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Discussion

A discussion of the paper "Mathematical model for kinetics of alkali–silica reaction in concrete" by Zdeněk P. Bažant and Alexander Steffens☆

G.M. Idorn*

Tovesvej 14B, DK 2850 Naerum, Denmark

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Many researchers with experience in the occurrence and effects of alkali–silica reaction (ASR) in concrete structures will be interested in this paper. Laboratory testing models have, even after about 60 years research and use for engineering practice, not been able to show whether reactive aggregates may cause harmful or harmless ASR in field concrete [1]. The test methods are modelling either the kinetics, such as silica dissolution in NaOH, ASTM C289, or chemical shrinkage in closed reacting systems [2], or the mechanics, with linear expansion as the effect of the chemical reaction, such as ASTM C227. The methods have not been developed for combined utilisation or engendered substantial studies of their underlying interdependence. Consequently, more realistic ASR-simulating modelling studies are of interest.

The following remarks concerning the authors' basic model, as depicted in their Fig. 1 (p. 422), intend to offer information for a supplementary or alternative model that synthesise numerous investigations since the 1940s of ASR-affected field concrete structures in many countries. They are comprised of macro-/microexaminations with thin section microscopy, XRD, SEM, chemical analyses, etc. The achievements from these, now worldwide, undertakings constitute a well-founded, integrated chemical/mechanical story of the nature of ASR, although admittedly, without the creation of a general mathematical model.[1] With the announced aim to do that, the authors concentrate on the kinetics of the reaction, leaving the modelling of the mechanics to a future second part. However, the mentioned heritage of ASR knowledge offers indispensable information on the inseparable applicability of the kinetics and mechanics, and is therefore related to the subject of both the present and the forthcoming paper.

Before discussing the basic issue of modelling, a comment about the initiating research referred to — the use of waste bottle glass as concrete aggregate — seems warranted. Why not use the glass, finely ground, as a pozzolan rather than facing all kinds of problems with broken glass flake aggregates on building sites and in concrete production? Such an alternative recycling processing seems reasonable, since the researchers are mentioned to have made the startling discovery that crushing the glass to about 0.1-mm grain size renders it nonexpansive alkali-reactive. In fact, Vivian [3] made this discovery in 1951 with opal as aggregate and Bredsdorff et al. [4] established the interdependence of particle size and expansivity for Danish porous flint in 1966. They included the ratio of reactive-to-inactive material and the alkali concentration of the system as parameters [4]. Their study was closely related to a contemporary investigation of the preventive effects on ASR of different siliceous materials in pozzolanic particle size ranges by Andreasen and Haulund Christensen [5]. In fact, the interdependence of the particle size of reactive aggregates and the mode of ASR as either harmful, harmless, or beneficial (pozzolanic) now seems to be generally acknowledged by the industries concerned and in much of the engineering practice.

Returning to the main objective of the paper, the following characteristics of ASR in field concrete ought to be incorporated in the creation of mathematical models:

- Aggregates in concrete are due to processing circumstances usually presaturated by water and therefore attaining cement paste pore liquid saturation in the course of the

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* Tel.: +45-4580-0856.

E-mail address: gunnar.idorn@get2net.dk (G.M. Idorn).

[1] The references for documentation, with few given exceptions, are omitted due to the tremendous amount of literature on the subject, such as the proceedings from the 11 international conferences on AAR since 1974, several books, and numerous articles in different research journals.

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hardening of concrete. (Flakes of bottle glass, granulated slag, and other melted materials excepted.)

- The pore liquid of cement paste is a saturated $Ca(OH)_2$ solution. The $Ca(OH)_2$ concentration is depressed by the presence of alkali hydroxides and in the case of temperature rise during hardening of concrete and during exposure in warm environments.
- The absorption of calcium ions by the alkali–silica gel makes it rigid and nonswelling.
- In closed systems, likely to exist frequently in field concrete, the creation of alkali–silica gel causes shrinkage, not swelling.
- As a hydration reaction, the kinetics of ASR follows Arrhenius' law.

The chemical characteristics correspond to the consistently observed mechanical effects of harmful ASR in field concrete:

- Expansive pressure, due to gel formation, develops at reaction sites inside the reacting particles. This was first observed by Mielenz and Witte [6], then described by Mc Gowan and Vivian [7], Mather [8], and Idorn [9], and subsequently in case study investigations from all over the world.
- It is the swelling of the gel in the reacting particles that causes their cracking and causes the cracks to pass out in the much weaker, ambient cement paste. Expansive reactions in cement paste in concrete, such as freeze–thaw or DEF, do not cause cracking of the 8–10 times stronger aggregate particles.
- Gel, which exudes out in the cracks in the paste, does not exert pressure due to its solidification by the calcium enrichment.

These comments about ASR in actual concrete are meant to suggest adjustments of the chosen model basis. Further discussion may appear of interest to the announced, second paper on the modelling of the mechanics of ASR. The mechanical model studies [10–12] should be considered in such a progressive model development.

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