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Cement and Concrete Research 35 (2005) 3–10
CEMENT AND CONCRETE RESEARCH

Innovation in concrete research—review and perspective

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Received 11 July 2002; accepted 9 September 2004

Abstract

The heritage of concrete making as a craft has made testing of laboratory specimens the basic principle for research and standard control systems; this has corresponded well with the conditions for field concrete technology and structural performance throughout the 19th and the first half of the 20th centuries' developments. New demands for concrete in the wake of World War II made tremendous development possible for the cement and concrete industries. However, deleterious reactions in field concrete appeared in many countries over the next decades, among other reasons because the laboratory testing systems were preserved without recognition that rates and intensity of the reactions in the actual concrete caused changes of the processes, which did not occur in the test samples. That made the reproducibility of the tests incompatible with the sought predictability for the properties of the concrete.

In recent years, senior scientists have commenced to caution that the ordinary laboratory tests do not reliably simulate the behavior of concrete in the field. Besides, fractal appearance of micro- and macrostructures in concrete has been reported in international research journals. Meanwhile, progress in the natural sciences with the introduction of the *chaos theory* has made it possible to investigate turbulence, i.e. nonlinear processes in Nature and their visual fractal patterns.

Keywords: Cement; Concrete; Modeling; Nonlinear; Chaos theory

1. Introduction

Concrete is in essence "man made geology". Portland cement is the output of a man-moderated kind of a volcanic, eruptive reaction complex. Aggregates are sedimentary or crushed, natural rocks. The mixing, placing, compaction, curing, and the subsequent gradual alterations in hardened concrete during its service life are akin to geological processes in nature, albeit in an accelerated and monitored technology fashions. The pioneers of the Portland cement development in the 19th century realized this basic nature of cement and concrete. They applied thin section petrography for identification of the minerals in cement clinkers, designated alite, belite, celite, and felite, and for examination of hardened cement paste. Toernebohm [1] suggested in 1897 that the common examination methods were insufficient because: "...for the most part the examination methods were purely chemical of nature; but cement is not a purely chemical product, it is an artificial rock, and the constitution of a rock can not be explored only by chemical methods; also other, and in particular the microscope, are necessary". Toernebohm acknowledged the research by Le Chatelier (who introduced clinker petrography in 1883) and W. Michaelis. The interactive studies by these researchers were fundamental for the formidable development of cement production and uses through the 20th century.

Cement clinker petrography and, later, X-ray diffractometry, X-ray fluorescence, and electron microscopy became indispensable tools for cement production research and quality monitoring in the course of the 1960s, along with the advances in cement chemistry knowledge. In the 1980s, the Fuzzy Logic system was introduced and, herewith, the cement industry—as commodity supplier—

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doi:10.1016/j.cemconres.2004.09.006

recognized the turbulent, nonlinear nature of the chaotic processes in the cement kilns, and made the direct production monitoring decisive for the quality assessment.

The inherited, empirical sample testing has been maintained primarily as customer service for assurance of homogeneity and other performance qualities.

2. The evolution of concrete research

The evolution of concrete research through the 19th and 20th centuries is different from the cement research history. The making of concrete was from the birth in ancient cultures a "hand and shovel" low-temperature craft. Strength and durability have been attained by means of experienced masonry technology practice with gradual improvements of:

1. Portland cement as binder,
2. subsidiary materials refinements, such as pozzolans, air-entrainment, chemical admixtures, fly ash, slag, silica fume, fibers, and polymers,
3. technology progress such as mechanical vibration, pumping, ready mix, and prefabrication, and
4. concurrent structural and construction development.

Laboratory testing of cement paste, mortar, and concrete specimens has through the two centuries remained the general principle for concrete quality control and in concrete research, despite the absence of calculable transfer from the models to the reality of field concrete technology and performance. In other words, laboratory specimen testing became commonly and legally accepted as representative and predictive for the properties of field concrete, and authorized by ASTM, RILEM and the various national standards—and by the concrete research communities. In fact, participation in the continuous refinements of standard test methods became a major occupation and funding basis for many private and public research institutes.

It is an exception that coastal engineers in Europe, in the second half of the 19th century, became concerned about concrete deterioration in many important port and coastal structures, piers, breakwaters, sluices, etc. Comprehensive international research programs concluded after thorough field and laboratory studies that the reason was sulfate—"sea water"—attack with ettringite as the expansive reaction product. Pozzolanic cements, and much later special low C_3A cements, were found effectively preventative. However, this early recognition of investigations of field concrete as the outset for the research was exceptional. During the contemporary and later growth of the uses of cement and concrete, the laboratory specimen testing was found sufficient and convenient for all parties involved.

Then, in the 1940s, substantial American investments in public construction programs for development of the infrastructure coincided with alarming cases of deterioration in major, exposed concrete structures all over the continent. Alkali–silica reaction (ASR), sulfate attack, and freezing and thawing were found to be the predominant causes.

The contemporary interest in American research institutes for application of basic physics, chemistry, and mineralogy led to involvement of talented young scientists, including geologists. This created a remarkable renaissance for studies of field concrete as the outset for application of the related materials science disciplines [2], [3,4]. Use of thin section microscopy [5,6] led in some research communities to a new concrete research paradigm, which adopted the "concrete as man made geology" concept. This was in context with that the crystalline products of reactivity in concrete were phases identical with minerals found by geologists in natural rocks.

3. Reproducibility—the counterpart of predictability

Fig. 1 is a symbolic configuration of how two different models of a body may provide complementary information on the nature of the body. The figure may for instance be seen as symbolic for a study of ASR, represented by a core drilled out of an affected field concrete. The one projection may be taken to symbolize the mechanical effects of the reaction, cracking and sometimes expansion of the concrete. The other may be seen as symbol for the chemical alterations which in fact are causing the mechanical damage. Conceived in this way, the figure says that true comprehension of ASR requires knowledge of the mechanics and the chemistry *as an entity.* The early ASR researchers in USA and Australia in the 1940s recognized this interdependence, such as realized for instance in the two classical ASTM test methods C 227, the mortar bar test, and C 289, the quick chemical test.

However, notwithstanding the recognition of the complementarity of the two tests, C 289 was actually developed to meet demands from engineering practice for a test faster

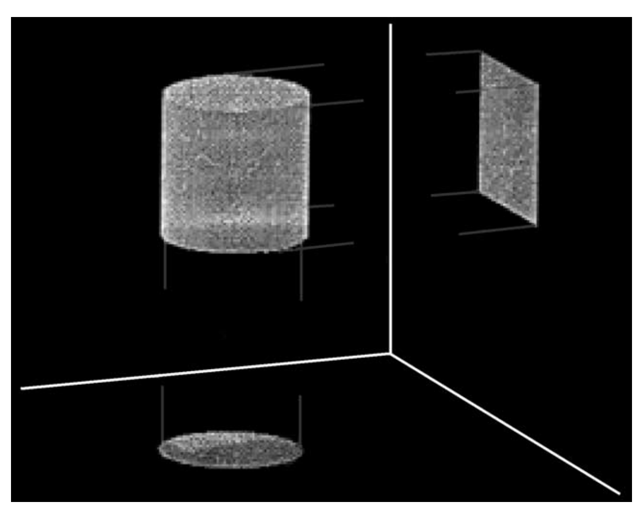

Fig. 1. A generalized, symbolic display of how two projected models of a body may provide complementary information about the nature of the body.

than C 227. Also, both methods were homogenized and standardized for attaining reproducibility to such extents that they became utterly arbitrary models of ASR in field concrete. Nevertheless, C 227 and its many subsequent refinements gained preference as standard tests, presumably because they visualize the mechanical effects, cracking and linear expansion, which is what engineers can see as evidence of harmful ASR in the field.

Fig. 2 from Plum et al. [7] shows the visibility of the mechanics of ASR at the end of a mortar bar, which is cracked and has expanded in vertical and horizontal directions. The only measurement, linear expansion—in the length direction of the bar—is therefore merely accounting for an unknown share of the expansive mechanism. In field concrete, expansive reactions are of course multidirectional and the linear expansion based test is therefore a modeling misconception of the expansive mechanism. The prepared particle size distribution of the reactive aggregate and the use of the same test procedure and acceptance criteria for different rock types are other sacrifices for reproducibility. The prescription of room (or other constant) temperature and 100% RH for the test run represents an arbitrary simplification of the kinetics of the reaction, which even further prevent the transfer to reality concrete.

The chemical method C 289—dissolution of a certain quantity of a siliceous aggregate material in a strong alkali solution—represents with 80 °C reaction temperature a kinetics closer to the reality of ASR at the early stages in field or prefabricated concrete than does C 227. However, the used dissolution process is in principle different from how ASR develops in siliceous aggregate particles in mortar and concrete. The model is, in other words, fictitious.

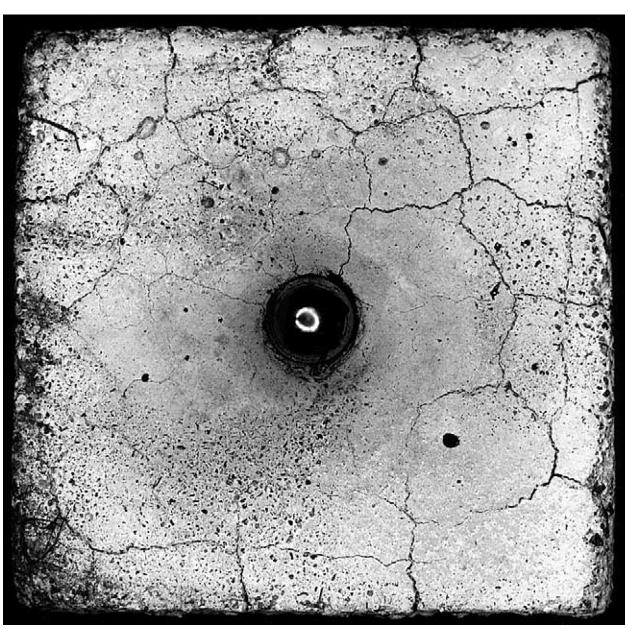

Fig. 2. End of a mortar bar that has expanded due to harmful ASR. The measurement steel ball has loosened from the mortar due to cross-sectional expansion and cracking. Hence, the measured longitudinal expansion does not model the mechanics of the reaction.

4. The reasoning

The development of ASR tests is a characteristic example of the substantial investments in empirical laboratory modeling of properties of concrete materials and concrete since World War II, not only in standard testing, but also in the research. Without a scientific basis for the simulation reliability, there must have been other reasons that made them attractive for the industries, the structural engineering professions, academia, and public authorities.

The primary reason for the above is that the simplicity of the modeling concept versus the complexity of the factors affecting field concrete was unnoticeable as long as the development of the uses of concrete was within the benign Northern temperate regions. This corresponded to the gradual evolution of the craftsman technology until the decade after World War II, when further industrial development became a basis for widespread growth and innovation in building and construction enterprises. The cement and concrete research followed suit, but was too occupied by the inherited model empiricism to see that new technologies were changing the kinetics and mechanics of reactions in concrete during processing and performance. This was what happened in North America, Europe, Japan, and the USSR, where the technology and structural development with cement and concrete was confined to until the 1960–1970s.

The 1970s oil crisis, with severe constraints on building and construction, and the competitive investment priorities for new industries hit the cement and concrete enterprises very hard and, therewith, also the research communities. Concurrently, three waves of serious field concrete deteriorations had hit Europe, the Middle East, and North America. In Europe, the unnoticed thermal cracking during the early phases of steam curing was the cause of comprehensive repair or even condemnation of residential, precast concrete building projects from the 1950s. In the Middle East, the hot climate caused also initial thermal cracking in practically all new concrete structures and the hot, high-salinity atmosphere and sea water exposure added severe reinforcement corrosion, leading to catastrophic 20 years or less service life. In North America, warm and humid seasons following severe winters with de-icing of highway bridges and pavements, etc. caused severe chloride-induced corrosion of reinforcement. Concurrently, the occurrence of ASR in many countries became undeniable. In the late 1980s, heat-induced internal sulfate attack (DEF) appeared as another consequence of insufficiently controlled steam curing in the prefabrication industries.

The main reason for these serious cases of deterioration was that the standard specifications and the modeling control test methods failed to function for concrete of intensified, unknown reactivity. This was due to the much higher energy conversion rates during the concrete production and performance than corresponding to the test conditions.

5. Present, global cement and concrete research

Cement and Concrete Research is an excellent source of information about the state of the international cement and concrete research. Although it does not cover information about magnitudes of investments in research and the funding sources in different parts of the world (no publications with such data seem to exist), it does show that, in the last decade, much new research is growing in countries outside North America and Western Europe (unfortunately with fewer contributions than earlier from the CIS countries).

Volume 31, Nos. 1–12, represents characteristic features of the global research situation at the beginning of the 21st century. Of the 203 articles and 30 communications, 143 (63%) describe, analyze, and interpret modeling studies of cement paste, mortars, and concrete specimens, which have been produced, tested, and examined under strictly regulated and homogenized laboratory conditions. In *one* of these papers [8], the conclusion says that "the results presented are valuable only for the conditions of the tests and the materials used". In a few other articles, it is implied in the conclusions that the results are valid for concrete made with the same materials as used in the tests. But in most of the reported laboratory model studies, the accomplishments are either considered addition to the general science/research knowledge bank "as are", or appear as assumed to be directly representative for field concrete characteristics or properties.

There are three articles [9–11] which describe cases of field concrete deterioration, and one [12] which provides climatic data from tropical American coastal regions for a study of chloride profiles in marine concrete; but basic physical/chemical knowledge is not extracted from the obtained field examination results. In one article [13], the dependence of ASR reactivity of rock types on their geological history is examined by a new digitized microscopy method, an innovative development for optical microscopy. One article [14] refers to cost/benefit considerations as reason for the development of an updated curing monitoring system for the New York State Highway bridge projects.

The examination methods used in modeling studies are both conventional measurements of mechanical properties, such as strength and deformations, and more sophisticated methods for revelation of micro- or submicrostructural characteristics by means of BET, EMPA, MIP, etc. The critical review of the latter method in Volume 30 [15] has apparently appeared later than the article, which are based on the method, were delivered for Volume 31. The different modes of electron microscopy are much used for descriptive illustrations of submicroscopic features and components of cement paste and mortars. In many of the articles, these micrograph reproductions appear as less convincing documentation for what they are meant to show, than they have been to the authors of the articles.

Every 1 of the 230 contributions in the Volume is a single jig-saw puzzle element of background knowledge which somehow may lead to progress, but without much revealed reflections about how and where the elements are placed in the entity of the puzzle. The Volume illustrates therefore the fragmentation of the contemporary international cement and concrete research.

The Volume contains one special, unfortunately rare, synthesis of the research on one particular subject, namely the: *Review of the Delayed Ettringite Formation (DEF) research* [16]. The references to this article have 8 entries from before the 1980s, in the later years of which the DEF concept appeared—with 9 entries. Then there are no less than 52 entries from the 1990s, and still 5 from the beginning of the new millenium. The majority deals with laboratory-based studies.

The review is in ways also an argument for a study of the cost/benefit issues of modern concrete research and its lacking coordination and management principle. Although such an investigation is deemed desirable, an even more profound aspect of the contemporary research situation, which the CCR Volume 31 represents, deserves further debate:

The philosophy of empiricism which takes regulated courses of chemical/physical reactivity in laboratory specimens as its research basis must be abandoned in concrete research. In other words, the hegemony of laboratory model testing must be replaced by quests for exploration of the complex nature of the reactivity in field concrete.

6. The entrance of science in concrete research

The early recognized need to apply more than chemistry in cement research, as referred to in Ref. [1], is reasonable for anyone who has looked in an operating cement kiln. For the early researchers with geological training, the turbulent reactions in the reactor (kiln) were similar to chaotic turbulence in many natural processes.

Turbulent, nonlinear natural or man-derived processes (incl. clinker-forming reactions) are not visually recognizable. Classical concrete making was seen and comprehended as a predictable, linear alteration of the material from the mixing of ingredients, through placing, compaction, and two to three weeks hardening in free air. Engineering experience and laboratory modeling of the development of specified performance qualities made the underlying linear process concept adaptable also for in research, and engendered acceptable solutions to the otherwise insurmountable "research and practice" gap problem thanks to the engineering friendly predictability.

The assumed linear nature of the chemical reactions in concrete corresponded also to the crude laboratory facilities and simple mechanical measurements, and to the common lack of test facilities on construction sites until after World War II.

In the post-war 1940s, four landmark innovations in concrete research became decisive in further development of the research itself and of concrete technology in practice:

1. T.C. Powers' and colleagues' exploration of the physical structure of the cement paste.
2. H.F.W. Taylor's, L. Copeland's, S. Brunauer's, and many co-operating colleagues' exploration of Portland cement chemistry and the hydration process.
3. Development of field concrete investigation with optical microscopy of thin sections of sampled specimens of concrete.
4. Application of the Arrhenius law for the relationship between concrete curing time and temperature. (At that time, for prolonged, low-temperature curing during winters; later also for high temperature curing, such as for precast concrete and in hot climates).

These new approaches were forecasts of further studies of concrete as dependent on the actual conditions for its production and performance rather than solely on arbitrary modeling circumstances. However, Powers', Taylor's and other studies were still based on measurements of the behavior of small experimental specimens, mostly of cement paste, while the new wave of field concrete investigations represented the "real thing", but did not provide much data information about the influence of mass and environments on the reactions and their effects in the concrete. Hence, there was still a scientific gap to cover between the two approaches and the empiric testing preserved its position in research despite the application of the sciences and the concurrent sophistication of laboratory methods and instrumentation.

This coincided with a gradual technological and construction evolution by utilization of chemical admixtures, GGBS, fly ash, silica fume, and by mechanization of construction work, all leading to the much promoted *High Performance Concrete* (HPC). However, the established standard and tests systems and modeling research were preserved. A few successful applications of science without dependence on the ruling empiricism appeared, such as for instance the development of the curing monitoring system based on Arrhenius' law [17,18], and the inventions of the Densified systems containing homogeneously arranged ultrafine particles, and Compact reinforced Concrete (CRC) [19,20].

7. Reconnoitering for a new concrete research paradigm

The increasingly competitive demand on structural design, construction, and materials development has for some time caused concern about the inherited simplistic modeling philosophy in concrete research.

Mehta [21] has in recent years in several articles suggested general introduction of the concept of holism, i.e. acceptance of the interdependence of laboratory model studies and field behavior, energy and resource saving, etc., and wrote in 2000: "...that the results from DEF laboratory tests involving small scale samples are of limited value. This is because the concrete processing variables and the conditions to which structural elements would be exposed in the field cannot readily be simulated in the laboratory". Also in 2000, Diamond [22] cited evidence from different laboratory-based DEF studies to indicate that leaching of alkali hydroxide, mix design, specimen dimensions, and the immersion of specimens control the development of DEF in fashions different from the reaction conditions in field concrete. In 2001, Taylor et al. [16] emphasized "...the need for caution in extrapolation from laboratory tests to field conditions. Conversely, one must be even more cautious in trying to establish basic chemistry from field evidence, because this rarely if ever presents all the necessary facts and field conditions are generally more complicated than at first appears". Grattan-Bellew [23] summarized in 1996 close to 60 years of development of laboratory test methods for alkali-reactivity of aggregates: "Blindly following standards may lead to accept of an aggregate which may be potentially expansive in a particular structure, or rejection of an aggregate which would perform satisfactorily in the field, leading to unnecessary expense with finding and possibly trucking in alternative aggregate..." The writer designated in 1983 the prevailing use of room temperature in cement and concrete testing and modeling research as the "room temperature syndrome" due to the customary neglect of the impact of the actual cement hydration kinetics [24]. These few critical views on the overly simplistic simulation of field conditions ought to be considered in conjunction with other studies with observations that substantiate the need for innovation in concrete research.

The Fuzzy Logic system [25,26] is such an innovation. Its basis is the recognition that visual observations and measurement data in experimental research and testing inevitably are subjective and approximate, and that reactivity in nature and technology is, in principle, irregular. The monitoring of the visibly irregular clinkerisation process in the cement kiln was the first industrial implementation of Fuzzy Logic [27]. Processes in concrete are not readily observed as irregular, and in laboratory specimen research and testing, any irregularity is deliberately minimized and disguised in order to make the courses of studied reactions appear as smooth and regular—i.e. linear—as possible. The introduction of the system in concrete research is only recent and it is still not widely adopted [28,29].

8. The Chaos theory

The Fuzzy Logic approach leads logically to the Chaos Theory [30,31]. (Incidentally, both these approaches were introduced independently by several American "serendipity" scientists in the 1970s). The Chaos Theory says that for all reactions, there is a sensitive dependence on the initial conditions, that the initial reaction in a given mass is followed by random clusters of further reactivity which continuously changes the whole system in an irregular, nonlinear mode towards the termination of the reactions.

Nonlinearity is difficult to calculate, but it creates richer more complex kinds of behavior—properties and structures—than do linear reactions. It creates reaction patterns, which appear as disturbances of regularity but, in fact, are higher orders of regularity. Minor nonlinearity is easy to overlook and disregard, or to be considered to be imperfections of applied examination/testing methods. Regression techniques may mislead researchers to overlook the overwhelming nonlinearity of processes in nature.

Nonlinear dynamics leads to fractal mechanics. The classical example is the beautiful, fractal patterns of falling snowflakes that are crystallized in the turbulent environment of humidity, freezing, and wind. Other examples of visible fractal patterns due to reactions in nature are:

Conchoidal fracture patterns on hewn surfaces of hard flint, obsidian, etc.
Crystallisation of minerals in cavities in rocks.
Layered rock sediment formations.
Dried clay surfaces.
Wave patterns in dune and desert sand surfaces.
Sequences of faults in earthquake zones.
Vortexes in turbulent streams.
Blends of small and large waves on windswept seas and rivers.
Foam in breaking waves and in wakes after sailing ships.

The patterns of fractality signal disorder (i.e. nonlinearity), since no point or system of points is ever repeated. Yet, the "self-similarity" in the patterns signals a superior grade of order, a hierarchy of scaling.

In concrete, fractal patterns are observed for instance as:

Map-cracking on surfaces of concrete affected by harmful ASR and/or DEF.
Submicroscopic fracture patterns in broken hardened cement paste.
Crystalline, secondary mineral compounds in deteriorating concrete.

The Chaos Theory offers a yardstick for researchers who face the incongruities of nonlinear processes in nature, thus also in concrete.

9. Fractal patterns in concrete

Map-cracking on concrete surfaces was observed in USA in the early 1940s as typical evidence of the deterioration of highway bridges and pavements, and as an early identification of harmful ASR; since then map-cracking been accepted to be an initial indication of occurring ASR. At the 10th International Conference on Alkali–Aggregate Reactions in 1996, Wang et al. [32] described map-cracking of concrete surfaces by harmful ASR as fractal. The fractal dimension was found to depend on the size of aggregate particles, the magnitude of the expansion, and the age of concrete.

In 1997, Chiaji et al. [33] observed fractality in fractured surfaces made by splitting tests performed on different types of concrete, initiated by microcrack nucleation at interfaces, which became attractors for macrocracks development. The fracture mechanism was found to be highly complex and different at different scales. Wang and Diamond [34] described fractality of fractured surfaces of specimens of hardened cement paste using a stereoscopic SEM method.

Fractal patterns of secondary mineral compounds in fractured concrete that has been affected by ASR or by sulfate attack (due to exposure to seawater)—portlandite, ettringite, gypsum, brucite, aragonite, and calcite—were early observed by petrography of thin sections prepared of drilled samples from the concrete, e.g., by Idorn [35]. Regourd [36] showed light microscopy and SEM photomicrographs with fractal patterns of mineral compounds in granodiorite, granite, and flint, and of quartz and phyllosilicate before and after a 3-day immersion in NaOH.

Admittedly, these early observations of fractality were not examined as examples of *fractality*, because that characterisation was yet unknown in the natural sciences. Proceedings of the later ICAAR's have numerous supplementary observations and, for instance in articles in Volume 33, 2003 of CCR, there are many figures showing micro- and submicroscopic fractal crystallisation of mineral phases in laboratory cement paste and mortar specimens. Incidentally, this can be observed also in a specimen of natural tobermorite, namely Fig. 1 in Maeshima et al. [37]. Neither have any of such more recent observations been identified as examples of fractality patterns.

10. Nonlinear reactions in field concrete

Diamond showed in Fig 1 of Ref. [38] interdependent variation of the concentrations of calcium, sodium, potassium, sulfate, and hydroxide ions in pore solutions expressed from cement paste at ages up to one day. Diamond further writes: "…In practical concrete it is clear that the level of alkali hydroxide in the pore solution will depend on a number of factors. Obviously, the alkali content of the cement used, the cement content of the concrete, and the amount of mixing water used will be the primary factors. If the cement has appreciable alkali in solid solution in belite, the completeness of cement hydration may be important. In addition to these "built in" factors, environmental factors can play an appreciable modifying role. Concrete that dries up will develop high local concentrations of alkali hydroxides, but the residual fluid will be confined to discontinuous interstices within the capillary structure of the material, at least until the concrete is re-wetted. Since drying is usually non-uniform, the concentration may be expected to vary from place to place in a large concrete structure”.

The impact of the temperature on the reactions was also a factor, albeit not yet a generally recognized one. Increasing concrete temperatures due to cement hydration during early curing or too hot environment, decrease the calcium ion concentration in the pore solution and may activate ASR. Concurrently, the sulfate reactivity changes (at higher than 70 °C ettringite becomes unstable) and leads to a risk of DEF.

Hwan and Won Cha [39] described the temperature and moisture distribution in early age concrete based on the degree of hydration as nonlinear, thus further substantiating the complexity of the whole system.

The concurrent mechanical effects are deemed to comprise of:

1. ettringite formation that may under certain, but not all, circumstances lead to swelling and expansion,
2. cracking in reacting particles caused by swelling gel, alternating with particles that do not crack,
3. autogenous and drying shrinkage.

All these processes appear in different, discontinuously occurring combinations in a concrete mass. Only a nonlinear course is conceivable for such a complex reaction system.

11. Chaos theory as science basis—also in concrete research

The Chaos Theory accepts that processes in nature may—under some circumstances—be linear, such as for instance the laminar flow of liquids at low velocities. In ordinary concrete (for example, in field concrete in benign, northern temperate environments), there are apparently also some low velocity processes, such as the hardening of concrete, the rate of deformations like shrinkage and creep, and the development of chemical reactions like ASR and sulfate reactions. In fact, the conventional testing systems have deliberately aimed at making the processes to appear laminar, i.e. linear, and measured them that way in order to achieve reproducibility and comparability of the test results.

The use of the same test principle in research has had a somewhat different purpose, namely to isolate specific kinds of reactivity for scientific exploration of their basic nature. This has indeed over the last two centuries also helped cement and concrete technology to become a decisive basis for the development of industries, infrastructures, and residential urbanization, now spreading over the whole globe. Hence, research by means of such modeling of processes in concrete is not meaningless. Each particular model test represents one among many fashions of the possible alteration of the material, corresponding to the preselected and monitored course of the studied reactivity. The thereby acquired tremendous knowledge base is indispensable for use in the new research on the nonlinear, complex interactions of the reactivity in actual concrete. In the long term, this innovating research paradigm corresponds to, or rather is prerequisite for, the much debated change from the conventional prescriptive standard system to new performance based standards, which requires reliably predictive knowledge of the behavior of real (field) concrete.

12. Concluding remarks

The writer has in Refs. [40,41,42] precursory proposed that chaos theory as means to make recognition of the holistic research paradigm as a landmark of a new 21st century era in concrete research, eliminating the science–technology gap syndrome in concrete technology. In the present review, the arguments for its application are still circumstantial and without supporting experimental and theoretical investigations. These will require long-term programs with new approaches, *inter al* the mathematics for analyses of nonlinear, complex reactivity data. Synergy may emerge with available expertise in advanced computer modeling studies for simulations of field concrete performance in aggressive performance conditions. Advice is also available from newer studies of the Chaos Theory in other fields of the natural sciences, and from industrial, high-technology applications.

The barriers against such an iconoclastic innovation in concrete research may initially appear insurmountable in many research communities, and also for funding suppliers, standard organizations, etc. However, it has happened before in the history of science and applied research, and also in concrete research, that new visions meet reservations and resistance and that audacity and open minds for innovation will overcome.

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