30 YEARS WITH ALKALIS IN CONCRETE

by

G.M. Idorn D.Sc.
G.M. Idorn Consult ApS, Naerum,DK

*"The announcement of a new conception
is just as much an event as the com-
munication of a new experiment. In
fact, this will only gain an impact
which may be great or small, through
its association with the theatre of
ideas".*

H.C. Ørsted in his autobiography

ABSTRACT

Needs and opportunities for improvements of the durability of concrete by uti-
lisation of its content of alkalis are outlined. The increasing concern about
concrete deterioration in many countries represents the needs, while the long-
term research and research exchange preceding the present conference, the a-
vailability of cement substitution materials and the development of cement ma-
nufacture technology are the primary causes for the emerging opportunities.

The reactions between alkali hydroxides and silica in concrete are designated
hydration reactions. On this basis a conceptual approach is suggested to al-
kali-aggregate and to pozzolanic, fly ash, blast-furnace slag and silica fume
reactions in concrete. With particle size distributions and energetics consi-
dered decisive parameters it is explained how the reactions of the alkali hy-
droxides with the cement substitution materials may ensure incorporation of
alkalis in the basic cement paste morphology during its hardening and thereby
provide high denseness and resistance to well hardened concrete.

The two-phase conception of the reactions: "during the concrete curing at ele-
vated temperatures, and during the subsequent performance at ambient tempera-
tures" is emphasized. The development of powerful tools for examination of the
reactions with alkalis in concrete is discussed also as guidance for revisions
of testing principles and methods. In ways the classic tests do involve par-
ticle size distribution and kinetics as parameters, but hitherto not in a sy-
stem approach aiming at international consensus and based upon contemporary
concrete practice and basic physico/chemical theory.

Recommendations are presented for application of research for quantification
of design of concrete compositions and processing monitoring so as to make ef-
fective use of the reactivity of alkalis in concrete.

KEY WORDS

Alkalis, Fly ash, Slag, Concrete

INTRODUCTION

It is tempting to make this address a narrative of a long-term international advance of technology know-how which from its early days has enjoyed intense voluntary cooperation between science and engineering, authorities and industries and in particular within a group of scattered, dedicated people.

Such a story would, though, easily assume the flavour of a grandfather's tales. That would be justified if we were gathered to terminate research efforts of global applicability, and now settling opportunities and problems with alkalis in concrete once and for all, some forty years after discovery of their potentially venomous chemical energy.

But the basic issue of the conference is not one of terminating the established research exchange. It is much more to stimulate to new development with a background of urgent demands for solutions to problems which have accompanied the research and practice over the years like demons. They have indeed repeatedly been exorcized, but mostly in vain.

The energy crisis, which has been blamed for evil changes in our societies since 1973, has in fact sharpened the technical means for exorcism of the alkalis in cement. Concurrently, the various cement substitution materials have presented options for beneficial utilisation and accommodation of the alkalis in concrete to a formerly unthinkable extent of availability, and some of these materials are almost intoxicatingly addicted to alkalis.

The emerging new technology development becomes economically attractive with the growing costs of capital investments and energy consumption in cement industries, with increasing needs for selective utilisation of the natural resources, especially aggregates, and with the soaring expenses to repairs and replacements of concrete structures.

To these new conditions for the work with alkalis in concrete, primarily based upon the situation in the old world, comes now with increasing emphasis the effects of what is happening in "the third world" from which representatives of more than 1100 million people are present, more indeed than all the rest of delegates represent together.

This is why the conference also ought to be made an offer of new opportunities to the developing countries, not a transfer of unsolved problems.

Thus, altogether, the discussions will no doubt reflect a rare clash of new opportunities with needs for immediate service to engineering practice and for planning of further research to match changing conditions.

THE STRUCTURE OF THE CONFERENCE

Where does the civil-engineer fit into this presentation of the conference theme? He does in the way that design and making of 8000 million tons concrete a year over the world are the foundation for social life and progress everywhere on the earth and will remain so longer than we can see into the future.

Therefore, both the responsibility to use alkalis in concrete to the benefit of users, and the blame for deterioration and for accompanying waste of resources rest with the engineers.

But if for this obvious reason the civil-engineer is pushed forward in the conference assembly - and this has been a desire on the part of the organizing body - is then not the scientific research inevitably to feel or actually be less effectively brought to bear, compared with the course of preceding meetings?

The conference is intended to prove differently. There are in fact already new basic findings and updated implementation of research on alkalis in concrete under forceful outfolding, and the deliberate research and practice approach is chosen with the purpose to enrich the communication for both sides of the professional community.

Somebody present may still fear that if such science/engineering confrontations become catalytic stimulation for new progress of alkali-incorporating technology, how can then resources be found at all to make it be implemented, while recessions everywhere are cutting down on innovative efforts both in research and practice.

To this one must say: don't forget the young people. If the conference leaves a trail of new thinking and dedication with its contributions and discussions, then there will come unpredictable resources to continue the work. That is in fact, why the organizers have placed a session on the professional education and training early on the program, Avowedly, that is an unusual issue to bring into interference with science and technology discussions. But it corresponds to the belief that the conference is more an opening to new trends in the research than a salute to terminated accomplishments.

The domicile of our meeting has a basic awareness of clashes between science and technology. When the father of the Technical University of Denmark, H.C. Ørsted, discovered the electromagnetism in 1820, he considered it a confirmation of the existence of a superior divine ruling of nature's forces. He had no visions in the direction of future utilisation of electricity. Even some years later, when he discovered that metallic aluminium could be made by electrolysis, he did not envisage any practical applicability. Denmark in those days saw science as a cultural entity, not a basis for technology development.

About hundred years later when Th. E. Stanton in California discovered the reactions between alkalis and silica in concrete, this was a progress attained by trouble-shooting research for engineering technology, and the fundamental scientific aspects of this kind of reactivity attracted only minor resources. Inadvertently this created a lasting picture of alkalis as almost evil things - a discriminated minority, which one should rather have as little of in cement as possible.

To lift the issues out of this unduly bias does, in fact, require that science be restored in its recognition as the indispensable fundament for technology involving alkalis in concrete.

INDUSTRIAL ASPECTS

The reference to Ørsted's classic, academic emphasis on science per se (as far as his physical discoveries go) in conjunction with Th.E. Stanton's phragmatic use of chemical knowledge to solve an engineering problem, makes it natural that the first theme to be discussed by the conference is the industrial aspects of alkalis in concrete.

The accumulation of knowledge on the high temperature side of the "alkalis in cement" theme is startling, and truly enviable seen from the low temperature, concrete side. There is much more knowledge established in the first realm, than what can effectively be utilized in the latter.

It seems clear that the primary motivation for the cement equipment makers and the cement producers: "to save energy", for a long while has been a driving force for efforts to learn about alkalis in the cement, and how to remove them efficiently when need for that arises. One must remember that until a few years ago, many cement companies preferred to serve their customers with high-alkali cements due to the beneficial effects on early strength. Sometimes their concern has been traceable about the continuing infection of deleterious alkali-silica reactions "over the borders" from one country to another. The general move towards low-alkali preference has, therefore, rarely been a straight-forward one, cost and marketwise seen.

Surely high-alkali cements will gain appreciation again. The appearance of the cement substitution materials, (or mineral admixtures), suggests that the knowledge from the cement chemistry might be used in exploration of the characteristics and effects of alkalis on natural pozzolans, fly ash, slag and silica fumes, and also in approaches to the complex effects of alkalis, when present both in cement, in the substitution materials, and sometimes also in the aggregates or intruding from the environment. Work on these issues is in rapid progress, and the potential benefits are promising.

The availability of more than 300 mill ts/year fly ash and more than 200 mill ts/year blast-furnace slag in the world today with 30-50% cement replacement capability (or more in the case of slag) is a driving force of inherent development energy which cannot be neglected. The exciting reactivity demonstrated with silica fumes can almost be designated a "purified" proof of the opportunities for use of the less refined fly ashes and slag, and the natural pozzolana available.

THE BASIC THEORY ISSUE

The first session on the effects of alkalis in concrete deals with the basic physico/chemical issues. We certainly have experienced that without clarification of the basic nature of the effects of alkalis engineering practice cannot be effectively served: neither in technology development, nor for prevention of deleterious reactions.

More overbridging system approaches between the anhydrous and the hydration kinds of reactivity or, in other words, more joint work on the alkalis in cement and their effects in concrete, would be fruitful. Fortunately, in recent years there are moves in this direction.

However, even within the "hydration-research community" itself after more than 40 years' activity there does not seem to have been reached much of a consensus on the fundamental nature of the alkali-silica reactivity.

Much disciplinary chemical knowledge on stochiometry, osmotic theory based investigations, surface chemistry etc. has been scholarly applied and constitutes altogether an impressive accumulation of assessments. - But it has yet to be comprehended, communicated and applied as the wanted entity.
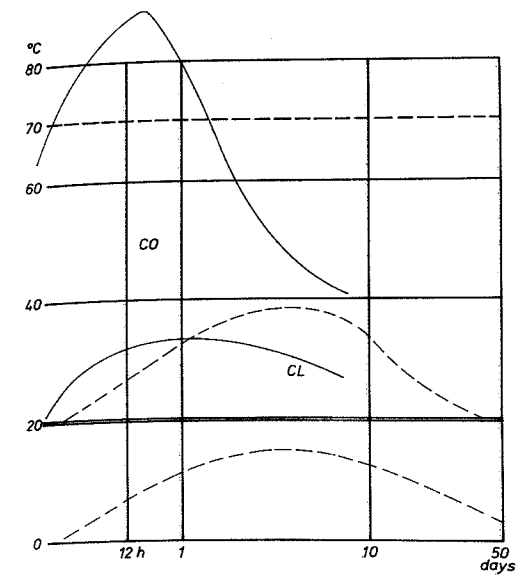
FIGURE 1. Ranges of temperature development during the curing of "contemporary" (Co) and "classic" (Cl) concrete. The room temperature line (= +20ºC) represents the modelling for testing and research corresponding to "classic" concrete, and is still in use despite the radically changed curing process in contemporary concrete.

Progress may sometimes have suffered backlag because much past research has taken its outset in available experimental techniques, phragmatic theory, and empiric models of what goes on in concrete. This may be the reason why certain features of the reactions remain to be fully identified and acknowledged.

For instance, the classic works by Powers and Steinour /1/, /2/ implicitly established that alkali-silica reactions in concrete in principle are hydration reactions akin to the hydration of cement. It follows that the same is true for the reactions between the various siliceous substitution materials and the alkalis in cement paste.

This indisputable statement means that expansive and non-expansive reactions of siliceous materials with alkalis in concrete may be designated a range of "subspecies" in the hydrating system in concrete. Therefore, the Arrhenius equation can be applied regarding the dependence on the rate of reactions of the reaction temperature.

There are several implications hereof in contemporary concrete works, which generally are made with much higher rates and peak temperatures during the concrete curing phase than only 30 years ago as shown in FIGURE 1. Concrete is also now exposed to much wider ranges of climatic exposure during performance than before.

It follows that:

- The reactions of alkalis with silica in concrete may be pronounced already during the curing of concrete. The lasting effects of reactions at this stage are not well explained.

- In large concrete bodies the rate of the reactions may at an early stage be much higher in the interior than at surfaces, and may act congruent with the thermal stresses caused by the heat of the hydration of the cement, and its dissemination to the ambient exposure media.

- Hot climates or hot industrial environments maintain higher reaction rates than colder ones during the performance of concrete works. In cold regions the seasonal temperature variations may cause the chemical reactions between alkalis and silica to be enhanced during summer periods, and thus if deleterious, to act synergistic with freezing/thawing, active during winter seasons.

- Temperate climates should be considered to represent the most "smooth" moderation of reaction rates, useful for comparative laboratory experiments, but not descriptive for the nature and effects of the reactions in most field concrete, which is also - not to forget - exposed to stress conditions imposed by the functional service of buildings and structures.

The mentioned ranges of the rates of reactions between alkalis and siliceous materials in concrete cannot be fully appreciated without considering the mass effects, in this respect comprising both the mass of the reactants per se, and that of the concrete masses as the "superior" reacting system. In other words:

- The total quantity of reactants
- The particle size distribution of siliceous materials and of cement
- The availability of alkalis and hydroxil-ions to the reaction sites
- The driving forces for ion-migration in the concrete
- The availability of pore liquid as vehicle for mass transport and for gel-formation in the concrete
- The characteristics of the pore and crack systems in the concrete and their alterations during the reactions
- The reaction kinetics

FIGURE 2. The reacting cement-silica systems graded after particle size distribution ranges of the silica supplying constituents.
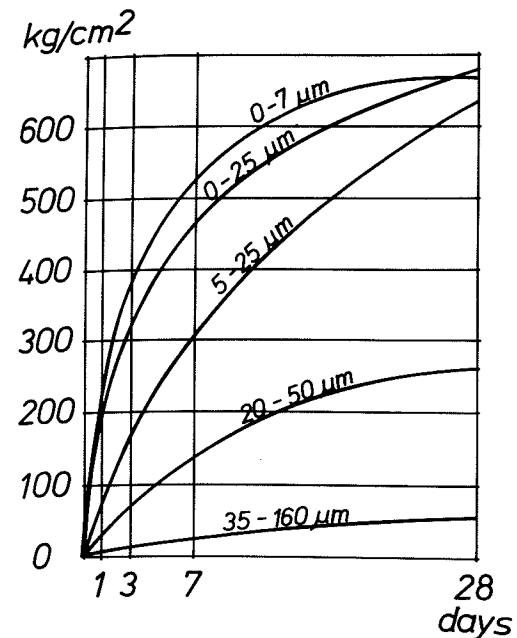
FIGURE 3. The influence of particle size distribution of cement on the development of compressive strength. After Duda (1977)

PARTICLE SIZE DISTRIBUTION

FIGURE 2 emphasizes the three major modifications of the alkali-silica reacting system based upon a particle size graduation. First the silica-bearing, reactive aggregate-cement system, characterized, among other things, by the order of magnitudes of different particle sizes of aggregates and cement, respectively.

Second, the natural pozzolana, fly ash, blast-furnace slag (cement substitution materials)-cement system, characterized, among other things, by approximately the same order of magnitude of particle sizes of the substitution materials and of cement.

Third, the silica fume-cement system, characterized by silica particles order of magnitudes smaller than cement particles.

FIGURE 3 from Duda /3/ demonstrates the remarkable impact on the particle size distribution of cement on the rate of strength development. Knudsen /4/ and others have discussed the theory of influence of the particle size distribution of cement on the rate of hydration in more detail, and this implies that similar interrelations apply for the cement substitution materials.

In the first modification of the above systems shown in FIGURE 2 it seems that the particle size distribution of the reacting aggregate particles ought to have more influence on the rate of long-term alkali-silica reactions, than has the particle size distribution of the cement fraction. Numerous research works do confirm the pronounced effects of the particle size of reacting aggregates, but the mode of occurrence of the silica in the aggregates and their physical/mineralogical characteristics are influential as well, so that a detailed mass-effect consideration must be applied for each particular type of aggregate. This has not yet been clearly elucidated in applicable terms regarding safe use of reactive aggregates.
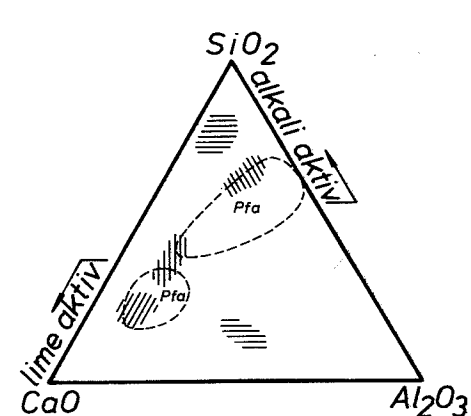
FIGURE 4. The three-phase CaO-SiO$_2$-Al$_2$O$_3$ diagram showing the well known "lime-activation" range towards the low left corner and the less studied "alkali-activation" range towards high right corner.
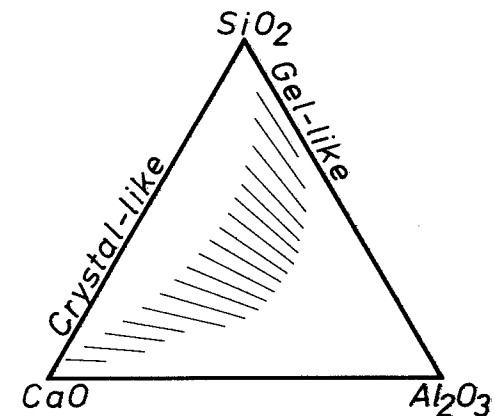
FIGURE 5. The three-phase diagram displaying that the "lime-activation" range of cementitious compositions predominantly creates "crystal-like", fibrous or foiled hydrates, while the alkali-activation range of "pozzolanic compositions predominantly creates sol-colloid, gel-like hydrates.

In the second modification - the predominant cement/substitution material systems - the particle size distribution in both fractions should be considered equally influential, and ought to be identified as pronounced parameters for the behavior of the system. (One must be aware that these systems comprise cement/substitution mixes within ranges from about 85-10% by weight of cement). For the substitution materials, as for aggregates, the specific chemical composition and constitution, for instance whether glassy or crystalline, silica and alkali rich or poor etc., are also influential, and we still don't really have explained how to engineers and industry.

The third modification - the silica fume type/cement mixes - is at present the least studied of the three as regards the system behavior. Presumably the particle size of the fume fraction is of overwhelming influence, but dependent upon effective dispersion in the cement paste.

The silica fume type materials are interesting also due to their high silica content and correspondingly low content of other cations. It may be possible to arrange fume agglomerations so as to use the silica "up through the particle size ranges" and in this way to get a desirable reactive, pure silica reference material for comparisons with the other cement substitution materials and the reactive aggregate reacting systems.

It follows from the above that knowing the characteristics of each of the displayed system modifications, it is possible to determine their interactions when mixed. Accordingly, when silica fume and/or fly ash, slag etc. are used in concrete with alkali-reactive aggregates it is possible to design the concrete so as effectively to prevent deleterious reactions.
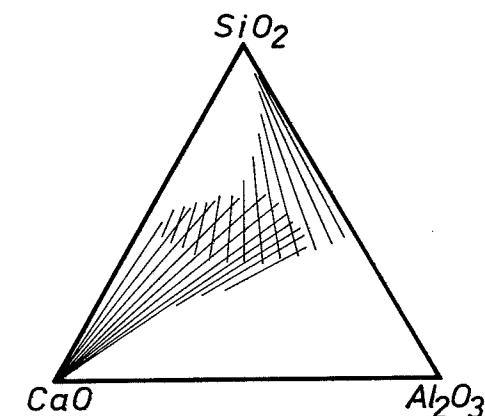

FIGURE 6. The three-phase diagram displaying that blended cements provide the opportunity to monitor hydrating composites so as to create a "crystal-like" Portland cement paste morphology incorporating "pozzolanic" gel-like constituents.
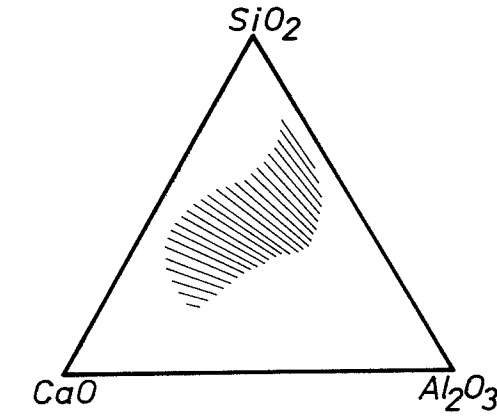
FIGURE 7. Illuminates the concept displayed in FIGURE 6 in a range of lime and alkali activated blends of Portland cement and substitution materials for concrete. Optimum combinations may be sought when functional requirements to the processing and performance are identified.

THE ENERGETICS ASPECTS

The classical concept of the reactivity of pozzolana, fly ash and slag in cement paste assumes that the presence of lime, which is released during the hydration of Portland cement, is needed to release the chemical energy for activation of their hydration.

Regourd /5/, Van den Bosch /6/, Roy and Idorn /7/ and others have shown that these materials can be activated by alkalis as well as by lime. Forss /8/ practised this by demonstrating the manufacture of precast concrete with alkali-activated slag as the binder without Portland cement.

FIGURE 4 from Idorn /9/ displays the lime versus alkali activation prevalence in the three-phase lime-silica-alumina diagram.

FIGURE 5 suggests a gradual change of predominance from lime to alkali-activation in the considered range of reacting systems. With the basic composition moving from the low left (high-lime/low-silica) comprising Portland cement and lime-rich fly ashes towards the high right (low-lime/high-silica), comprising natural pozzolana, low-lime fly ashes, and in the upper corner silica fumes, increasing alkali content becomes advantageous for effective hydration of anhydrous siliceous phases to occur.

FIGURE 6 further suggests that the high alkali-silica hydrates may be characterized as being of a primarily sol to gel-like behaviour and morphology in contrast to the high lime-(alkali)-silica hydrates which may adequately be characterized as fibrous to crystal-like. These designations implicitly suggest correspondingly less or more thermodynamic stability as discussed by Farrauto and Haynes /10/ and Roy /11/, and also more or less swelling or non-

swelling capability in the presence of water, as earlier discussed, e.g. by Powers and Steinour /1-2/ and others. The figure also implies that reacting systems which are preferable with regard to concrete durability may be those which combine the more stable intertwined, crystal-like morphology of the hydrates (as known from Portland cement paste) with incorporated, densifying gel-like substance in the entirety of the basic C-S-H structure.

FIGURE 7 therefore suggests an "optimum region" of compositions of Portland cement and substitution materials, covering the marked area within the three-phase diagram, and comprising compositions with regard to CaO, SiO_2, Al_2O_3 and constitutions as known from pozzolana, fly ashes and slag.

These compositions would allow for the highest possible replacements of Portland cement at different alkali/calcium concentrations and different ranges of w/c-ratios etc. The criteria for selection of compositions within the region would primarily comprise attainment of low-porosity, low-permeability paste structure and assured stable, long-term incorporation of alkalis in the basic C-S-H structure.

Practical experience already sustains the proposed concept by having established that generally the relatively high-lime containing fly ashes and blast-furnace slag can be used in higher proportions of Portland cement replacement than the lower-lime fly ashes, pozzolana and (in the extreme) silica fume. Correspondingly: the higher the proportion of Portland cement replacement the higher alkali content of the blended cement - consisting of the alkalis from both fractions of the blend - can be accommodated favorably in the permanent structure of the hydrated phases. Limits for safe incorporation of alkalis in the C-S-H morphology are imposed by the C_3S-content of the Portland cement or the total lime content in high-lime fly ashes in accordance with work by Bhatty and Greening /12/, Tang Ming-Shu and Han Su-Fen /13/ and other workers.

Numerous recent investigations have shown that thermal activation is as important a characteristic for the alkali-silica predominated hydrating systems as for the lime-silica predominated (Portland cement) hydrating systems. In fact, the ASTM C289-81 Test for potential reactivity of aggregates (Chemical Method) is based upon this principle. Also early studies of alkali-silica reactions by the mortar bar method demonstrated increasing rates of expansion with higher temperatures. Experiments by Gutteridge and Hobbs /14/ indicated that the rate of reactions of opal in NaOH-solutions follows the Arrhenius equation, Idorn /15/.

Owens and Buttler /16/ found similar time-temperature relationships for the reaction of fly ash in concrete, and Regourd /5/ found that the Arrhenius equation applies for the reaction of blast-furnace slag in concrete.

Idorn /15/ mentioned earlier work, as e.g. reported by Lea /17/, which shows that the solubility of $Ca(OH)_2$ in cement paste is suppressed by the presence of alkalis, and increasingly so with increasing temperatures. Roy and Idorn /7/ suggested that the reactivity of blast-furnace slag in cement paste at the early stages of curing is enhanced by synergistic impact of the heat of hydration and the alkali concentration, and explained the energetics of the complex hydration on this basis, supported by research presented by Wu et al /18/.

Altogether, this increasing amount of recent research on the kinetics of the alkali-silica predominated systems in cement paste shows that the thermal activation is an essential, integral parameter for the monitoring of the reactions.
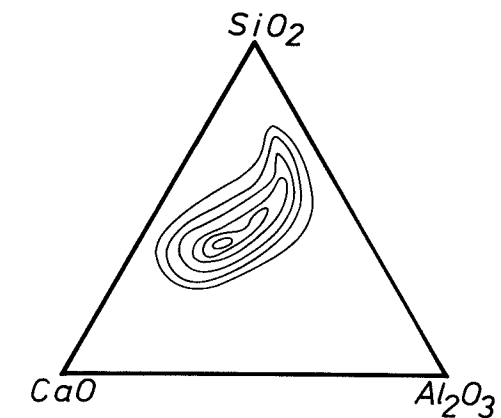
FIGURE 8 displays the concept shown in FIGURES 6 and 7 with horizontal curves representing that the reaction temperatures during hydration is a decisive parameter to account for when optimum compositions of the reacting systems are sought during the design of concrete works. The temperature developments during curing and performance require a two step design.

FIGURE 8 introduces on this background the thermal activation as the essential parameter it deserves to be considered in the conceptual display of "optimum regions" of the alkali-lime-silica hydrating system.

FIGURES 7 and 8 represent together a basis for practical mix design of concrete with Portland cement and cement substitution materials, ensuring effective combined utilisation of the latter and of the alkalis present, and prevention of deleterious reactivity with alkali-subsceptible aggregates. The design method requires trial testing of the concrete under curing conditions approximately simulating those to be anticipated under actual concrete making circumstances, i.e. application of modern curing technology systems.

ALKALI-SILICA HYDRATION, A TWO-PHASE REACTION

Van den Bosch /6/ suggested that the hydration of blast-furnace slag cement encompasses an initial alkali-predominated and a subsequent lime predominated phase. Roy and Idorn /7/ elucidated this by relating the initial and the secondary hydration phases to the energetics of the hydration process or, in practical terms, to the heat development and the monitoring of curing temperatures.

It is appropriate to broaden this as follows:

- The reactions of alkalis in concrete with subsceptible aggregates and/or substitution materials comprise two phases:

    1. Initial alkali-silica hydration congruent with the cement hydration at elevated temperature levels early during the curing of concrete.

    2. Long-term alkali-silica and lime-alkali-silica reactions at ambient temperatures during concrete performance.

The advantages in further quantitative elaboration of this approach is that effective utilization of any amounts of alkalis originally present in the concrete can be ensured by designing the composition of the concrete with regard to granulometry and kinetics of the reacting system so as to achieve effective incorporation of the alkalis in the C-S-H structure during the curing phase. The second phase of the alkali hydration will then become a type of "buffer" reactivity to absorb residual alkali-ions with no deleterious effects on the concrete.

The designation "effective utilization of the alkalis" therefore covers the following consequences of using the suggested approach:

The Curing Phase

Heat, released by the Portland cement fraction in blended cements, is consumed by activation of the alkali-silica reactions, thereby ensuring both effective hydration of the substitution materials and reduction of peak curing temperatures.

The alkalis of the reacting system are supplying a certain quantity of solids of a "gel-like" constitution to the C-S-H paste morphology. This serves to decrease the porosity, permeability and diffusivity of the hardened paste.

The Performance Phase

The monitored utilization of the alkalis in the system during the curing phase creates permanent immunity to deleterious alkali-silica reactions of the hardened concrete, and high chemical resistance in general due to superior denseness, relative to pure Portland cement concrete

---

METHODS OF EXAMINATION

The first application of microscopic thin section examinations of field concrete the writer has been made aware of were made by the Swedish geologists N. Sundius and G. Assarsson /19/ for the Royal Waterfall Board in the 1920's in a study of concrete deterioration in hydraulic works.

Application of geological/mineralogical methodologies and knowledge, in ways even tectonic modelling, was pioneered by American researchers in the 40's and 50's comprising the names of W.H. Parsons and H. Insley /20/, L.S. Brown /21/, B. Mather /22/, K. Mather /23/, Mc Connell et al /24/ and others. They introduced investigation systems comprising field observations, sample collection succeeded by macro and microscopic examinations of concrete specimens, and appurtenant chemical and other kinds of analyses.

Subsequent investigations in Denmark emphasized the use of drilled cores and of epoxy-impregnated thin sections, Plum et al /25/, Idorn /26/.

In principle the same basic modular principle of concrete investigations prevails today. But there is an immensely increased power and variety of examination methods available due to introduction of X-ray diffractometry, DTA and DTG, Scanning and Electron Diffraction microscopy etc. Sample collection, preparation methods and photographic recording have been refined, and much more basic knowledge on cement paste and concrete is accessible for interpretations of observed features and phenomena.

The modern thin section manufacture technique combined with the submicroscopic observation power of the electron microscopes and accessoric analytical instrumentation represents enormous progress since the early days, though at the same time considerable challenges to critical interpretations. This is because the major part of currently prevailing theories on cement paste and concrete behavior are based upon studies of simplified laboratory models with the reac-

tion kinetics projected to room temperatures, while examinations of field concrete in distress do not usually offer many clues for tracing what has happened to the concrete during a curing period long ago.

Concurrently, many more "exposure variations" occur in contemporary investigations, like for instance the impact of de-icing, of aggressive solutions from industries, of heat in saline cooling water, chlorides in swimming pool waters and so forth. And also new exposure conditions in developing countries.

Scrutinized, systematic field investigation methodology is described by Fookes et al /27/ with special regard to the Middle East region, but actually applicable everywhere. Thorough field investigation has also in recent years been presented by the Danish Ministry of Transport, the Road Directorate /28/.

Undoubtedly, the theoretical research, incidentally also concerning sulfate attack, corrosion, freezing/thawing etc. can benefit much from updated field investigations by targeting their studies in compliance with contemporary problems and opportunities in practice.

TESTING METHODS

Recent years have seen an increasing variety of testing the alkali-silica reactivity of cement/aggregate combinations, in particular aiming at acceleration of the tests in order to comply with engineering demands. One outset for this development is the ASTM Quick Chemical Method (C 289-81), which approaches a cement fineness reacting system at a high temperature level. Another outset is the equally classic ASTM mortar bar test (C227-81), which operates with a fine-aggregate/cement reacting system, to an increasing extent both at room and moderately increased temperatures (in order to reduce the duration of the test period).

Aberrant procedures introduce additional alkalis (e.g. as NaCl) in the system, Jensen et al /29/, or excessively high temperatures, as in a suggested autoclave test, Tang Ming-Shu et al /30/.

All these procedures deal in one or another way with variants of the kinetics of the hydration of the reacting system. It is, therefore, suggested that the results from the various test programs be interpretated on the basis of clarification of the energetics.

It is badly needed in this way to find a common denominator and evaluation criteria for the different testing procedures, in such a way that adequate simulation of the behavior of field concrete can be made basis for consensus regarding the testing principles and methods.

It is urgently needed that the two-phase concept of the reactions: 1. during concrete curing, and 2. during structural performance, appears distinguishable in the testing methods. As mentioned above, this is in a way the case already, but only implicitly so, and with the aim to save testing time, rather than to acknowledge field performance criteria.

It follows that the conventional tests regarding the effects of fly ash, slag, silica fume and natural pozzolans also need revisions. Their reactions are primarily alkali-silica hydration during the curing phase in contemporary concrete, and they ought to be tested at a combined early alkali-predominated/elevated temperature exposure and a subsequent, residual lime-predominated reaction phase.

EFFECTS IN PRACTICE

During the last 10-15 years there has been growing concern in engineering communities about earlier concrete deterioration and more repair needs than ever before experienced. In periods the concern has come close to alarm due to sudden collapse cases of catastrophic character, ascribed to several causes comprising handling of the fresh concrete, curing or early or later performance failures.

It looks as if a variety of technology features beyond the engineering control trickle by trickle has played poker with the material's behavior during its processing and performance.

Deleterious alkali-aggregate reactions are rarely referred to as a primary cause of collapse or demolition needs, but they do contribute as one among other causes to the increased rates of general deterioration, when they occur. They are also a nuisance because they are difficult to bring to termination by repair or maintenance work. And in our time they do become more widespread, common and aggravated, than in the past when they were discovered. Moreover, the cracking which results from deleterious alkali-aggregate reactions enhances carbonation and corrosion, and when concrete has become porous from the commencement due to excessive temperature rises during the curing, a susceptibility is created even to moderate exposure conditions.

It is evident that engineering specifications, based upon accumulation of singularly specific precautionary measures to counteract anyone of the potentially deleterious factors, cannot ensure resistance to complex aggressivity. Sulfate resistant cements to counteract sulfate attack give easier access for chlorides to corrosive action than do high C_3A cements, and initial, thermally induced porosity helps in the same direction, more so the higher cement content has been specified for protection. High exposure temperatures accelerate both alkali-aggregate reactions, chloride diffusion and the corrosion processes themselves. And so on.

Altogether, the earlier proposed "safe/unsafe" alkali-aggregate reactions concept ought to be broadened to a general "safe/unsafe" concept for contemporary design and making of concrete, comprising all essential aspects of its complex reactivity during processing and performance.

As one consequence scrutinized failure case studies are as much in demand as are thorough descriptions of concrete specifications and quality assurance undertakings at sites where the above guidelines are to become realized.

Another fruitful approach will be engineering courses for students as well as professionals - which teach the needed, physico/chemical/geological basis for assessing why modern concrete is more sensitive to its processing and performance conditions than existing textbooks say, and here scientific knowledge need to be more widely applied for adjustments of the conventional technology.

Above all the *"room temperature syndrome"* ought to be made an issue of historic description of past concrete testing, research and specification practice.

CONCLUSIONS

The views and research results referred to above intend to serve as a presentation offered for quantification and amendments during the forthcoming contributions of actual research findings and, hopefully, beyond. As preliminary guidelines for what may emerge of recommendations for the making of concrete with alkali-susceptible aggregates it seems justified to suggest the following:

- Use blast-furnace slag, fly ash or silica fume (or mixes of these if feasible), or special low alkali cements.

- Design the concrete in accordance with its functional requirements concurrent with the structural design and the manufacture conditions for two sequences of behaviour: The curing phase and the performance.

- Test alternative trial mixes by realistic simulation of the actual exposure during the two above sequences.

- Redesign the concrete if desirable before decisions regarding final specifications.

Count with the additional advantages by the calculated use of substitution materials:

- Reduction of peak temperatures during early curing, concurrent with intensified hydration of the substitution materials.

- Incorporation of alkalis in the cement paste morphology.

- Increase of the denseness of the cement paste on short and long-term, and thereby increase of ultimate strength and physico/chemical resistance in general.

There are numerous research studies available already for quantitative breakdown of the suggested approach to be suitable for different materials' availability, structural requirements and concrete making and exposure situations. Many more results and opinions will be presented during the present conference.

Whichever trends the conference may outline as desirable for further research and advice to current practice, the following fundamental circumstances, which have influenced the writer's presentation, must be considered:

- Concrete as a material has been radically changed in the course of the 43 years the effects of alkalis have been an issue. The demands on concrete with regard to load bearing capability and rates of strength development have increased considerably, and the ranges of exposure conditions have been much extended.

- Research has largely maintained the original concepts and methods, because coherent efforts beyond problem solution oriented research has received minor support.

- Research instrumentation and basic physico/chemical theory have concurrently been subject to impressive development, but not been correspondingly applied due to lack of resources and interest in the issues.

The consequence of this development has been increasing uncertainty about the effectiveness of standard specification regulations and about reliability of test results as basis for prediction of the behaviour of concrete in practice.

It is a reasonable assumption that about 20% of the concrete production in the world is made with alkali-susceptible aggregates (more types of aggregates are susceptible than 40 years ago due to the development of concrete), and that there are enough slag and fly ash available to ensure their utilisation without deleterious effects. Besides, by using slag and fly ash properly, improved general resistance of concrete can be attained, and energy saved. Moreover, the development with the most refined substitution materials is on the threshold of sophisticated innovations.

On this background effective and coherent research on the effects of alkalis in concrete should be acknowledged as more needed than ever during the past 40 years, and deserves to gain not merely an attitude of defensive actions against long-term deterioration, but a stronger drive towards profitability.

For the writer this is an interesting outlook to present - after 30 years with alkalis in concrete.

ACKNOWLEDGEMENTS

REFERENCES

1- Powers, T.C. and Steinour, H.H., 1955. Proc. ACI, 51, 491-514 (Part 1), and 2. 785-810 (Part 2).

3. Duda, W.H., 1977. Cement Data Book, 2nd ed. Bauverlag GmbH, Berlin/Wiesbaden, 539 pp.

4. Knudsen, T., 1982. Eng. Found. Conf. Henniker, N. Hampsh., 29 pp. (in press).

5. Regourd, M., 1980. Proc. 7th Internat. Congr. Chem. Cem., Edit. Sept. Paris, VII. III 2-18.

6. Van den Bosch, V.D., 1980. ACI, Publication SP-65, 474-487.

7. Roy, D.M. and Idorn, G.M., 1982. ACI Journal, Title No 79-43, 444-457.

8. Forss, B., 1982. Internat. Conf. Slag and Blended Cements, University of Alabama, Birmingham, 14 pp.

9. Idorn, G.M., 1982, Workshop Proc. EPRI CS 2616 SR. Special Report, Electr. Power Res. Inst., Palo Alto, Cal., 2-1 - 2-33.

10. Farrauto, R.J. and Haynes, W.L., 1973. Am. Cer. Soc. Bulletin 52:3, 276-278.

11. Roy, D.M., 1982. Workshop Proc. EPRI CS 2616 SR. Special Report, Electr. Power Res. Inst., Palo Alto, Cal. 5-1 - 5-5.

12. Bhatty, M.S.Y. and Greening, N., 1978. Proc. 4th Inst. Conf. on Effects of Alkalis in Concrete. Purdue University, Ill., Pub.No CE-MAT-1-78, 87-112.

13. Tang Ming-Shu and Han Su-Fen, 1980. Proc. 7th Internat. Congr. Chem. Cem, Edit. Sept. Paris, V. II. II 94-99.

14. Gutteridge, W.A. and Hobbs, D.W., 1980. Cem. and Concrete Res., V.10 No 2, 183-193.

15. Idorn, G.M., 1980. Cem. & Concrete Res., V.10 No 6, 581-82

16. Owens, P.L. and Buttler, F.G., 1980. Proc. 7th Internat. Congr. Chem. Cem. Edit. Sept. Paris, V-IV, 811-816.

17. Lea, F.M. (and Desch, C.H.), 1956. The Chemistry of Cement and Concrete. E. Arnold, London, 2nd Edit., 637 pp.

18. Wu, X., Langton, C.A. and Roy, D.M., 1982. Personal communication.

19. Sundius, N. and Assarsson, G.V., 1929. Part report in: Tekniska Meddelanden från Kungl. Vattenfallsstyrelsen, Serie B, No 10 (in Swedish with Engl. summary) 145 pp.

20. Parsons, W.H. and Insley, H., 1948. Proc. ACI, V.44, 625-632.

21. Brown, L.S., 1955. ASTM Bulletin No 205, 40-56. (PCA, Research Department, Bulletin 54).

22. Mather, B., 1948. ASTM Proc. V.48, 1120-27.

23. Mather, K., 1952. ASTM Spec. Tech. Publ. No 143.

24. Mc Connell, D., Mielenz, R. Holland, W. and Greene, K.T., 1947. Proc. ACI, V.44, 93-128.

25. Plum, N.M., Poulsen, E. and Idorn, G.M., 1958. Ingeniøren, Internat. Edit. (SBI-reprint No 94) 26-40.

26. Idorn, G.M., 1967. Durability of Concrete Structures in Denmark, Danish Concrete Institute, Holte, DK, 208 pp.

27. Fookes, P.G., Collis, L., French, W.J. and Poole, A., 1981. Concrete in the Middle East, Reprint of five articles from CONCRETE, Cement and Concrete Association, Wexham Spring, Slough, 24 pp.

28. Danish Ministry of Transport, The Road Directorate (Bridge Division), 1980. Concrete Durability, An Investigation of Recently Constructed Motorway Bridges in Denmark, 63 pp plus 8 enclosures.

29. Jensen A.D., Chatterji, S., Christensen, P., Thaulow, N., and Gudmundsson, H., 1982. Cem. and Concrete Res., V.12, No 5, 641-648.

30. Tang Ming-Shu, 1983 - Contribution to the present conference.

Session 1a

"ENGINEERING AND INDUSTRIAL ASPECTS OF

ALKALIS IN CEMENT AND CONCRETE"

Chairman: Dr. W. Schrämli

Introduction: Ib Worning & V. Johansen:

"Alkalis in cement and cement manufacture"