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ALKALI–SILICA REACTIONS IN RETROSPECT AND PROSPECT

G.M. Idorn

G.M. IDORN CONSULT A/S
Blokken 44, DK-3460 Birkeroed, Denmark

1. ABSTRACT

This paper is a personal review and evaluation of essential features and accomplishments of the research and engineering practice regarding alkali silica reactions in concrete from 1940 until now. The development is divided into two epochs. First, the 1940 to 1960 decades during which concern appeared primarily in the USA, Australia, England and Denmark. Thereafter, the 1960 to 1989 span of years during which the reactions attracted attention all over the world and launched concurrent research and engineering precautions.

Conclusions resulting from 37 years of personal participation in research, consulting services and international cooperation are presented for consideration to those who are going to continue the research and technology development.

2. THE FIRST DECADES OF RESEARCH AND PRACTICE WITH ASR

Building and constructions became a mandatory part of the societal development already during the 1930's, and concrete assumed an increasing role in complying with the demands. The discovery of alkali silica reactions became an outstanding example of how international cooperation could make research efforts profitable for applications under different circumstances in the countries involved, primarily the USA, Australia, England and Denmark, as briefly reviewed in the following.

2.1 USA 1940 - 1960

The discovery in 1940 of alkali silica reactions in concrete in California made this kind of deterioration the subject of public concern and research all over the states. This was associated with the contemporary boom in construction and the concurrent increase in cement consumption, and also with the basic research funded by the American cement industry. The nature of alkali silica reactions as inherent chemical reactions in concrete, which might cause mechanical damage in the form of cracking in concrete structures and sometimes expansions or warping of elements of structures, was explored. The overall access to low alkali cement and to pozzolans made it attractive for engineering and the public construction agencies to rely on a general, non-restrictive policy regarding the use of susceptible types of aggregates.

The combined research/engineering approach also made it possible to adopt an integral testing and examination system all over the states. The chemical reactivity of aggregates received its particular test, coupled with the test of the mechanical effects, cracking and linear expansions of mortar bars. However imperfect and simplistic these two tests were, considered as models of alkali silica reactions in concrete structures, their general reproducibility in the United States was ensured by comprehensive round-robin testing. The participation of geologists and mineralogists warranted that petrographic examinations of aggregates became part of the precautionary examination system, and also of research on the nature of the reactions and their effects in concrete.

The complex geology across the United States ensured that alkali silica reactivity once and for all became identified as a chemical reaction between alkali hydroxide and any susceptible silica modification in mono or polymineral, siliceous rocktypes, and not empirically confined to one or a few specific kinds of aggregates. The participation of geological and mineralogical expertise also helped to conceive that "concrete is geology alive". Thereby, the methods applied in field geology and in the related laboratory studies became successfully introduced for examination of field concrete. Considering the comprehensive investments in American research, it is not surprising that so many of the accomplishments have remained essential for later research and development elsewhere of testing methods and precautionary measures.

In hindsight it is of interest to note that the American studies were not concerned with the amount of undamaged field concrete with alkali silica reactions. Laboratory studies had revealed the "pessimum proportion" perception, which implied the existence of a "threshold" concentration of the alkali hydroxide in the cement paste, and observed the required abundance of moisture as a vehicle for making the chemical reactions proceed in concrete (and in mortar bar testing). These findings were not used for comparative "sample" studies of the behaviour of field concrete. Like ever since that time the behaviour of concrete structures without damage was rarely examined. Neither were studies made of the absence of gross expansion in members or sectors of affected concrete structures in many cases, and of the gradual termination in the reactions in the course of 10 - 20 years in most affected structure, due to exhaustion of moisture and alkalis. (It is remarkable that subsequently, older mass concrete dams in the USA, which represent environments with abundance of moisture and long-term migration potential for alkali hydroxide, have been shown to cause alkali silica reactions to continue and cause partial structural expansions over about 30 - 40 years before termination, notably without causing structural unreliability).

The tradition and facilities available for research in those days, together with the predominantly temperate to warm environments in those regions, where construction development was intensive, caused that the interdependance of the rate of alkali silica reactions on temperature did not become a matter of concern. Neither was attention drawn towards the synergy of deleterious alkali silica reactions through warm summer seasons and freezing/thawing damage through cold winters. De-icing of highway structures was not introduced before later on and the aggravating influence on alkali silica reactions of sodium chloride was therefore not made the subject of studies.

2.2 AUSTRALIA 1947 - 1961

In 1947 the public CSIRO of Australia became concerned about the possibility of the occurrence of alkali silica reactions in concrete structures in the country because silica-rich volcanic rocks and secondarily weathered igneous rocks were commonly used as aggregates. Moreover, the extensive occurrence of opal - though not used as aggregates in concrete - probably played a part. The most informative and thorough long-term study ever performed on the influence of physico/chemical and mechanical parameters on the course of alkali silica reactions were then performed by CSIRO scientists in the course of the next fourteen years, resulting in altogether 27 published reports. Apart from the first introductory study these were based upon experimental mortar bar testing with opal as the reactive aggregate. This long-term study represented an exceptional and coherent investigation of the various parameters which influence the course of alkali silica reactions, such as: particle size ranges, amounts of opal to inert aggregates, levels and migration of alkali hydroxide, w/c of the cement paste, pozzolanic materials, etc. The thoroughness of these series of experiments is still outstanding among previous and later studies elsewhere using mortar bars. In contrast, the research apparently did not return to studies of alkali silica reactions in concrete structures in Australia. No structures were reported to have been investigated as a result of deleterious alkali silica reactions, and no correlations were sought between the research accomplishments and the behaviour of field concrete. No studies dealing with the susceptibility of aggregates other than opal were undertaken. Neither was the secondary silicification of crystalline, igneous and volcanic rocks, due to the effects of the special hot climatic conditions in large parts of the country, further considered.

2.3 ENGLAND 1947 to 1958

Like the Australian CSIRO, the Building Research Station in England became concerned in the late 1940's. The American research had found chert and flint to be susceptible, and the abundance of flint in gravel and sand in South England therefore made it urgent to assess whether flint in England might also cause deleterious reactions. Meticulous research and testing resulted in the general conclusion that the flint used at that time did not cause deleterious alkali silica reactions in mortar bars or in concrete, even if made with high alkali British cement. No concrete structures with evidence of deleterious reactions were found or brought to the attention of the BRS research during the years of the programme. Close contacts and cooperation with the research in Denmark further convinced the BRS that while flint in Denmark in some cases did cause deleterious reactions, the geologically older types of British flint were not deleteriously reactive. This message settled the issue of alkali silica reactions in England until 1976. Actually, the British studies confirmed that alkali silica reactions, while occurring in concrete with siliceous aggregates, usually do not cause damage to field concrete.

2.4 DENMARK 1951 - 1967

The Danish research on alkali silica reactions resembled the preceding American research in that its outset was the occurrence of deleterious reactions in concrete structures. Structural expansion and warping were found in a few concrete bridges where concrete pillars were exposed to continuous absorption of sea water. Elsewhere the field evidence of damage was map-cracking, gel exudations and pop-outs, but no structural expansions. It was different to the American conditions in the sense that all concrete aggregates used in Denmark contained flint but not other reactive rock types. The investigations of structures 1952-54 confirmed that the reactions in most cases did not cause any damage. The Danish cement industry developed an "alkali resistant cement", consisting of a low alkali Portland cement interground with 10-12% pozzolan (calcined moler) as a non-compulsory precaution, available from about 1957. The research relied heavily upon contacts and exchanges with the efforts in the USA, Australia and England. Extensive mortar bar experimental testing revealed dependancy of the course of the reactions on the particle size range, the porosity and the quantity of the reactive particles vis a vis the alkali content. The development pioneered a systematic field investigation procedure, comprising the first transportable concrete core drilling equipment, macro and micro core examination procedures, and the manufacture of epoxy impregnated thin sections for petrographic examination of the microstructure of concrete. This development resulted in a diagnostic system for identification of the effects of deleterious alkali silica reactions, freezing/thawing, sulphate attack, aggressive carbon dioxide attack and weathering in field concrete.

In severe cases of alkali silica reactions combined with percolating sea water, intensive crystallisation in cracks of ettringite, aragonite, gypsum and magnesium hydroxide was found. Freezing and thawing were found to cause alterations in the crystallisation of calcium hydroxide, and aggressive carbon dioxide to cause the formation of a calcium aluminate hydrate. Alkali silica reactions were found to cause the formation of alkali silica gel with varying contents of calcium. Complex deterioration was sometimes also found to break down the original cement paste into impure silica gel and carbonates. A broad variety of flint types were characterized and their characteristics related to their susceptibility.

2.5. THE 1960 PERSPECTIVE

The research from 1940-60 in the countries referred to above was to a large degree complementary. This was to some extent because the activities had very different conditions regarding cement and aggregates, industry structures and research. It was also because there were powerful research and professional bodies able to assume managerial influence, combined with insight, regarding the scientific aspects. Furthermore, intensive, free exchange was created among the research professionals. The investigations clearly played a part in classifying alkali silica reactions as a matter of concrete technology, i.e. initial costs and later on sometimes repair needs. In no cases did problems of sudden collapse risks emerge, and no cases of structural failure became associated with the occurrence of alkali silica reactions.

The public agencies, the engineering professions and the industries in the USA became, with good reason, satisfied with the precautions and testing system arrived at there; the British and the Australian research dismissed the problem as nationally irrelevant. In Denmark, effective precautionary measures were made available, but largely the engineering professions and their clients accepted the observed low risk for getting deleterious reactions. Alkali resistant cement, granitic coarse aggregates and flint-free sand were only rarely used during the next decade.

Seen from the research point of view, the complementary international efforts had revealed essential aspects of the basic chemical nature of alkali silica reactions, and also quite a few issues worthy of more exploratory research. Petrography of concrete had been recognized as a powerful means of investigating concrete and suitable methodology and procedures had also been developed. The issue of the environmental influence on the course of alkali silica reactions, especially humidity and temperature, had been approached in relation to the development of the test methods. This was due to the requirements for having access to the evaluation of the reactivity of aggregates with shortest possible notice rather than waiting 6 to 12 months. The influence of these parameters were neither scientifically related to basic silica chemistry, nor to the course of the reactions in concrete structures dependant upon their environments. Neither were the reasons for the apparently common occurrence of harmless alkali silica reactions - Eastern USA, England, Australia, Denmark - in concrete with susceptible aggregates, vis a vis the more rare cases of deleterious reactions, recognized and made the subject of systematic research.

Nevertheless, taken as an entity of acquired experience of alkali silica reactions, theoretically and in concrete structural practice, the 1960 state of the art knowledge represented a formidable basis for the elaboration of engineering applications.

Today in 1989, this knowledge basis could profitably be researched for updating expert systems which are desirable for use under the current and future changed circumstances.

3. THE BROADER INTERNATIONAL DEVELOPMENT 1960 - 1989

The above reviewed accomplishments of the research on alkali silica reactions from 1940 to about 1960 resulted in that research and engineering thereafter concentrated on other issues of concrete technology. This was associated with the concurrent advance of knowledge in concrete design, with mechanisation of concrete production, and with considerable progress within cement manufacturing technology and cement strength increases. The societal value of these developments created new research priorities.

In most countries where alkali silica reactions had not yet been found to occur, this was apparently considered a fortunate convenience which ought to, and was widely believed to, remain unaltered. Late in the 1960's this perception was shattered in some European countries and during the early 1970's deleterious reactions appeared in concrete structures in several countries in Europe. Concern was also renewed in Denmark mainly due to damage observed in newer highway structures, where precautions had not been taken (alkali resistant cement, coarse granite aggregates and flint-free sand imposed premium cost on the concrete).

There were two primary decisive factors which were not at that time recognized as reasons for re-evaluations regarding alkali silica reactions.

Firstly: The concrete technology and construction development raised the cement content per m^3 of concrete significantly during the late 1950's and onwards. Consequently, the alkali concentration also increased vis a vis the calcium concentration in the pore liquid of the concrete.

Secondly: The rapidly increasing building and construction enterprises consumed correspondingly increasing quantities of concrete aggregates. Natural aggregate resources are by nature not homogeneously deposited, if sedimentary, nor of gross homogeneity, if solid rocks. In Europe occurrences of aggregates in the Nordic Inland Seas, the North Sea, the Channel (and bays of the Atlantic Ocean around Iceland) became major new sources of sea-dredged materials. At the commencement, these were not washed to remove the salinity. In most countries outside the USA, petrographic examination of aggregates and testing of their alkali reactivity were neither requested nor carried out. Consequently, the use of susceptible aggregates increased along with increasing alkali concentrations in concrete.

During the early 1970's some researchers therefore found that renewal of the international exchange was justified and gathered in Koege, Denmark, in 1974, initiating thereby inadvertently the series of international conferences on alkali aggregate reactions of which the present one in Kyoto, Japan, is the eigth. The published proceedings from the preceding conferences and additional research studies elsewhere represent such a tremendous amount of effort and results that a synthesis cannot be made in the present brief review. Certain issues ought, though, to be mentioned as gradually having created changes in emphasis of research programmes and policies:

Alkali aggregate reactions became, expecially due to early and later Canadian experience, recognized as comprising alkali carbonate and alkali silicate reactions. However, in the global picture alkali silica reactions have so far appeared to predominate, and a review about alkali carbonate reactions is left to the Canadian experts by the writer.

Alkali silica reactions have now appeared to occur in practically all parts of the world, and the increasing occurrences are clearly reflected in the proceedings of the conferences. Practically all kinds of aggregates have also appeared to be potentially reactive. Limestone may be reactive because its geological origin has often introduced a certain content of susceptible interstitial silica in the calcitic morphology. Volcanic rocks may have sufficiently variable contents of glassy silica to cause varying extents of reactivity. A variety of sedimentary, solidified and low metamorphic rock types are likely to contain silica of low crystallinity. Igneous and volcanic rocks may contain distorted, crystalline quartz which is susceptible due to internal stresses.

The use of concrete has steadily increased since the 1960's. Concurrently, old and new aggregate resources have been increasingly exploited, and their characteristics changed without being recognized, where engineering has relied upon conventional standard specifications and testing methods. Likewise, the development of cement manufacturing technology has tended to increase the alkali contents of Portland cement, and civil engineering has further increased the cement contents of concrete. Thus, from a concrete composition viewpoint, the potential for alkali silica reactions have gradually increased, as the actual development has also shown.

The increasing uses of concrete have since the late 1960's occurred more and more in developing countries and regions in the warmer belts of the earth, where experience with the characteristics of aggregates are the least known, and where rejection of potentially reactive materials may be economically unfeasible. Recent years of investigations of deleterious reactions in rather new structures in tropical regions suggest that geological and climatic conditions may render originally innocuous, crystalline rock types secondarily silicified, and susceptible. Such potential reactivity may also occur in such rock types which today are found in colder regions, if warmer climates have prevailed in past geological periods.

The elevated chemical reactivity in concrete in warm climates relative to constant + 20°C or colder environments has not appeared as the subject of thorough research regarding constructions in the "sun belts" of the world. Civil engineering has therefore not been advised through research about the aggravating effects of heat.

The progressive development of the design and construction of concrete buildings and structures have made these more sensitive to damaging reactivity, and public attention has escalated this issue into concern about structural unreliability. However, all published evidence show that even severe surface cracking due to alkali silica reactions does not penetrate deep into concrete bodies, and confirm the reliability of the ordinary structural systems in reinforced concrete. Consequently, remedial work can always be undertaken well ahead of the progress of cracking which might initiate corrosion of the reinforcement, and thereby reduce the performance capability.

Looking through proceedings of the preceding conferences one observes increasing emphasis on the development of new testing methods in many countries. The original ASTM mortar bar test is still the predominant basis, and a wide variety of later adjustments have not changed its principal aim, to reveal the potential reactivity of a certain aggregate. The Nordic mortar bar test which uses storage in saturated NaCl solution at + 50°C for reduction of the required duration of the test has, like the original ASTM C-227 test, been subjected to comprehensive round-robin testing. Several other new test methods have not been taken through similar pre-acceptance trials. While the 1940 - 1960 decades represented intensive international exchange and cooperation, the recent developments seem to rely significantly more on individual, institutional or national efforts with each their own particular signature.

Procedures for case investigations of concrete structures have been considerably developed since the pioneering 1940 - 1960 decades. In some cases such procedures have almost been standardized with the risk that procedural compliance prevails over the individual experience and basic comprehension for interpretation of observed evidence of damage. Also the incorporation of drilled core samples in case investigations for micro and macro examinations have been developed with the concurrent requirement that cores are understood to represent concrete inwards perpendicular to external surfaces. This means that in most cases observed evidence of damage will not be representative of damage to the interior concrete or in the longitudinal direction of concrete elements under examination.

Case investigations made in recent years suggest that without additional supplies of alkalis and moisture, alkali silica reactions, even if occurring with initial high alkali concentrations, will usually mature and cease in the course of about 15 - 20 years, more in very cold environments and less in hot countries.

In recent years, monitoring of the structural effects of alkali silica reactions and means of mitigating or arresting reactions in progress have also become interesting for owners of buildings and structures. Major case investigations have shown that assessments of structural expansions and warping or displacements require careful pre-planning and execution because the reactions are of widely different, local intensities. Monitoring of surface cracking cannot reliably measure overall effects of the reactions in a concrete body, element or sector, and especially not be taken as measures of gross expansions.

Theoretically, the role of the calcium:alkali ratio in alkali silica reactions, and the calcium aluminate of the cement and chloride ions has attracted attention in recent years. It has also been substantiated that the hydration of blast furnace slag, fly ash, silica fume and natural pozzolans in concrete are alkali silica reactions in advantageous modifications and may effectively prevent deleterious reactions.

Changes of the research organisation and funding in many countries have mitigated long-term strategic planning of the research on alkali silica reactions, and have tended to advance concentrated national efforts rather than international integration, and also short-term problem solution activities at the expense of the classic basic oriented, exploratory research.

4. DESIRABLE CONTINUATION OF RESEARCH ON ASR

The following proposals for further international exchange and cooperation are offered on the basis of close to 40 years of personal experience with alkali silica reactions in concrete.

* More and better quantified assessments of why the major part of concrete structures built with reactive aggregates up until the present have been affected by harmless reactions, even where they occur alongside structures of practically identical concrete which have developed severe damage.

* Influence of deleterious alkali silica reactions on the structural capability of certain special types of concrete structures, like for instance, unreinforced dolosses in breakwaters, and reinforced concrete exposed to advanced corrosion as a result of deep surface cracking.

* Coordinated research for mutually acceptable test methods. Clarification of the aims of testing, and concurrent research for modelling of the course and effects of alkali silica reactions in concrete structures.

* Theoretical and applied studies of the influence of environmental conditions - heat, moisture, salinity - on the course of alkali silica reactions.

* Preparation of engineering guidelines for effective prevention of deleterious alkali silica reactions, and for effective development of advantageous alkali silica reactions by means of blast furnace slag, fly ash, silica fume and natural pozzolans.

* Further assessments of the effectiveness of monosilanes for the termination of deleterious alkali silica reactions in concrete.

* Application of basic silica and surface chemistry knowledge and microfracture mechanics for updating theoretical perceptions of alkali silica reactions.

* Creation of national commitments to contribute continuous recording of published articles regarding alkali silica reactions, theory and practice. Compilations of such continuous recording as key-worded, generally available data bases.