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THE RELEVANCE OF RESEARCH ON ALKALI-AGGREGATE REACTIONS TO PRECAUTIONS IN CONTEMPORARY ENGINEERING PRACTICE

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SYNOPSIS

Increasing uncertainty in predicting the course and effects of alkali-aggregate reactions on concrete structures and the resulting concern in engineering practice, are discussed.

Over the last 30 - 40 years civil-engineering has emphasised the development of construction and design rather than concrete technology. This is considered to be a major cause of severe concrete deterioration problems which include the alkali-aggregate reaction.

Revised guidelines for the optimisation of precautionary measures are presented, and suggestions for contemporary research are discussed.

The term alkali-silica hydration is introduced as being a more accurate description of the reactions being dealt with.

SAMEVATTING

Groeiende onsekerhede in die voorspelling van die gang en uitwerking van alkali-aggregaatreaksies op betonstrukture en die gevolglike besorgdheid in die ingenieurspraktyk, word bespreek.

Gedurende die afgelope 30 - 40 jaar het die siviele ingenieurspraktyk eerder die ontwikkeling van konstruksie en ontwerp as die tegnologie van beton beklemtoon. Hierdie benadering word beskou as een van die hoofoorsake vir die ernstige probleme met verswakking van beton insluitend alkali-aggregaatreaksie.

Hersiene riglyne vir optimale voorsorgmaatreëls word gebied en voorstelle vir eietydse navorsing word bespreek.

Die term alkali-silikahidrasie word voorgestel as synde 'n korrekter beskrywing van die reaksies waarmee te te doen gekry word.

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INTRODUCTION

The last 30 years' development in concrete design and construction practice has imposed demands on concrete as a material, which it cannot always comply with, if made and used according to conventional specifications. This discrepancy causes, among other things, deleterious alkali-aggregate reactions to require more concern and repair work than in the past. Another consequence is that the achievements of research on alkali-ggregate reactions cannot be implemented because responsibility in the case of failure or repair would be allocated on the basis of compliance with specifications, however irrelevant these may have been under specific job conditions. This lack of return on the investment in free research tends to force researchers into one of two possible areas of investigation.

Either they must operate on the solutions to short-term problems within the framework of established practice and regulations, or they may confine their attention to long-term physico/chemical work with but little background in and impact on engineering problems, and often with neither in mind.

Altogether, this general picture (which is not without exceptions) provides less than in the past an actual and forward oriented service on the part of research to contemporary engineering design and construction.

In view of the present and future need for concrete, the industry deserves all possible support from science and technology, (see Table 1, page 2). Also because, as everybody knows, concrete can in fact be made so as to be practically indestructible, (see Figure 1).

This paper aims to bridge, to some extent, the gap between research and practice, which the above trend has caused to widen during the last decades. It attempts to emphasize the best possible advice one can give civil-engineering about how to reduce the risk of getting alkali-aggregate reactions as a serious contributor to structural distress, despite compliance with precautionary measures taken from acknowledged regulations and testing.

FIGURE 1 : Concrete in the Colosseum in Rome (after 80 AD). The Roman builders developed hydraulic mortars by mixing lime and pozzolanic fine sands with water. This reacting system was prepared, placed and compacted with great skill and patience. It worked without noticeable heat development during hydration, took a long time to harden and became thereby resistant to environmental aggressivity. With lime as the major reactant, the alkalis in the pozzolans could not gain any deleterious influence, despite that many of the volcanic aggregates were probably reactive themselves.

At the same time, the paper aims to expose to research those classic concepts in present concrete technology which in particular invite updating, and thereby to stimulate the introduction of thermodynamics and reaction kinetics in advanced research programmes.

Undeniably, for contemporary civil-engineering practice, some uncertainties about the alkali-aggregate reaction cannot be eliminated at present - but they are worse when they show up as deterioration after a construction has been made, than when considered at the design stage. Specialists can help a lot, if asked the right questions a sufficiently long time in advance of site-commitments for new construction and building enterprises.

TABLE 1: Projection to the year 2000 of cement production per capita and corresponding consumption of water and aggregates in concrete. Population is assumed to be 6000 million. By far the largest growth of concrete usage will be in the developing countries, and knowing how to prevent deleterious alkali-silica reactions has great potential value[1].

CEMENT kg/capita	Billion tons		
	Cement	Water	Aggregates
300	1,8	0,7	17
400	2,4	1,4	23
500	3,0	1,8	28

THE DR JEKYLL - MR HYDE CONCEPT

There is a tempting allusion in designating the research on alkali-silica reactions as being the Dr Jekyll - Mr Hyde alkali-silica garden theatre.

First, alkali-silica reactions really ought to be called alkali-silica hydration reactions, because by nature they are akin to any other hydration process within the cement/concrete system. Thus, in fundamental research they belong indispensably to the studies of the complex hydrated-phase-diagrams, and ought to be an appreciated subject of a noble, truth-searching Dr Jekyll-science approach, just as the calcium-silicate hydrates have been now for such a long time.

Second, the kinetics of alkali-silica hydration considered in terms of geological science represent exceptionally fast authigenic transitions of inorganic phases, so remote from thermo-dynamic equilibrium that initial, violent conversion of even small quantitites of energy may cause considerable and lasting, qualitatively different courses of the subsequent reactions. Neither pure geology nor basic cement-paste research have many other low-temperature reacting systems, which are so pronounced as to represent almost logarithmic compressed in time' models of long-lasting conversions of mineral phases and which are accompanied by such spectacular effects as those occurring in the conglomerate concrete: violent dissolution of solid rock particles, accompanied by distorting expansive pressures and intense migration of substances in the pore-liquid.

FIGURE 2: Most houses in Reykjavik, Iceland, are built of solid concrete. Changing building habits during the late '60s have caused alkali-silica hydration to become a cause of intensive cracking. The consequent repairs and added depreciation costs are more unpleasant for the individual, who puts his life savings into a house than for public bodies or industry which own plant and buildings which continuously form part of the earnings for depreciation.

Third, the civil-engineer should, deep in his heart, appreciate that the expansive power exerted during the development of the alkali-silica hydration in concrete masses, frequently exceeds what he pays for to achieve with specially produced cements for pre-stressing or shrinkage compensation, or by pre- or post-stressing the concrete reinforcement. It ought to be attractive to find ways to harness and utilize this inherent energy in concrete.

Then there is, unfortunately from a convenience point of view, the Mr Hyde side of the coin. The expansive power of alkali-silica hydration has, so far, proved rather uncontrollable in practice. The only completely safe precaution is to use no more than insignificant quantities of the ingredients of the 'drug', alkalis, silica and water together. However, the general industrial economics and engineering requirements demand that the alkali-content of cement increases and the cement-content of concrete increases; the selection of safe aggregate turns out to be ever more difficult and uncertain, and concrete making methods, which promote expansive reactions are becoming more commonplace both in hot countries, and in heavily urbanised regions. And even precautionary materials like pozzolans and fly-ashes, or seemingly innocuous aggregates may add 'drug injections' in the form of available alkalis. In fact, several case-studies in recent years have demonstrated that in any concrete under design or investigation one must consider the entire reacting system.

It is not enough to control the alkali-content of the cement, or the mortar bar expansions of 'crushed down' aggregates, or their pessimum proportions, or to rely upon automatic, 'safe' reactions with pozzolans.

This does not encourage that researchers continue to experiment with simplified models of the alkali-silica hydration reaction, or with studies of the 20 ^{o}C isothermic hydration of the ternary (N, K) S, H-system. Although both approaches are rewarding in their own right, as 'Dr Jekyll' - truth searching efforts, the 'Mr Hyde' face of alkali-silica hydration will meanwhile continue to spread and probably increase early deterioration in concrete constructions and buildings. This in turn demands not only capital and people to repair and maintain buildings but denies energy and resource conservation and incurs expenses beyond the justified expectations of the public.

Figure 2 shows how the innocent must suffer. No research in the world could at the proper time have told how to prevent the deleterious reaction.

TABLE 2 : Preferential materials precautions, and a check list for corresponding engineering options. Optimum selction from these, and concurrent risk analyses ought to form part of contemporary design procedures for concrete structures

PREFERENTIAL MATERIALS PRECAUTIONS	OPTIONAL ENGINEERING PRECAUTIONS
ALKALIS Low alkali content in conrcete	1. Low alkali cements (< 0,3 - 0,4% equivalent Na_2O) 2. Low cement-content 3. Slag cements 4. Low alkali pozzolans (< 1,0% equivalent Na_2O)
SILICA Low content of available silica confined in aggregate particles	5. Basic igneous, metamorphic and sedimentary rocks with stable crystallized silicates and silica 6. Calcium carbonate rocks 7. Synthetic aggregate without metastable silica
CONCRETE COMPOSITION AND MAKING Low level of convertible energy concentrations within aggregate particles	8. Low level of available energy in aggregate particles X alkalis 9. Low heat development during curing 10. Low water-content
CONCRETE PERFORMANCE Low quantity of liquid as migration vehicle for energy and flow activation in the concrete pore system	11. Low heat exposure 12. No saline intrusion 13. High compactness 14. 'Drying' exposure and design

THE BEST ADVICE TO ENGINEERING AT THIS TIME

There is an urgent need to establish what dependable precautions are available at present after about 40 years' research in this field.

It must also be assessed fundamentally what is decisive for the deleterious course of the reactions, in order to stimulate research to look for refined means of cure, so that the development of cement and concrete technology economy soon can attain a stage, at which to be bothered the least possible by alkali-silica hydration - maybe even advanced by unforeseeable, new discoveries.

Table 2 summarises what can be said today to the civil-engineer on the subject of precautions to avoid the deleterious effects of the alkali-aggregate reaction. It is derived from practical experience and research.

The table encompasses parameters, which are not much dealt with in present regulatory practice, which more often than not also disregards the availability of resources. This means that a civil-engineer, who is preparing a cost/benefit and risk-analysis, to aid in subsequent engineering decisions, may need guidance beyond his own interpretation of the information in the table.

TABLE 3 : Engineering guidelines for obtaining satisfactory performance reliability from concrete structures and buildings without blindfolded responsibility.

GUIDELINES FOR THE DESIGN OF PERFORMANCE RELIABLE CONCRETE with special regard to alkali-silica hydration
Step 1: Design in accordance with the structural performance requirements.
Step 2: Design for resistance to environmental energy activation: heating/cooling wetting/drying saline/acidic at any stage from the time of mixing, through placement and curing to performance under load.
Step 3: Check the resulting design specifications according to step 1 + 2 against optional engineering precautions as listed in Table 2.
Step 4: Re-adjust the resulting design, if required, to reach the desired risk level.
Step 5: Check compliance with, or request dispensation from, regulatory specifications, or accept the resultant risk of excessive maintenance/repair expenses.
Step 6: Detail the required testing and control specifications.

For those exercising special expertise the principal contents of the table may serve as a starting point for job-specific investigations. These may well need to go in depth into the impact of changes in one or another of the influential parameters. It is recommended that the system be fully controlled, so that no factor that may influence the product be ignored, simply because existing regulations take no cognizance of it.

The special design check list procedures listed in Table 3 are recommended for all construction and building projects for which Table 2 does not give the answers in sufficiently practical terms. And the suggested procedures are by no means ineffective. This is because in many regions experience from practice can sustain the empiric knowledge about which ranges from reasonably safe to definitely unsafe sets of parameters, one is dealing with. And also, because more detailed calculations regarding the concrete curing conditions, water-content etc. may reveal an additional possibility to reduce the calculated risk.

For this approach Figure 3 (Idorn[2]) page 5, ought to be kept in mind. It says that it does not suffice today to apply the very simple precautionary measures which were established during the '50s in the USA, and which served effectively there, because they were related to concrete compositions and manufacturing practices which are now obsolete.

These regulations have not prevented severe cases of deleterious alkali-silica hydration appearing in the USA and elsewhere later on both with low alkali-cements, and with officially acceptable, yet expansively reacting aggregates.

Neither do the classic precautions take account of 'grades' of environmental aggressivity, which any risk analysis today must consider seriously. Moreover, classically accepted pozzolans may be found to contain significant amounts of alkalis, and thus be risk-increasing rather than precautionary, and therefore need to be scrutinized beyond the standard and code requirements.

The study of any complex of conditions must also include the reaction-kinetics which governs the heat/strength development in a particular concrete work, (see Figure 4).

Design procedures in accordance with these guidelines will enable a specific project risk analysis to evaluate the risk situation. With the research knowledge at hand it is hardly practical to define the risk much closer than to say that that there is 'none', or that it is 'small', 'medium' or 'high', except where special job-specific research can be carried out.

THE NEED FOR RESEARCH

All things considered alkali-silica hydration leans more to the Dr Jekyll side than towards Mr Hyde, because much knowledge exists which has not yet been properly disseminated for use in practice. On the other hand, as long as fundamental problems remain unsolved, uncertainty as to the economics of precautionary measures will persist. Further changes in cement and concrete technology though independent of the alkali-silica hydration issue, may yet influence its cause and effects.

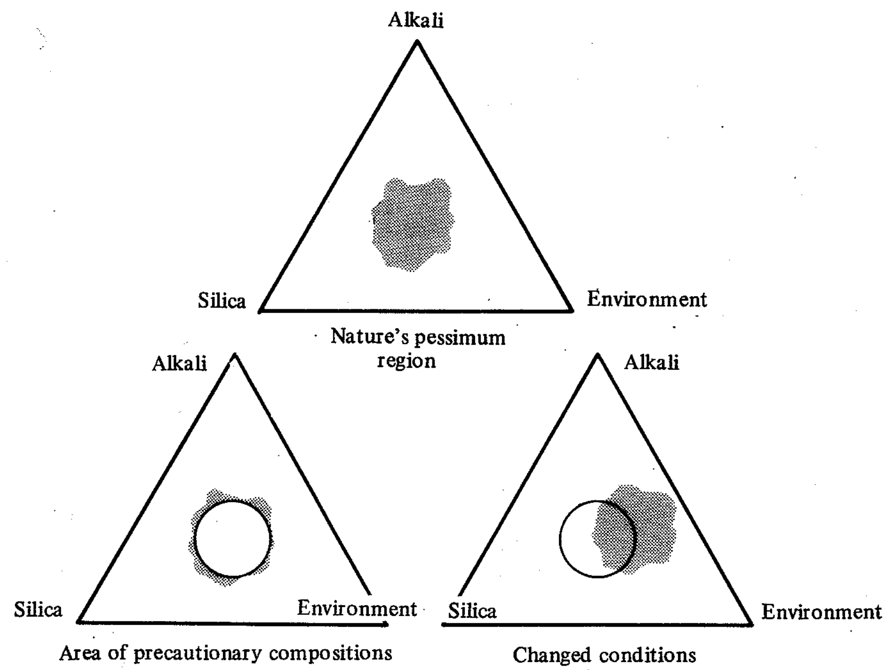

FIGURE 3: American research on alkali-aggregate-reactions attained during its first decade a remarkably useful identification of the 'pessimum region' in the alkali-aggregate-environment system, well related to the construction practices of those days. Corresponding regulations advising designers to avoid the encircled pessimum conditions made alkali-aggregate-reactions a matter of either paying for precautions with a probability of suppressing the reactivity, or knowingly taking the risks.
Concrete composition and construction practice, types of aggregates, environments, etc, have now changed so much that where regulations are largely unchanged there may be a considerable risk that the pessimum conditions sneakily have moved, and in some cases even grown as a result of factors such as higher cement-content and higher alkali-content in cements. As a result conventional safety factors become rather formal and unsuitable as a starting point for further investigations[2].

To summarise the state of research on the subject at present:

(a) We do not know how alkali-silica hydrates can be manipulated to make them stable, or at least unable to convert to expansive alkali-silica gel complexes after solidification. The discovery of a stabilizing compound or a concrete processing procedure, which would eliminate the expansive capability and reversibility of gel formation, would be a major break-through. Before this is attained some doubt must also remain as to the long-term effects of pozzolanic admixtures, as well as the interpretation of laboratory experiments concerning expansive reactivity, ie about the expansive potential of concrete containing any quantity of reactive aggregate.

(b) We do not know how the considerably higher early curing temperatures in most modern concrete affect the course of the alkali-silica hydration compared with the 20 ^{o} - 40 ^{o}C isothermic storage of laboratory specimens. We know the basic laws of time/temperature dependency for cement paste hydration, (P Freiesleben Hansen[3]), but not its significance for alkali-silica hydration in practice, under a variety of reaction-kinetic conditions.

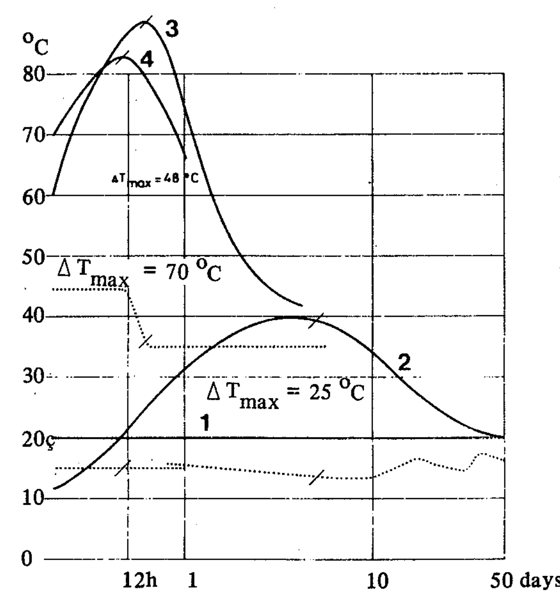

FIGURE 4: Temperature/time development in laboratory concrete or mortar specimens (1); in mass concrete the Hanstholm pier 1951 (2); in contemporary mass concrete constructions in a hot country (3); and in a temperate, coastal climate (4). Curves (2) and (4) are derived from actual measurements; (3) is calculated as part of an investigation, showing severe, early microfracturing due to rejected heat of hydration, while (1) is the basis for most research predictions and quality control in the world today.

DISCUSSION

Dr F G Buttler (Teesside Polytechnic, England) said that he was delighted to hear that someone had found some potassium in the gel. Chemists knew that the size of the hydrated potassium ions was smaller than that of the sodium ion, and that if one was diffusing alkali metal ions through a gelatinous system the smallest one should go through fastest. He referred to some work Mr Vivian had done a long while ago where he had found that the reaction rate of silica with LiOH had been much less than with NaOH and KOH. It was well known that if one put the alkali metal ions down an ion exchange column the caesium would come out of the bottom first and the lithium last. He suggested it would be very interesting for someone to do the experiment with a concrete containing caesium, because then the gel would perhaps be a caesium silicate as there would be a continuous change through the system depending on how far those ions had moved. In connection with the temperature rise during cement hydration, he felt it was a logical result, because the phase composition in Portland cement had unquestionably changed and there was more tri-calcium silicate now than previously. The current temperature rise would be greater. This phase composition change in Portland cement had to be considered when this very complicated alkali-silica reaction or any question on the durability of concrete was discussed.

Dr Idorn said in principle he thought it was very necessary at the moment for construction engineers to develop and implement risk analyses on a probability basis. They had been doing this in the larger companies for a time because the insurance companies had asked them to do so. He wanted to emphasise to the researchers that civil engineering forced one to introduce probability analysis, in the evaluation of the research results and in the use of them for standard specifications, because the ultimate figures dealt with there, could increase reliability.

(c) We know that alkali-silica hydrates sometimes cause expansion, but have not identified the decisive parameters in enough detail to make general predictions suitable for concrete mix design and casting procedures.

(d) We know that individual aggregate particles may expand and fracture the surrounding paste or mortar. We also know that huge masses of concrete in dams, slipways, bridges, etc., may become displaced and cracked by interior expansion, (Coombes[4], 1976). However, it is not yet possible to establish correlations between the inherent reactivity of a certain type of aggregate and the expansive effects in concrete.

(e) A related problem is that while we know something about the basic expansivity of gels, we still cannot explain how concrete masses as a whole can expand, or how the particularly expansive compounds are created in some circumstances, yet replaced by non-expansive compounds under other conditions.

(f) We know that inhomogeneities in reacting particles and the migration of alkalis and pore-liquids in concrete exposed to external energy (heat, humidity, etc) may distort the use of any recommended practice based on generalised results achieved under laboratory conditions. But we do not know much about fracture mechanics related to partial gel-formation in dense, reactive rocks, or to the optimum/pessimum conditions for the accumulations of alkalis and hydroxides etc at reaction sites, and the good versus bad effects of such migrations.

Civil-engineers should not anticipate that research soon can present solutions to all the above and related problems because there is a great deal of basic information to be collected before researchers can develop the foundations for a new set of working practices.

On the other hand, the time has come, when civil-engineers should ask researchers not to continue investigating earlier findings in ever greater detail. These had their roots in past engineering practice, and in over-simplified laboratory models. Instead researchers and engineers should get together to conduct up-to-date problem analyses which should then form the basis for identifying the most pertinent unsolved problems and the most promising routes to achieve safe, economical, solutions.

CONCLUDING REMARKS

Alkali-silica hydration in concrete is only one cause of growing world-wide concern over the unsatisfactory performance reliability of structures and buildings. Therefore it might be thought that a re-orientation in research thinking is not justified in relation to the importance of the issue. However, the adjustment needed in relation to alkali-silica hydration will lead to the acceptance of concepts which will be relevant to the whole field of concrete technology development, including such problems as sulphate attack and the corrosion of re-inforcement.

This perspective is not massive expenditure on new research, but rather to economise by channeling some of the ongoing work into more rewarding goal-setting.

The rewards are foreseeable: the removal of uncertainty from practising engineers, plus the elimination of unnecessary costs and the consumption of resources on repairs to structures. Much can be achieved with existing knowledge. It is only necessary to use that knowledge adequately to design effective concrete technology for each specific structure along with the structural design and the specifications for the job-operations.

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