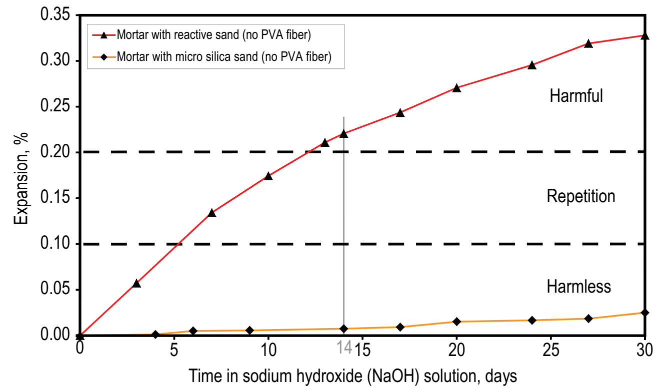

Fig. 5: Mortar specimens made with microsilica sand show substantially lower ASR expansion that that of mortar with reactive sand

Table 1:
Composition and physical properties of portland cement and fly ashes

Chemical composition, %	PC	FA-C*	FA-F*
CaO	63.3	25.7	7.8
SiO_2	19.6	31.4	58.8
Al_2O_3	5.9	18.5	17.7
Fe_2O_3	3.4	5.2	5.4
MgO	0.95	6.4	—
SO_3	2.5	2.4	0.8
K_2O	0.54	0.48	0.56
Na_2O	0.47	2.2	1.5
Loss on ignition	3.0	0.2	0.3
Physical properties			
Specific gravity	3.18	2.78	2.35
% retained on No. 325 sieve	—	13.8	24.3

*Both fly ash Classes FA-C and FA-F contained considerable amount of alkalis

Table 2:
ECC mixtures with fly ash for ASR testing

Mixture ID	Portland cement (PC)	Silica sand	Reactive silica sand	*w/cm**	FA/PC	PVA, kg/m³	HRWRA†, kg/m³
F-ECC-1.2	1.0	0.80	—	0.27	1.2	26	4.2
F-ECC-2.2	1.0	1.16	—	0.27	2.2	26	3.0
C-ECC-1.2	1.0	0.80	—	0.27	1.2	26	4.6
C-ECC-2.2	1.0	1.16	—	0.27	2.2	26	3.5
F-ECC-1.2R	1.0	—	0.80	0.27	1.2	26	4.2
F-ECC-2.2R	1.0	—	1.16	0.27	2.2	26	3.0
C-ECC-1.2R	1.0	—	0.80	0.27	1.2	26	4.6
C-ECC-2.2R	1.0	—	1.16	0.27	2.2	26	3.5

*cm is cementitious materials (portland cement + fly ash)

†HRWRA is high-range water-reducing admixture

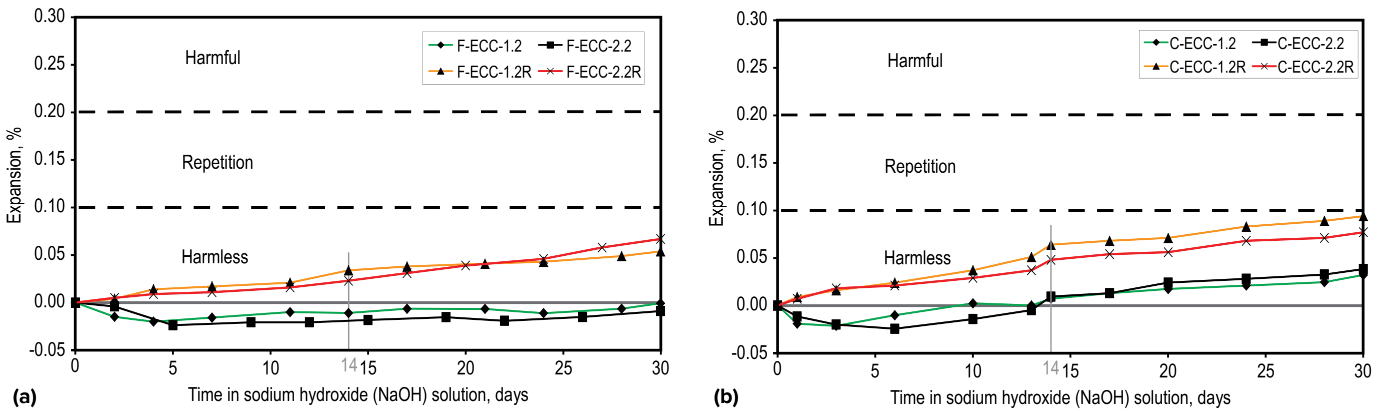

Fig. 6: ECC with different fly ash types shows little ASR-based expansion: (a) Class F fly ash; and (b) Class C fly ash

Fig. 7: ECC patch repair placed alongside concrete patch on Michigan bridge deck

ratio (*w/cm*) of 0.27 and two different sand types (microsilica sand and reactive silica sand). Mixtures produced with reactive silica sand with MAS of 4 mm include "R" in the mixture ID (Table 2). Figure 6 summarizes the results of tests conducted per ASTM C1260 on mortar bars produced using the ECC mixtures.

Figure 6 clearly indicates that ECCs, even after 30 days of severe alkaline exposure, are safe against ASR, regardless of the amount and type of fly ash used in the mixtures. Moreover, negative effects of reactive silica sand use on ASR damage seem to be inhibited to a great extent when fly ash was incorporated in ECC systems. When microsilica sand was used in the production of ECC mixtures, reductions in the percent expansion results became even more evident. In some instances, especially those with Class F fly ash, contraction took place in specimens. This contraction can be attributed to the autogenous shrinkage of the mixture's highly packed cementitious pastes with very low *w/cm*. The remarkable effect of different fly ash particles (especially Class F fly ash) in decreasing the ASR-based damage can be due to the reduction of calcium hydroxide amount as a result of further pozzolanic reactions.[13] The high fly ash content is also expected to refine the pore structure, reducing alkali diffusion from the host solution into the sample and binding the alkalis into pozzolanic calcium silicate hydrates.[13-15]

Although Fig. 6 shows that all mixtures performed well, ECCs with Class F fly ash performed better than ECCs with Class C fly ash. Compared to the FA-C particles, the FA-F particles have lower total alkali content and higher pozzolanic capacity. Therefore, specimens incorporating Class F fly ash particles are more likely to have reduced alkalinity of the pore solution, particularly at the later ages of the test.

The superior performance of ECC mixtures with Class F fly ash can also be due to the fact that F-ECC specimens tend to exhibit narrower crack widths,[16] restricting the ingress of alkaline solution during ASR testing. The ASR mechanism may be further suppressed when space is not available for gel generation due to intrinsically tight crack widths in ECC, consistent with the observations of Ostertag et al.[5] Moreover, narrower cracks have been reported to be sealable, with the effect of self-healing even under severe alkaline environment.[17]

Field Application of ECC

One of the first field applications of ECC was its use as a patching material to repair a concrete bridge deck in Michigan. The project was completed in cooperation with the Michigan Department of Transportation (MDOT) in 2002. A complete summary of this work can be found in Li and Lepech.[18] Repairs were made using ECC as well as a commercially available concrete patching material commonly used by MDOT (Fig. 7). The two patching materials were installed side by side and at about the same time (1 day apart), and thus they were subjected to identical environmental conditions and traffic loads. Between 2002 and 2007, the condition of the ECC patch was continuously monitored. Only minor microcracks, with widths limited to less than 50 µm (0.002 in.), were found. Figure 8 shows the recorded maximum crack width and surface conditions of the two

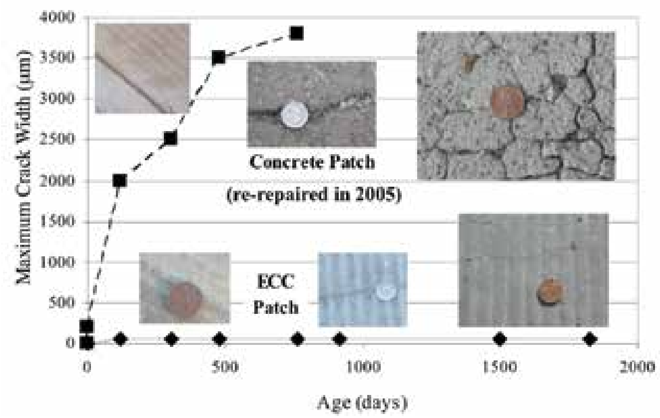

Fig. 8: Maximum crack width development in concrete and ECC repair reveals no ASR in the ECC patch (Note: 1 μm = 0.00004 in.)

patches during this period. No signs of ASR were found in the ECC. In contrast, the concrete patch showed ongoing increases in maximum crack width, reaching widths exceeding 3.7 mm (0.15 in.) by 2005. The concrete patch was re-repaired in 2005. By 2007, MDOT determined that deterioration of the deck was sufficient to warrant a complete deck replacement.

Another field application of ECC is a "link slab" in a two-span bridge. The first application of this type was completed in cooperation with MDOT in 2005 (Fig. 9(a)). In this use, the material ductility of ECC is leveraged to replace problematic expansion joints between adjacent simple spans with a ductile ECC slab linking the spans.[19] In the 2005 project, about 32 m^3 (42 yd^3) of ECC were mixed and placed using standard ready mixed concrete trucks.[20] With a strain capacity exceeding 2%, the link slab material fully accommodates the thermal and live-load deformations of adjacent bridge spans. After 10 years of service, the link slab (Fig. 9(b)) continues to function as intended, without repair or maintenance. No signs of ASR are evident.

Summary

Due mainly to the limited durability of conventional concrete, concrete structures tend to have a shorter service life than expected. At the root of this problem is the brittle nature of concrete. To overcome this persistent problem, ductile ECC can be effective in eliminating the need for repeated maintenance. Given that cracks tend to accelerate the deterioration by creating additional pathways for aggressive agents, many durability problems can be reduced and/or overcome by the high ductility and self-controlled microcracking behavior of ECCs.

Along with many other mechanisms affecting the durability of infrastructures, ASR has been shown to be harmful, especially for concrete structures subjected to prolonged service periods. While ECC applications in the field have been relatively recent, the limited experience indicates that ASR is not a concern for structures comprising ECCs. This is

Fig. 9: After 10 years of service, the ECC link slab on Grove Street Bridge, MI, shows no ASR damage: (a) immediately after construction in 2005; and (b) in 2015

corroborated by laboratory test results that demonstrate the ASR suppression mechanisms of ECC—high pozzolanic material content, nonreactive aggregates, and microfibers. ECCs therefore exhibit small pore sizes and low alkali concentrations in the pore solution; ECC aggregates are less likely to form hygroscopic gels; and ECCs exhibit self-control of crack widths to less than 60 μm, reducing the potential for intrusion of damaging water. The evidence shows that ECC can serve as a durable material for repairs, airport pavements, railway sleepers, and other structural elements prone to ASR attack.

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Note: Additional information on the ASTM standard discussed in this article can be found at **www.astm.org**.

Selected for reader interest by the editors after independent expert evaluation and recommendation.

Mustafa Şahmaran is an Associate Professor in the Department of Civil Engineering at Gazi University, Ankara, Turkey. His research interests include advanced materials technology and composite materials development for sustainable infrastructures.

Victor C. Li, is the E. B. Wylie Professor in the Department of Civil and Environmental Engineering at the University of Michigan, Ann Arbor, MI. His research interests include the micromechanics and design of ultra-ductile and green cementitious composites, their application to innovative and sustainable infrastructure systems, and integration of materials and structural design.