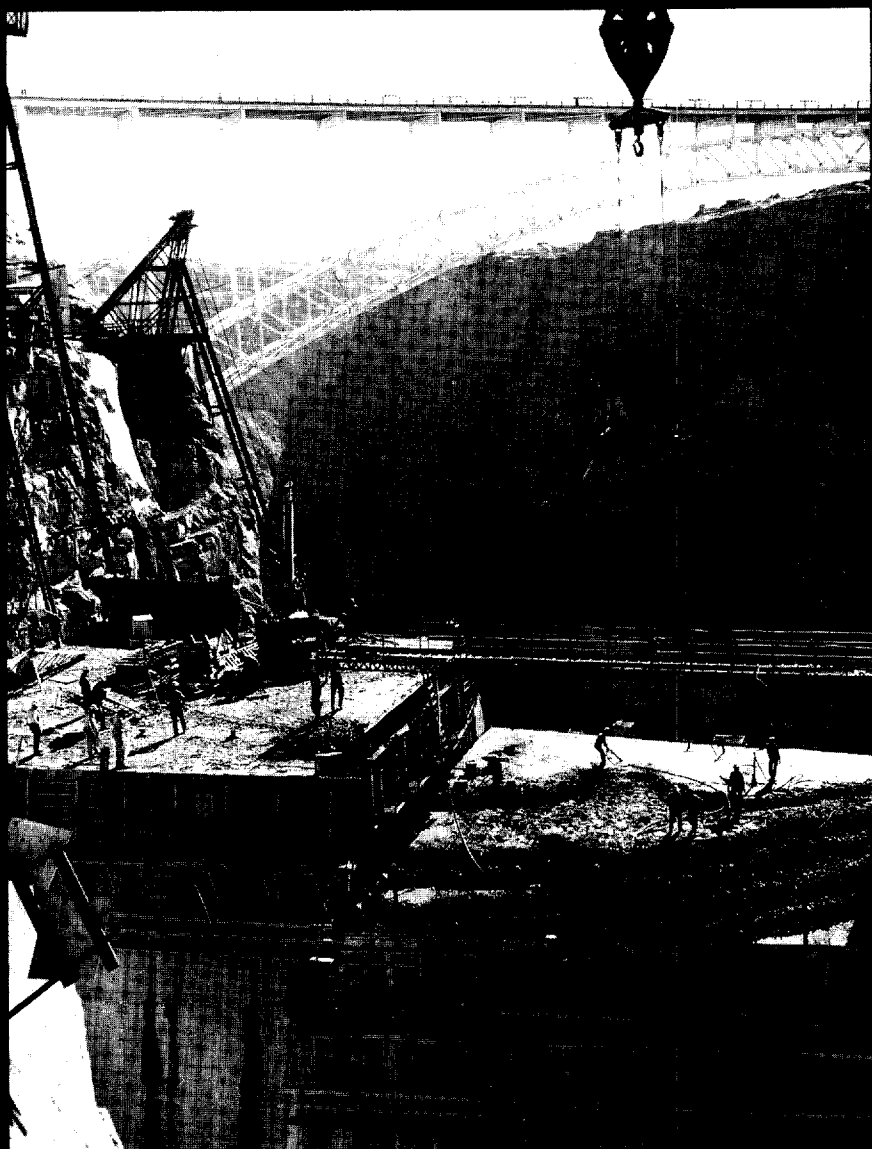


NEW CONCRETE TECHNOLOGY

Robert E. Philleo Symposium



Tony C. Liu
George C. Hoff
Editors

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NEW CONCRETE TECHNOLOGY

Robert E. Philleo Symposium

Tony C. Liu and George C. Hoff — *Editors*

American Concrete Institute SP-141

DISCUSSION of individual papers in this symposium may be submitted in accordance with general requirements of the ACI Publication Policy to ACI headquarters at the address given below. Closing date for submission of discussion is September 1, 1994. All discussion approved by the Technical Activities Committee along with closing remarks by the authors will be published in the March/April 1995 issue of either ACI Structural Journal or ACI Materials Journal depending on the subject emphasis of the individual paper.

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PREFACE

At the 1991 ACI Fall Convention, Committee 214, under the Chairmanship of Mr. Kal R. Hindo, sponsored this Robert E. Philleo Symposium on Concrete Technology as a memorial to Mr. Philleo who contributed so much to our knowledge of concrete materials and technology. The ad-hoc committee for the Robert E. Philleo Symposium consisted of:

Kal R. Hindo, Chairman
George C. Hoff
Joseph F. Lamond

Tony C. Liu
V. Mohan Malhotra
John M. Scanlon

The ad-hoc committee selected 16 papers as outstanding and relevant to the symposium theme for presentation. Twelve of these 16 papers are included in this symposium volume. Each paper was reviewed in accordance with ACI publication procedures.

This volume covers a wide range of subjects on concrete materials and technology, including statistical methods for evaluation of core strength and in-place concrete test results, roller-compacted concrete dams, concrete rigid pavements, reliability models for precast concrete slabs, quality assurance and quality control, and the needed concrete research.

The ad-hoc committee is grateful to the authors for their contributions and to all those who made the symposium and the publication of this volume possible.

Tony C. Liu
George C. Hoff
Editors

ACI Committee 214
EVALUATION OF RESULTS OF TESTS USED TO
DETERMINE THE STRENGTH OF CONCRETE

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J. Derle Thorpe
Woodward L. Vogt
Don J. Wade
George Y. Wu

DEDICATION

Robert E. Philleo (1923-1990) was an internationally recognized expert in concrete materials and technology. He was also a talented engineer, a gifted author, and a leader.

Bob was born in Spokane, Washington. After graduating from Carnegie Institute of Technology (now Carnegie Mellon University) in 1946, Bob joined the Research and Development Division of the Portland Cement Association in Skokie, Illinois. He was involved in research projects on concrete creep and drying shrinkage. He was instrumental in development of the air meter for use on concrete construction projects.

In 1959, Bob left PCA to accept a position with the Office of the Chief of Engineers, U.S. Army Corps of Engineers in Washington D.C. He served until his retirement in 1984 as Chief of the Structures Branch, Directorate of Civil Works. He was an advocate of innovative concrete technology. He was involved in the design and construction of the largest concrete gravity dam in the U.S, the first all roller-compacted concrete dam, the use of fiber reinforced concrete, and other advancements in concrete technology. After retiring from the Corps of Engineers, he was a very active consultant specializing in concrete materials and concrete construction.

Bob was an ACI member for 44 years, served as ACI President in 1974, and was awarded an Honorary Member in 1978. He served as Chairman of the Concrete Materials Research Council at the time of his death. His many ACI honors included the Henry C. Turner Award in 1984 for "broad contributions to practice of concrete engineering and development of consensus standards for concrete and concrete constructions."

He was also very active in the American Society for Testing and Materials. He joined ASTM in 1953 and served as Chairman of both Committee C1 on Cement and C9 on Concrete and Concrete Aggregates. He held ASTM Honorary Membership and received the Award of Merit. He served on its Board of Directors from 1978-1981. He was also a trustee of ASTM's Institute of Standards Research.

Bob was a member of the Transportation Research Board and served as Chairman of the Concrete Committee.

Bob's desire for concrete excellence is typified by his last two papers published in *ACI Concrete International*, "Back to the Concrete Future," and "Working to Make Efficient, Safe, and Durable Concrete."

The excellence of the papers presented in this symposium is a fitting tribute to Bob Philleo who contributed so much to our knowledge of concrete materials and technology.

Kal R. Hindo, P.E.
General Chairman, Robert E. Philleo Symposium

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SP 141-1

How Soon is Soon Enough? Revisited

by B. Mather

Synopsis: The customary criterion for establishing grades of structural concrete is the crushing strength measured in an arbitrary manner on a standardized specimen stored in a stipulated fashion for approximately a month after making. In some parts of the world the specimen is a cube and in other parts of the world the specimen is a cylinder. There have been debates as to how the strength at 28 days can be predicted from procedures performed at early ages, especially 24 hr, on the grounds that a month is not soon enough. The intent of this paper is to suggest that the only time that really is "soon enough" to know that the grade of the concrete in any batch is correct is before the concrete is discharged from the concrete mixer into the forms. It is suggested, therefore, that effort would preferably be expended upon insuring that the materials used are those intended and the proportions in which they are used are those that were intended. If such is the case, the grade of concrete will be proper at all ages and testing at any age is merely confirmation.

Keywords: Age; age-strength relation; building codes; concrete construction; concretes; fresh concretes; mix proportioning; quality control; specifications; tests

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Bryant Mather is Director, Structures Laboratory, Waterways Experiment Station, U.S. Army Corps of Engineers, Vicksburg, Miss., and has been with the Corps since 1941. He is an Honorary Member and a past president of ACI and is a member of several technical committees.

FOREWORD

In 1974 I reviewed a manuscript prepared by Mohan Malhotra that discussed the benefits of accelerated strength testing as compared to waiting 28 days for results of strength tests. He used the title "How Soon is Soon Enough?" I concluded that he had a good paper but 24 hours wasn't the right answer, even in 1974, to the question "How Soon is Soon Enough?" I believed then, and I still believe, that the time to be sure that the concrete for any use is right is *before*, not after, it has been placed. Mohan's reaction to this comment was: "All right, I will get another title for my paper but only on condition you write one developing your concept." I accepted and prepared a manuscript that was accepted and presented on March 20, 1975, at the Second International Symposium on Concrete Technology at the University of Nuevo Leon, in Monterrey, Mexico. A Spanish translation: "Que Tan Pronto es lo Suficientemente Pronto" appears in the proceedings of that Symposium on pp. 137-142. Shortly thereafter, Ravindra Dhir asked me to submit a paper for the First International Conference on Ready-Mixed Concrete at Dundee University, Dundee, Scotland, in September 1975. I sent him the same manuscript, since it had not then been published in English. It was presented in Dundee by Ken Newman and it appeared in the Proceedings of that conference which were published by Pergamon Press as "Advances in Ready Mixed Concrete Technology." ACI heard about it and asked me to send it there, I did, it was reviewed, accepted, and published as Title No. 73-12 in the ACI Journal for March 1976. There was discussion by Ed Abdun-Nur, Douglas Haavik, Ted Hersey, Mohan Malhotra, Darrel Sluder, and an author's closure in the September 1976 ACI Journal.

Now that 19 years have passed, it seemed appropriate to re-examine this idea in the light of such technological and administrative progress as has been made. Also the original paper was never presented orally at any ACI meeting. We were recently confronted with a paper that says "Water-Cement Ratio is Passé" (Barton 1989) and there have been other developments including ACI editorial adoption of "water-cementitious material ratio" to replace "water-cement ratio" and a 318 Building Code requirement for a minimum cement content under certain conditions, that make

this appropriate. This is in addition to the fact that the most valuable contribution to clarifying the original idea came when an early draft was reviewed and commented on by Bob Philleo. Finally I would observe that, according to an editorial in Nature for 15 August 1991 (p. 554), anything published 25 years ago is forgotten; so maybe the way to avoid having what one wrote forgotten is to republish at convenient intervals.

INTRODUCTION

Widely and generally used codes for concrete construction, which are part of the "law of the land" in many jurisdictions, set forth what must be done to avoid trouble in concrete work. There is little if any real need for some new or novel approach to avoiding trouble—new or novel, that is, in the sense of something different than what is already required, for example, in the ACI Building Code.

CODE REQUIREMENTS

"Building Code Requirements for Reinforced Concrete (ACI 318-89)" provides, among many other things, that:

"Use of plain concrete for structural members shall be in accordance with ACI Standard Building Code Requirements for Structural Plain Concrete (ACI 318.1)" (Section 1.1.6).

Drawings and specifications "shall show... (c) specified compressive strength of concrete at stated ages or stages of construction for which each part of structure is designed" (Section 1.2.1).

"The inspector shall require compliance with design drawings and specifications...records shall include: (a) Quality and proportions of concrete materials and strength of concrete..., (d) Mixing, placing, and curing of concrete" (Section 1.3.2).

(a) "Cement shall conform to..." ASTM specifications C 150 or C 595 (Section 3.2.1).

(b) "...aggregates shall conform to..." ASTM specifications C 33 or C 330 (Section 3.3.1).

(c) "Tests of materials and of concrete shall be made in accordance with standards of the ASTM..." (Section 3.1.2).

(d) "Cement used in the work shall correspond to that on which the selection of concrete proportions was based."

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(Section 3.3.2).

(e) "Cement and aggregates shall be stored in such a manner as to prevent their deterioration or intrusion of foreign matter." (Section 3.7.1).

(f) "Concrete shall be proportioned to provide an average compressive strength...(and) produced to minimize frequency of strengths below f'_c ." (Section 5.1.1).

(g) "Proportions of materials for concrete shall be established to provide workability and consistency...resistance to special exposures...conformance with strength test requirements" (Section 5.2.1).

(h) "If data (from trial batches or field experience) are not available...concrete proportions shall be based on the water-cement ratio limits in Table 5.4..." which, for example, requires a water-cement ratio not to exceed 0.35 for air-entrained concrete having $f'_c = 4000$ psi (27.6 MPa) (Section 5.4).

(i) "Cylinders for strength tests shall be molded and tested in accordance with ASTM methods" (Section 5.6.2.2).

"Normal weight and lightweight concrete exposed to freezing and thawing or deicer chemicals shall be air entrained with air content indicated in Table 4.1.1. Tolerance on air content as delivered shall be ± 1.5 percent...for specified compressive strength f'_c greater than 5000 psi, air content indicated in Table 4.1.1 may be reduced 1 percent" (Section 4.1.1). The values in Table 4.1.1 range from 7-1/2 percent for 9.5-mm (3/8-in.) nominal maximum-size aggregate in a severe exposure to 3-1/2 percent for 75-mm (3-in.) nominal maximum-size aggregate in a moderate exposure. Note that with the ± 1.5 percent tolerance and the 1 percent reduction, if the f'_c was 6000 psi, the exposure was moderate, and the nominal maximum size was 3-in., the concrete would be acceptable with an air content with 1 percent air content; a requirement easily met by nonair-entrained concrete.

"The minimum cement content of concrete mixtures exposed to freezing and thawing in the presence of deicing chemicals shall be 520 lb of cement meeting ASTM C 150 or C 595 per cu yd of concrete" (Section 4.1.3. (The folks that adopted this did not recall the ACI Board action that forbids a minimum cement factor specification limit, used by itself.)

"Concrete that will be subject to freezing and thawing in a moist condition, intended to have low permeability to water or be exposed to deicing salts, brackish water, sea water, or spray from these sources shall conform to Table 4.1.2." The table

limits the w/c to 0.50 maximum for "low permeability," 0.45 for "exposed to freezing and thawing in a moist condition," and 0.40 for corrosion protection for R/C exposed to deicing salts, etc., but there is a footnote that allows w/c of 0.45 maximum if the cover is increased by 0.5 in. 4.1.4 provides that the "w/c values in Table 4.1.2 shall be calculated using weight (sic) of cement meeting C 150 or C 595 plus weight (sic) of fly ash or pozzolan meeting C 618 and/or slag meeting C 989." (Hence "water-cementitious material ratio.")

(j) "Samples for strength tests...shall be taken not less than once a day nor less than once for each 150 cu yd (115 m³) of concrete or for each 5000 sq ft (465 m²) of surface area for slabs or walls" (Section 5.6.1.1). "A strength test shall be the average of the strengths of two cylinders from the same sample of concrete tested at 28 days or at test age designated..." (Section 5.6.1.4).

(k) "Strength level of an individual class of concrete shall be considered satisfactory if the average of all sets of three consecutive strength tests results equal or exceed f'_c and no individual strength test result falls below f'_c by more than 500 psi (3.4 MPa)" (Section 5.6.2.3).

(l) "Concrete construction shall be inspected throughout the various work stages" (Section 1.3.1).

(m) "Inspection records shall include: quality and proportions of concrete materials and strength of concrete" (Section 1.3.2).

I submit that if the cement and aggregates are tested in accordance with applicable ASTM standard methods and are found to meet the applicable ASTM specifications; if they are stored properly; if those used in the work correspond to those used in selecting the mixture proportions; if the mixture proportions are selected as intended; and if the concrete is batched according to the selected mixture proportions, properly mixed and sampled, then there is no significant probability that the results of properly conducted strength tests will yield a result that will be considered other than satisfactory.

The strength tests may yield a satisfactory result and the concrete in the structure may be unsatisfactory or vice versa because the tests are made on samples not representative of the material in the structure. This can happen if the concrete used in making the test specimens is different from that used in the structure or if the concrete used in the structure or the specimens is not properly consolidated and cured.

A great deal of attention is being given to perfecting methods for discovering more quickly and more quantitatively just how bad the concrete is in a structure and much less

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attention seems to me to be being given to perfecting methods for assuring that the concrete in the structure will not be bad. Let me review with you some dialogue I had regarding practices in the United Kingdom.

UK REQUIREMENTS

In July 1973 (Anon, 1973) it was reported that the Director-General of the Cement and Concrete Association in the United Kingdom had devoted the introduction to the Association's annual report for 1972 to the topic of how best to specify concrete to insure satisfactory durability.

He stated that durability of concrete depends on impermeability of the cement paste. He argued that the *only* way to insure the necessary degree of impermeability of the paste for a particular durability requirement is to specify a minimum cement content for the mixture.

He noted that there was a school of thought which argued that durability requirements should be expressed in terms of compressive strength rather than minimum cement content. He, however, maintained that the relationship between strength and durability is indirect and imprecise, so that a safety margin would be necessary if strength grades were to be used for this purpose—and this could lead to excessive and uneconomical use of cement, thus increasing the cost of concrete construction. Without a safety margin, there would be a serious risk of inadequate durability.

My reaction to this was that both schools of thought were talking about durability in some sense other than what the term meant to me. So I turned to the C&CA Handbook on the Unified Code for Structural Concrete (Bate, 1972) and read there (Section 6.3.3) "The purpose of specifying a minimum cement content is to insure durability." It adds that the alternative approach of limiting water-cement ratio is not favored because of practical problems of enforcement.

I then obtained a copy of British Ready Mixed Concrete Association's report on Specification of Concrete for Durability (BRMCA, 1973). It suggested that, rather than specifying durability in terms of minimum cement content, it would be preferable to do so by minimum compressive strength. This concept was beautifully elaborated. It was brought out that the BRMCA and the C&CA agreed that "durability," as they were discussing it, depended primarily on the concrete having a paste of low permeability to water, which was assured by having an adequately low water-cement ratio concrete mixture. The report explored five relationships:

- (a) Permeability and water-cement ratio

- (b) Compressive strength and water-cement ratio
- (c) Compressive strength and permeability
- (d) Water-cement ratio and cement content
- (e) Cement content and permeability

The conclusion was reached that compressive strength is preferable to cement content as a basis for controlling water-cement ratio (—which, in turn, controls permeability— which, in turn, controls "durability") because, among other reasons, the determination of strength is based on a "simple long accepted" test method whereas "there is still no simple rapid means of measuring the quantity of cement (or water) in a batch of concrete."

This is an example of a preference for a test that can only be made after the concrete has hardened over a test that could be made before the concrete is placed.

In commenting on this, I wrote that I did not agree that there was no simple, rapid, inexpensive means by which the quantities of cement and water in a batch could be quickly measured. Scales exist which can measure, with any degree of reasonably desired precision, the quantities of materials going into a batch of concrete. Many ready-mixed concrete plants have entirely adequate scales. Truck-mixer water tanks have meters. Many truck-mixer water tank meters are completely adequate to measure the amount of water added to a batch of concrete after prior batching has occurred at the plant. Means exist whereby one can measure the water in the aggregates. Therefore, there is no technical or technological reason for not knowing the quantities of cement and water in a batch of concrete. If, in fact, one does not know, it is because it has not been required that facilities be available by the use of which one could know, or the requirements that have been imposed are not being complied with.

I then took this point up with Fred Bartel, then chairman of the subcommittee on specifications for ready-mixed concrete of ASTM Committee C-9, at its meeting during the first week of December 1973 in Florida, and Fred said that he knew exactly how much cement and water had been added to every batch of concrete made by his company with only the proviso that they may not have as good a method of keeping track of free moisture in aggregates as might be desired.

I make these remarks because I view with disfavor the use of *either* cement content or strength as a basis for controlling properties of concrete. I do not favor the use of cement content because it is largely irrelevant and misleading. For a cement content of 600 lb per cu yd (356 kg/m³) of normal portland cement, one can have strengths from 2000 to 6000 psi (13.8 to 41.4 MPa) depending on the water-cement ratio, all other things being equal except slump, and, today, with the use of high-range

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water-reducing admixtures, slumps can also be made equal.

I also do not favor the use of strength as a basis for controlling durability or anything else because by the time you have measured the strength it is too late to control the concrete whose strength is measured. This is why I favor controlling the concrete by knowing what is in the batch before the batch is placed in the work.

Many have given attention from time to time to methods by which one can take a sample of mixed concrete, as from a truck mixer, and perform operations on it sufficiently rapidly to get answers before the rest of the batch is discharged from the mixer, transported, and placed. At the present time, slump tests and air content tests can be made in this fashion. Others have worked extensively on systems involving more sophisticated approaches to testing (Tom and Magoun, 1986; Hime, 1990), especially using nuclear techniques for estimating the cement content or water content or both of the mixture. Such methods deserve to be studied and, if developed, no doubt will have their place; but in my view they would not be needed if one knew the composition of the batch before the concrete ever got to the job site, and, as indicated, I believe that the technology exists to do this. If one has confidence that the mixer contains a given mass of aggregate, a given mass of cement, and a given mass of water, measuring the slump and the air content should be all one needs to do before discharging the batch into the forms, to have adequate confidence that the requirements of strength and durability will be met, assuming only that the subsequent consolidating and curing are conducted in accordance with the current standards of good practice.

I sent a copy of the foregoing comments to Bob Philleo. His reply included the following paragraph.

"While I am in agreement with your point of view, I must quibble with the implication that structural adequacy and durability can be completely assured by pre-placing inspection. At the risk of sounding reactionary I want to put in a good word for the strength test. At a lock project on the Ohio River we removed 3000 cu yd (2300 m³) of low-strength concrete which had passed pre-placing muster with flying colors. What had happened, you will recall, is that the cement and fly ash (or pulverized fuel ash) in storage were separated by a single sheet of steel and the weld supporting the partition had torn loose over several feet of its length so that the cement bin was badly contaminated with fly ash. It had never occurred to anyone that the weld required inspection. While we have corrected that particular problem in our specifications, who knows what other gremlins may crop up in the future? I think the designer deserves assurance that the stuff in the forms will in fact develop strength. I believe, however, that this assurance can be given in 24 hr."

CONCLUSION

The time to know that the concrete mixer contains the proper amount of each size of aggregate, of cement, of water, and of each admixture called for by the mixture proportions, is when the addition of the ingredients to the mixer has been completed; not later.

The time to be sure that the strength will not be low due to excessive air entrainment is when the air content test is made or the texture of the mixture is judged by the inspector; not later.

The time to be sure that the strength will not be low due to inadvertent excessive water content is when the slump test is made or the slump is judged by the inspector; not later.

The time to be reassured that all is well is when the accelerated strength test results become available at 24, 28-1/2, or 49 hr after the specimens are made, depending on which of the procedures of ASTM C 684 one has elected to use, not later.

ACKNOWLEDGEMENT

I gratefully acknowledge permission from the Chief of Engineers to publish this paper.

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SP 141-2

Concrete in a State of Nature

by G.M. Idorn

Synopsis:

The three power centers in the world today must support the tremendous concrete construction and building investments which are needed in the developing regions where 90 percent of the world population lives. Concurrently, renovations and renewals are required in the industrial countries. It is discussed that profound updating of the conventional concrete technology is necessary, internal by recognition of the differences between the behavior of test samples of concrete under laboratory conditions and of field concrete. As an example, the historic development of curing concrete is reviewed with emphasis on the methods for monitoring the heat development during curing of modern concrete. Proposals for wider transfer of this technology are presented in the concluding remarks.

Keywords: Cold weather construction; cooling; curing; field tests; history; laboratories; precast concrete; research; temperature rise; tests

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Biographical sketch

ACI Honorary Member Gunnar M. Idorn is an international consultant. His research is widely known in areas of concrete durability, concrete technology, and research planning and organization. He is a member of ACI Committee 201, Durability of Concrete and International Activities Committee.

ABOUT ROBERT E. PHILLEO

This paper concerns some basic aspects of the nature of concrete as explored by concrete technology research since the 1940's. Implicitly the paper therefore also deals with the nature of the people in research, which is assuming increasing importance along with the profoundly changing conditions for the development of concrete technology and utilisation.

Fig. 1, from a paper published by CEMBUREAU, in 1973 (1), displays experience with people in research in their state of nature. There are good, solid workers of competence and diligence, but without any innovative creativity. There are both specific-minded and broad-minded, creative people, and there also use to be a few brilliant individualists, sort of floating in the air.

Seen from many years of contact overseas, Robert E. Philleo - Bob - was an exceptional, broad-minded innovator, reaching above the common research worker, yet never losing solid ground connections to existing engineering practice. But he was more than that - he also understood the synergic power of cooperative efforts of the different categories of research workers. And he was excellent in the art of moderating achievements of the different characters in one mould for gradual progress of general knowledge and technology.

Bob came to concrete when long term investments in basic research in the USA commenced to pay back, and to initiate worldwide developments in cement and concrete technology and structural design, along with a formidable American mechanisation of construction methods. Thus, soon after Bob along with millions of Americans had contributed to secure the survival of the West European democracies, his career in concrete research commenced at the time when the American industries and people decisively

contributed to make the subsequent reconstruction investments possible in our part of the world and when uncommon brilliance and dedication was the common feature in the American cement and concrete research community. In hindsight, this was a good time for the beginning of a new chapter in the world annals of concrete technology and construction.

Bob's display of leadership in the subsequent decades of the realisation of much new technology created by scientific research is very educational, and I believe he would have appreciated my experience in research as quite in accordance with his own, namely that:

Investments in high quality research are permanently profitable. They do not depreciate in value in the course of time like buildings and structures or investments in general knowledge and competence. High quality research achievements are probably the closest we can come to realize the perpetuum mobile concept.

THE NEW CHALLENGE TO CONCRETE CONSTRUCTION AND RESEARCH

Half a century after the time when Bob Philleo commenced his career with concrete we are once again at the gate of a new chapter in the world annals of concrete technology and construction, and once again the background is politics and economy.

Since 1989 it has become clearly visible that there are now three power centers in the world:

- North America
- * Western Europe
- * Japan (with parts of East & South-East Asia)

of about equal orders of magnitude of GNP and populations compared with the major regions of developing countries in between:

- * Central and South America
- * Eastern Europe and USSR
- * Africa, India, South-East Asia

The three power centers are at this time inhabited by about 10% of the world's population, but the developing regions represent the further population growth, predicted to reach 10 billion people during the next century.

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There are strong indications of this trend of the development in the growth of the world's cement consumption. This was in 1990 about 1150 million metric tons against about 900 million tons in 1980. Most of the increase of the decade has happened in Asia, notably China, South Korea, Thailand, India. After the 1989-91 events in Eastern Europe and the former USSR these regions will begin to follow suit, because their needs for reconstruction are enormous.

We also need concrete development within the three power centers for renovations and innovations of the infrastructure, of city slums and for environmental improvements. This is still what most of us are dealing with in daily technical occupations and short term planning. Also the new EC structure in Western Europe will result in such big investments.

Nevertheless, the problems and opportunities for the next decades of concrete engineering and construction, and for research, are in the demands and conditions of the developing countries. These demands will cause strain on and exhaustion of the available resources of capital, materials and trained work forces and as a consequence, we urgently need, and fortunately are also at the doorstep of, a new chapter in the world annals of concrete technology.

A GLANCE IN THE REARVIEW MIRROR

When the First North American Congress convened in Carpenters Hall, Philadelphia, on the morning of 5 September 1774, Patrick Henry of Virginia expressed the situation of the 13 colonies in the memorable words: **We are in a state of nature.** The truth of this gradually dawned on his fellow delegates and helped to shape the constitution of the United States.

The classical, plain rules for making good concrete were developed during the 19th century to become a simple constitution of concrete technology. It emerged from long-term field experience which recognized the state of nature of concrete created by the material properties, mix design, handling of fresh concrete, and curing. Technology development during the last 40 - 50 years has brought radical alterations of materials and methods without sufficient amendments to the original rules to accommodate the changed nature of the concrete.

American research early on made remarkable progress in

understanding the nature of concrete. An important early innovation for practice was Abram's law. This was followed by the exploration of the chemistry of portland cement in the 1930's. Physical, chemical and mineralogical science was applied to describe the physical properties of hardened cement paste and the essential aspects of concrete durability during the 1940's and 50's. The consistent emphasis of field concrete performance along with increasing application of basic, natural sciences helped to create the contemporary research concept that "concrete in its state of nature" should be the decisive objective of research. The concurrent development of ASTM test methods and ACI guidelines demonstrated the appreciation of experience with field concrete.

For instance, ASTM C33 has, since the introduction of test methods for alkali reactivity of concrete aggregates, preserved the cautionary advice that the test methods do not provide quantitative information about the effects of the use of the aggregates in concrete in service. Therefore evaluation of an aggregate *"should be based upon judgement and on the interpretation of test data and examination of concrete structures containing the aggregates and cements for use in the new work"* (underlined by writer).

The ASTM test methods regarding the resistance of concrete and aggregates to freezing and thawing refer to the ASTM C192 specification for the curing of test specimens. They shall be moist cured at $73.4^{\circ}\text{F} \pm 3^{\circ}\text{F}$ ($23^{\circ}\text{C} \pm 1.7^{\circ}\text{C}$). However, for the scope of C666-84 it is stated that: *"..... Neither procedure is intended to provide a quantitative measure of the length of service that may be expected from a specific type of concrete"*. C671-86 clause 3.1 states: *"The significance of the results in terms of potential field performance will depend upon the degree to which field conditions can be expected to correlate with those employed in the laboratory"*. C672-84 states in 3.3: *"No relationship has been established between the frost immunity of specimens cut from hardened concrete and specimens prepared in the laboratory"*. In C682-84 the advice to relate the evaluation to field service conditions is even more specific in clause 3: *"It is of utmost importance, therefore, that the user of this practice assesses at first the following anticipated field exposure conditions"*, and the subsequent clause 3.1.2 states that: *"The curing procedures anticipated for the concrete"* shall be used in the testing.

These clauses tell the concrete specifiers, among other things, that the test methods' constant room temperature curing of laboratory test specimens does not relate to actual curing conditions for field

concrete. In hindsight, the primary difference obviously is that the constant room temperature curing of laboratory test specimens continuously removes the heat of hydration of the cement from the hardening specimen. In contrast, the heat of cement hydration in field concrete is preserved for activation of the hardening process and utilized as long as it is not dissipated to the environment by heat transfer, and thereby lost. The laboratory test methods therefore violate the principle that concrete should be tested and evaluated as it behaves in its state of nature, especially concerning the generation and effects of the heat during early curing.

Concurrent with major investments in hydropower, infrastructure and defense projects before and during World War II, laboratory testing as a means of quality control and research was developed in North America. In Western and Eastern Europe and the USSR the emphasis was on industrialisation of concrete production in the service of the tremendous need for reconstruction and rehabilitation. The cement and concrete industries introduced higher C_3S portland cement ground to higher fineness, precast and prestressed concrete and system building concepts. The higher level of heat development in the hardening concrete than hitherto experienced in ordinary field concrete, and soaring fuel prices from 1973, have gradually paved the way for the development of curing technology to monitor the interactive heat and strength development during the processing of on-site and plant-made concrete. Unfortunately, cement and concrete research declined both in North America and Europe during the 1970's, and the research communities could not maintain sufficient basic research on the kinetics of cement hydration needed as the knowledge basis to avert the deleterious consequences of too intensive heat development during concrete curing. Nor was there applicable knowledge to take proper advantage of the heat as an effective production accelerator. Concurrently, the ASTM advice to take experience with performance of actual concrete structures into consideration passed into oblivion.

THE NATURE OF CURING

The curing phase of concrete processing creates by chemical hydration reactions three solid reaction products which are akin to known natural minerals:

Calcium silicate hydrate	-	Tobermorite (or Jennite)
Calcium hydroxide	-	Portlandite
Calcium aluminate sulphate hydrate	-	Ettringite

The hydration reactions which create the calcium silicate hydrate (referred to among researchers: C-S-H) cause simultaneously the crystallisation of calcium hydroxide in the porous microstructure of the C-S-H, which constitutes the cement paste. The calcium aluminate sulphate hydrate, better known by its natural mineral name ettringite, is the product of the reaction between the calcium aluminate (C_3A) in the cement and the gypsum added for controlling the setting of the cement in fresh concrete. The ettringite in the hardened concrete is found as aggregated crystallites in microflaws, water filled air bubbles and other available spaces.

As a set of exothermic chemical reactions, the hydration of the cement is accompanied by the development of heat. The heat accelerates the hydration process and therewith the development of strength in the hardening concrete. Excessive early heat development may cause microflaws in the cement paste, and macrocracking if the interior of concrete remains heated while external surfaces cool down to ambient temperatures. The hydration reactions of the cement clinker compounds and their reaction products are understandably the same as those which occurred in concrete after the invention of portland cement in England in 1824. It is the conditions under which the reactions take place which steadily and now profoundly have changed, especially during the last 40 - 50 years.

EARLY CURING TECHNOLOGY FOR WINTER CONCRETING

Before World War II, the inherent heat development in concrete during its curing was rarely recognized as deserving attention in types of structures other than large dams (2). In this kind of construction works, the overall range of heat development during the curing was small to moderate and slow, due to the low C_3S content and coarse particle sizes of portland cements and the low cement content per cubic meter of concrete. The need was recognized, however, to minimize cracking due to temperature differences in the large mass concrete volumes, for instance, in gravity dams. This was ensured by internal cooling, water pipeline systems for reduction of the peak temperatures and also by using fly ash or other pozzolans as partial cement replacement materials (3).

Broad international attention was given to the dependence of the rate of strength development in concrete on the temperature during curing at the RILEM Conference on Winter Concreting, Copenhagen 1956 (4,5,6). In the preceding years the simplified Arrhenius

equation which states that the rate of a chemical reaction doubles for every 10°C increase had been applied by European researchers (7,8,9) as the basis for maturity functions for concrete hardening in the 0 to 20°C temperature range. Danish research further applied the Fourier equation for calculations of heat dissemination through a concrete body (10). By application of concurrent American research on the physical properties of hardened cement paste (11,12) a maturity based curing technology for winter concreting was established (6). Measurements of internal temperatures of the concrete during the early phase of curing was used as input for the maturity calculations to determine the time needed for the concrete to reach resistance to the first freezing, and later, the time for sufficient strength for form removal. The market interest in this technology was due to government funding to stimulate house building all year round. The aim of this policy was to reduce unemployment and resolve the habitation problems. Winter curing technology R&D became a successful contribution to improvements of the social standard of living.

In hindsight, one must be aware that building sites in those days did not have access to compressive strength testing of concrete control specimens. The application of quality control by direct measurements of the temperature development in the field concrete itself was therefore genuine progress, despite the rather crude theoretical data bases for maturity calculations and the inconvenience of measuring site temperatures in very cold weather. In fact, this pristine curing technology would have been progressive even if standard 28 day compressive strength testing of specimens cured at room temperature had been part of ordinary quality control. This is because room temperature curing of test specimens would not have simulated the delayed strength development in the actual concrete at lower temperature ranges. Thus, the technology responded to the concrete in its state of nature under winter concreting conditions.

THE INTRODUCTION OF ELEVATED TEMPERATURE CURING

Winter concreting lost importance in Europe and also in the colder parts of the USSR during the late 1950's with the advance of precast concrete manufacturing and element system building techniques. In North America the concrete technology development took another course since the major growth areas for concrete uses became industry and infrastructure investments in the northern and the mountainous states.

Contemporary American concrete research was in a leading global position. At the 4th International Symposium on the Chemistry of Cement in 1960 in Washington D.C., the emphasis was therefore on the chemistry of cements, the fundamental nature and the physical properties of hardened cement paste, and related theories of frost resistance of concrete. General dependence of the rate of hydration of cement on hydration temperature, i.e. the kinetics of the chemical reaction, was mentioned in one paper (13) suggesting application of the Arrhenius equation. But this was not related to any application in engineering practice. At the time of the symposium the instrumentation revolution for scientific research commenced, the academic community and basic research gained strength, and laboratories with room temperature conditions were established. Experimental research with specimens made at room temperature became general practice. This built a solid "Berlin wall" between further development of concrete curing at elevated temperatures in practice and academic research on cement hydration.

At the 5th International Symposium in Tokyo in 1968, one session with two principal papers (14,15) from Denmark and the USSR was devoted to the subject of concrete curing because of the pronounced advancement of precast concrete technology and research in these countries. The papers reviewed the state-of-the-art knowledge of the effects of heat on cement hydration and the properties of concrete. They both attracted limited interest within the basic scientific cement and cement hydration research community and in contemporary precast concrete industries, except in the USSR and Eastern Europe.

At the 6th Congress in the series in Moscow 1974, the peak year for concrete production in Western Europe, 1973, had just passed with its recession turmoil caused by the soaring fuel prices. The principal paper on "The Effect of Elevated Temperatures and Pressures on the Hydration and Hardening of Cement" (16) summarized the accomplishments during the preceding years' further developments in precast curing technology and related research.

Fig. 2 depicts three variants of curing procedures in industries developed by trial and error since the late 1950's. The very fast curing cycle applied steam injection in the concrete mixer making the fresh concrete +40-50°C warm at placement. The medium cycle applied some hours delay of heating in the mould by steam curing at a peak temperature of +70°C, while the slow cycle

applied longer preheating times and +40-50°C peak curing temperatures. These modifications of curing procedures were remarkable feats of precast industry management skills. The very fast cycle was introduced first when social demands on housing were insatiable, the medium cycle was the reaction to the soaring fuel prices in 1973, and the slow cycle sufficed when subsequent recessions took effect, except for special products such as railroad ties, prestressed structural elements, pipes etc.

The concurrent research which was summarized in the principal paper did not represent an overall strategic R&D effort as the basis for the industrial development but rather multifaceted, fragmentary approaches to specific issues and troubleshooting problems. The Arrhenius equation was proposed to be used in studies of the kinetics of the hydration reactions, and relevant activation energies were determined experimentally. It was established that ettringite in concrete is unstable above about +70°C and that calcium silicate hydrate (C-S-H) accommodates more SO_3 with increasing curing temperatures. It was mentioned that the setting time of cement paste decreases with increasing temperatures, and that alkalis are setting accelerators. Recommendation to increase the SO_3 content of cement with 10-15% C_3A content was referred to with the comment that "cements for steam curing nearly always contain too little gypsum". Contrasting suggestions for keeping the C_3A content below +8% were also referred to. Another presentation (17) showing that rapid hydration of cement causes heterogeneity of the hardened paste was also referred to. This was also discussed by Idorn (14), and has further been the subject of recent studies (18). Other studies (19,20) were mentioned which showed that elevated temperature curing might damage concrete due to different thermal deformations of cement paste, water, air and aggregates, causing internal microcracking and thereby reduced strength and increased porosity. Air entrainment for frost resistance was referred to as acceptable provided there was a 2 to 3 hour preheating curing period. Radical increase of early strength, resulting in reduced later strength, was reported for temperatures elevated from +20°C through 35, 50, 70 to 90°C. Initial preheating at minimum 3 hours before a maximum rate of temperature rise of +10°C/hour was suggested. Insertion of thermocouples into concrete for temperature recording was recommended along with +70-80°C as peak temperatures and gradual cooling at 10-20°C/hour. Considerable loss of water at elevated temperature curing was also demonstrated, and reduction of shrinkage and creep was found as a consequence of steam curing, albeit at effective wetting.

Although the principal report thus gave evidence of the 1968 to 1974 progress of knowledge, of which much was applicable, it did not constitute or lead to systematic technology for curing at elevated temperatures with monitoring of the process to ensure that high quality concrete would be attained at much reduced production time and costs.

In North America, the American Concrete Institute issued reports by Committee 517 on accelerated curing of concrete in 1963 (21), 1970 (22), and 1980 (23). Reports on concreting in hot weather were issued by Committee 605 in 1958 (24) and Committee 305 in 1977 (25). These two series of reports were predominantly based upon experience in engineering practice in the United States and did not refer to the extensive research reported at the international cement chemistry congresses or other conferences abroad. The available methods for maturity and heat dissemination calculations were not incorporated in the advisory reports. Thus, the potentials for heat saving and for insurance against initial microcracking and ultimate strength decline remained targets for further development.

THE NATURE OF MODERN CONCRETE

The acceleration of concrete hardening by steam curing illustrates in a practical way that heat as a form of energy is a fundamental parameter of the kinetics of cement hydration or, in other words, an integral facet of the nature of concrete. The conditions for hardening concrete have therefore changed with the introduction of steam curing in precast industries and for site produced concrete.

Fig. 3 shows the modest temperature development during the curing of mass concrete elements at the Hanstholm jetty, Denmark, 1950 (26). The external environment was the North Sea air and water temperature ranges, the cement a 40-45% C_3S portland cement with 10% pozzolan, and w/c of the concrete was about 0.65. The peak interior (adiabatic) temperature in the concrete was about $+40^{\circ}\text{C}$ reached in 4 days and declined to ambient level in about 40 days.

Fig. 4 shows the violent heat development in concrete made for a structure at the coast of the Arabian Emirates in the early 1980's, where the environment is hot/dry in the day, cold/wet at night, and where continuous precipitation of airborne salt from the sea is unavoidable (27). The peak curing temperature was about $+80^{\circ}\text{C}$, reached in the course of 12 hours, and the peak temperature

difference between the interior and the surface was $+48^{\circ}\text{C}$.

The Hanstholm concrete was durable. In the Middle East case, the specified reliance on the 28 day standard room temperature compressive strength cube test for quality control resulted in a weak, porous cement paste, intensive initial cracking of the concrete, subsequent ingress of chloride ions and rapid corrosion of reinforcement creating advanced structural deterioration in the course of a few years. Fig. 4 could be a symbolic "logo" for the widespread deterioration of new structures in the Middle East during the 1970's and early 80's, and also for concurrent corrosion damage to precast facade panels of buildings in Europe, and oversalted highway structures in North America. Initially it was the reinforcement corrosion which attracted attention as the cause of failure because that represented more obvious risks for structural collapse than the indirect though preceding effects of curing damage due to high hardening temperatures.

During the 1980's, the concern in engineering practice regarding thermal cracking appeared along with changes of cement compositions, cement content in concrete and as failure cases made their mark (28-37). Studies on the application of the maturity principle for a theoretical based curing technology also appeared (38-42). The ACI conference in 1985 on concrete at early ages was further evidence that this concern was now appealing to the research community (43).

In 1987, ASTM adopted C1074: Standard Practice for Estimating Concrete Strength by the Maturity Method (editorially corrected in 1990). Apparently this standard anticipates broader use of maturity based curing technology, although it does not comprise descriptions of the corresponding curing procedures. Neither does it suggest criteria, for instance, for preheating time, rates for heating, peak temperatures or rates of cooling; in other words, it does not present information about how to use the method in quality management systems. Nevertheless, the adoption of the standard is an irreversible step towards the proper treatment of modern concrete in its state of nature during curing at elevated temperature.

CURRENT PRACTICE AND AVAILABLE DEVELOPMENT

Figs. 5 and 6 depict two different approaches to curing technology at elevated temperatures developed in current practice. Fig. 5 is a personal summary of recommended and existing practice in precast industries in several countries. Fig. 6 depicts the principle of the

monitoring system for curing technology based on the use of maturity function after Arrhenius and Fourier heat transmission calculations.

The range of procedures in Fig. 5 covers some which comprise a 1-3 hour "preheating" stage before application of heating by steam, others without this precaution, as well as curing processing without any exterior heat supply. Maximum acceptable concrete temperatures are sometimes $+75^{\circ}\text{C}$, other times only $+60^{\circ}\text{C}$. Rates of heating vary between about 10 to 20°C per hour. Attained compressive strength is often the criterion for cessation of heating, sometimes based upon the strength of cores taken from finished elements, elsewhere by testing specimens which have been stored by transfer of the same temperature cycles from the elements themselves to the test specimens (44). The procedure shown in Fig. 6 is based upon the principle that the degree of hardening of the concrete at any stage is a function of the time-temperature history until that time, including the effects of the heat of hydration, externally imposed heat, and loss of heat to the environment.

Fig. 7 shows the maturity function which this curing technology is based upon, along with the precursory editions which sufficed in the past for low temperature hardening for winter concreting practice. The method makes pre-design of the appropriate course of curing possible, calculating with estimated values of cement and concrete properties and the environment, and respecting specified limits for soak temperature and for temperature differences between surface and interior of structural or precast concrete elements (45). The preheating phase is "built into" the procedure which also makes it possible for contractors to design and optimize heating and cooling methods for given project conditions. During the actual construction or precasting operations, the temperature development in the concrete is recorded by thermocouples and can be immediately transformed by a maturity computerisation into attained resistance to first freeze and to strength values for determination of form removal or external stress impact.

The two systems for curing technology are related in the sense that they recognize and apply the accelerating effects of elevated temperatures on concrete hardening. In fact, they fundamentally recognize the effects of temperature on the hydration of cement; in other words, it recognizes the kinetics of the hydration process as nature's basic principle allowing us to use cement for making concrete. Implicitly, both systems therefore also recognize that effects of temperature on chemical processes in the hardening

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concrete, other than the rate of strength development, are the same whether in steam cured concrete in precast plants or in construction site concrete which attains temperatures at elevated levels during its curing. Both systems are relied on to ensure that curing temperatures are restricted so as not to cause initial cracking by too intense heating.

The two systems for curing control are different in some respects: The steam curing procedure shown in Fig. 5 is applicable for precast industries. The maturity based technology depicted in Fig. 6 as a genuine monitoring system, responding to the actual development of heat and strength in concrete masses, is applicable both at site construction works and in precast industries. The method can also be applied for adjustments in precast steam curing procedures with the purpose of optimizing the external heat supply dependent on cement types, cement contents, dimensions, ambient temperatures, element mass and dimensions and the required rate of strength development. In precast concrete plants and at site constructions with many repetitions of elements this curing technology can be applied as an effective control to reduce standard deviations from specified quality requirements.

CONCLUDING REMARKS

1. It is generally known that the intensity of heat development during early curing of modern concrete is much higher than in the past. The reasons for this are higher heat of hydration of portland cement, higher cement contents, the use of additional heating to increase the productivity in the precast industry, and the increasing amounts of concrete construction in the warm belt of the earth. The economic gains by accelerating the production of concrete in plants and at construction sites have often been spectacular. The trade-off is the risk that overheating, high rates of heating and high peak temperatures during the curing may cause irreparable cracking of the concrete. Such introductory defects, which may not initially be discernible, weaken the longer term concrete performance quality.
2. The precast industry has introduced testing based, regulatory control of temperature rise and cooling in concrete production. The advantages by broader introduction of the maturity based monitoring system are obvious. The hardware investment is confined to purchase of thermocouples, leasing of calorimeters

and access to computer processing of data, including thermocouple readings. The software investment is merely technical staff education in modern quality management.

3. Both the existing regulatory curing control in precast industries and the maturity system have been developed and implemented without corresponding updating of knowledge by basic research. This is illustrated by the absence of presentations of updated basic knowledge on cement hydration in dependence of increasing concrete temperatures during curing in two recent outstanding books on cement chemistry (46) and materials science in concrete (47). The chemistry of cement hydration and the mechanics of structure formation in modern concrete production is therefore in urgent need of applicable knowledge from new research essential for ensuring economy in production and satisfactory performance in service.
4. Planning and management of further research and education is required to make curing technology an indispensable part of modern design of the processing of concrete and of quality assurance systems.
5. The research should take note of the ASTM principle to identify the problems by analyses of experience in practice, with precast as well as site produced concrete. Hot topics seem to be the sensitivity of different types of concrete to preheating before steam curing (in precast plants), and to the entire course of curing cycles as dependent on the materials, the concrete composition and the conditions for the hardening.

Further development of the recording systems and refinements of input data for maturity calculations are also on the agenda for research planning analyses, for the organisation of which Concrete Materials Research Council of ACI seems an excellent forum.

6. For concurrent engineering education the ACI committees C231, C305, C306, C308, C517 and C201 seem to constitute the proper bodies for the formation of a joint "HEAT IN CONCRETE" committee or temporary task force. This should assume the responsibility for the assessment of the international state of the art knowledge in research and current practice in close association with research planning by Concrete Materials Research Council.

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7. ACI is also in a unique position to stimulate extensive input from international chapters and members in such a development, and to initiate cooperative, international management of coordinated research programs, for instance, in the manner pioneered by the American Strategic Highway Research Program organisation of international highway research programs.

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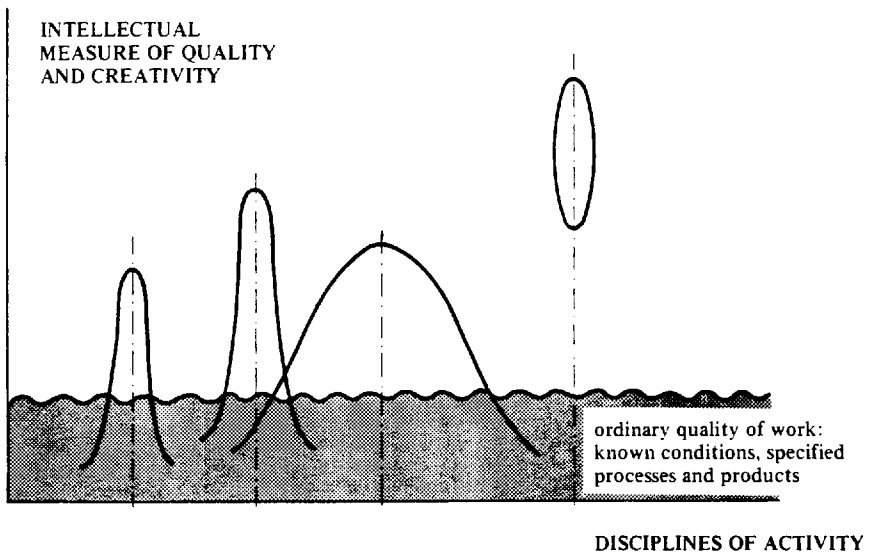


Fig. 1—Creative research and innovation work form peaks above ordinary quality of activity under secure conditions of work which aim at keeping specified processes going to produce known products of predicted characteristics. The laissez-faire management style easily lets the creative mind release itself like a balloon from its basis of assistance and sponsorship. The analytical management approach is inclined to cut off the peaks of creativity and is most likely satisfied with controllable ordinary quality of work, rather than the individualistic or team-spirited creation of new ideas for future technologies.

The demand to R&D management is a neither-nor and thus a continuous challenge to the manager who steadily must adjust the particularly suited style of managerial operations for ever changing conditions.

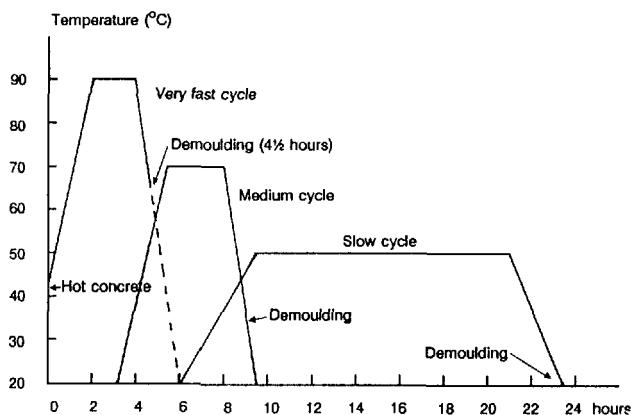


Fig. 2—Survey of steam curing procedures about 1974. Different ranges of temperature/time cycles for steam curing of concrete. The very fast cycle requires initial heating of the fresh concrete (except in hot countries) e.g., by steam injection in the mixer. It allows a peak temperature of up to +90 C. This procedure made 3 work shifts per day possible in precast plants. The medium cycle has a several hours preheating period before steam is turned on and the peak temperature is reduced to +70 C. This procedure made 2 work shifts per day possible. The slow cycle with +50 C peak temperature would usually not require external heat supply (except in cold weather concreting). A specially controlled preheating period as shown is therefore fictitious. The slow cycle corresponds in precast industry to a situation of over capacity for production. From (16)

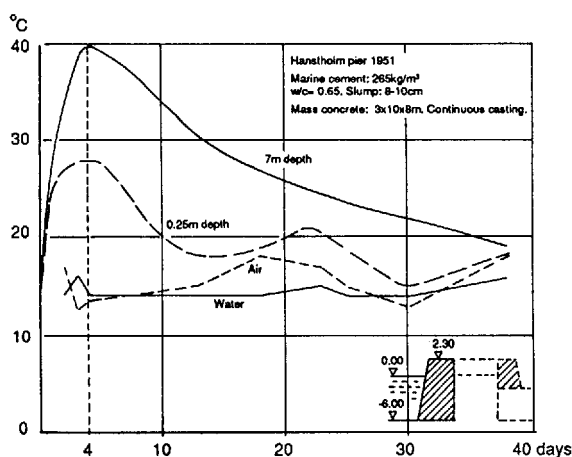


Fig. 3—Temperature development in mass concrete at Hanstholm pier, Denmark, 1951. Maximum interior temperature +40 C was reached after 4 days, and cooling down to environmental temperatures took about 35 days. From (26)

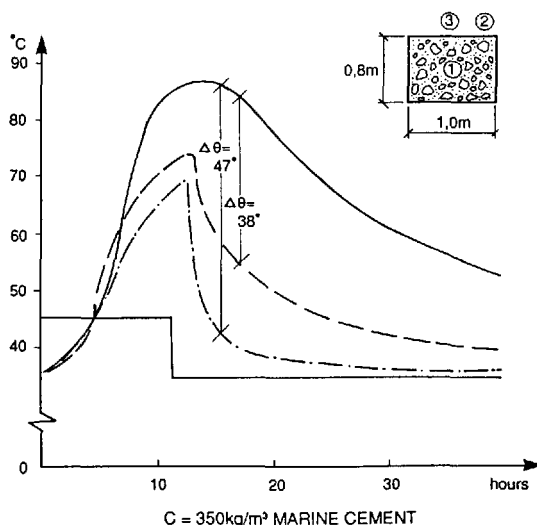


Fig. 4—Temperature development in the interior (1), corner (2) and mid-face (3) and of column in basement of building in a hot country. Post-calculation based on records on cement and cement contents, temperatures of fresh concrete and of ambient air during subsequent days, data on formwork, curing procedure, etc. New Danish Highway Authority regulations request temperature in the interior of concrete to be max. 60 C, and temperature differences between surfaces and interior to be max. 20 C. The limits are not complied with here, and this sustains an evaluation based on microscopy that the concrete cracked severely during early curing due to excessive thermal stresses. From (27)

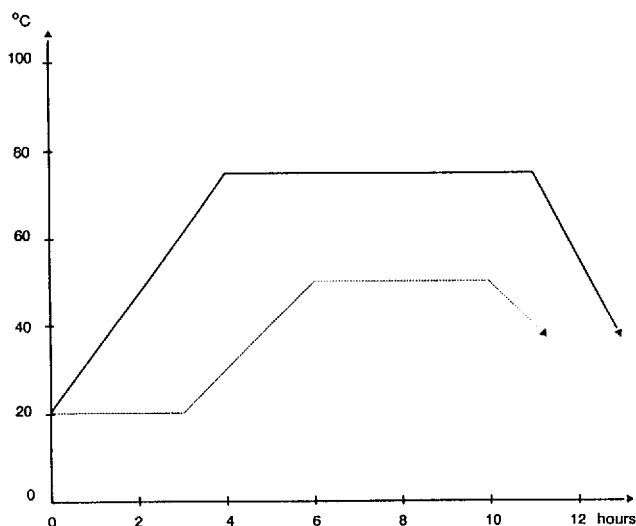


Fig. 5—Survey of the range of temperature/time cycles for steam curing of precast concrete based on published guidelines and information from current practice (published and private communication). The very fast cycles (Fig. 1) seem now to be abandoned everywhere, and peak temperature of 60-70 C seems to be increasingly common

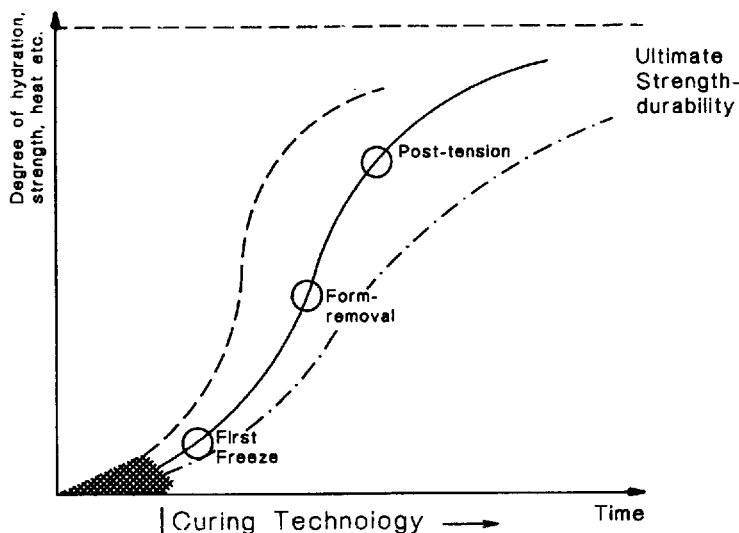
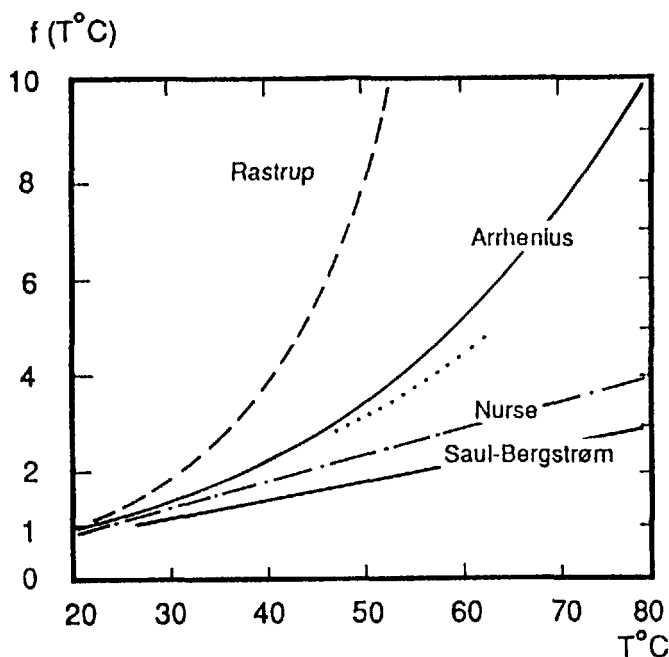


Fig. 6—A model display of the curing technology concept. The rate of strength development can deliberately either be chosen to be reduced or increased by using curing calculations during the preparations of the construction work. By means of temperature recording in the actual concrete during the curing phase the chosen course of the hardening can be controlled, and if need be means of adjustment can be applied.



TEMPERATURE FUNCTIONS : $f(T)$

NURSE : $K \cdot T$

SAUL-BERGSTRØM : $K \cdot (T + 10)$

RASTRUP : $K \cdot \frac{2 \cdot T}{10}$

ARRHENIUS : $K \cdot \exp\left(-\frac{E}{R \cdot T_K}\right)$

MATURITY FUNCTIONS : $M = \int_0^T \frac{f(T(t))}{f(T)} \cdot dt$

$M_{20 \text{ ARRH}} = \int_0^T \exp\left(\frac{E(T)}{R} \cdot \left(\frac{1}{293} - \frac{1}{T_K(t)}\right)\right) \cdot dt$

Fig. 7—Different temperature functions expressing the rate of hydration of cement paste as a function of the temperature of the reactions, and the general and Arrhenius based maturity functions by means of which the rate of hydration of cement paste in concrete at varying temperatures can be related to the comparable rate of hydration at +20 C. The maturity functions by Nurse, Saul-Bergstrøm and Rastrup were developed for winter concreting and satisfactory in the corresponding low temperature range with peak temperature in the 20-30 C range

SP 141-3

Statistical Methods to Evaluate In-Place Test Results

by N.J. Carino

Synopsis: In-place testing is used to estimate the compressive strength of concrete in a structure by measuring another related property. A strength relationship is used to convert the in-place test results to an estimate of the compressive strength. Statistical methods are needed for reliable estimates of in-place strength. Such methods should account for the uncertainties in the measured property, the uncertainty of the strength relationship, and the variability of the in-place concrete. Standard statistical procedures for dealing with these uncertainties have not yet been adopted in North American practice. Recommendations are provided for developing the strength relationship, and a reliable, easy-to-use approach is presented to estimate in-place characteristic strength.

Keywords: Compressive strength; construction; in-place testing; loads (forces); pullout tests; regression analysis; repeatability; safety; statistical analysis; strength; tests

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INTRODUCTION

On April 27, 1978, work was in progress on a hyperbolic reinforced concrete cooling tower located at Willow Island, West Virginia. At about 10:00 a.m., while concrete was being hoisted for the placement of the next 1.5-m lift of the shell, there was a sudden failure of the concrete ring placed on the previous day. The catastrophic accident resulted in 51 deaths, making it the worst construction accident in U.S. history. A subsequent investigation concluded that the most probable cause of the failure was inadequate concrete strength to support the applied construction loads [1].

This accident demonstrated the critical importance of considering construction loads and monitoring in-place strength development in concrete construction. This incident also provided great impetus in North America to modify construction practices and search for reliable methods for in-place testing of concrete.

In-place tests are used to estimate the strength of concrete in a structure by measuring a property, such as resistance to penetration or surface hardness, which is related to compressive strength: the critical property needed to assess load carrying capacity. In 1974, ACI president Robert E. Philleo was one of the first in North America to publicly champion in-place testing^b. In a later paper, Philleo provided convincing, rational arguments on the advantages of in-place testing [2]. In-place testing is more economical than testing cores drilled from the structure, and it provides information that is more representative of the concrete in the structure than is obtained from the traditional method of testing field-cured specimens. Philleo was also one of the leaders in the standardization of many of the in-place test methods in use today [3,4].

Due in part to Philleo's rational arguments and the work of Malhotra [3], in-place testing became a *recognized* alternative to testing field-cured

^b"In-Place Heresy," President's Message, *ACI Journal*, March 1974, pg. N1.

cylinders by the addition of the following sentence to the section of the 1983 ACI Code dealing with form removal [5]:

"Concrete strength data may be based on tests of field-cured cylinders or, when approved by the Building Official, on other procedures to evaluate concrete strength."

The Commentary to the Code listed acceptable alternative procedures, and further stated that these alternative methods *"require sufficient data using job materials to demonstrate correlation of measurements on the structure with compressive strength of molded cylinders or drilled cores."* Thus, to use any of the alternative methods, an empirical relationship must be developed to translate the in-place test results to equivalent compressive strength values. In addition, a procedure is needed to analyze in-place test results so that the compressive strength can be estimated with a high degree of confidence. Both steps require statistical analysis of test data.

Procedures for performing in-place tests have been standardized by ASTM [6] and other organizations, and a recent report by the American Concrete Institute [7] provides additional guidance on their use. However, while a standard practice exists for statistical evaluation of direct compressive strength results [8], there is no comparable standard in North America for the evaluation of in-place test results. This paper deals with the key aspects of a suitable statistical procedure. The goal is to propose an initial framework for future efforts to develop a consensus standard for analysis of results. First, the objective of in-place testing during construction is discussed. This is followed by a review of the statistical principles to be considered in applying in-place testing. Finally, a procedure is presented which accounts for the major sources of uncertainty when in-place testing is used to estimate the in-place compressive strength.

This paper is dedicated to the memory of Robert E. Philleo, whose logical thinking and application of statistical principles in concrete technology had a profound influence on the author's professional development.

OBJECTIVE OF IN-PLACE TESTING

In designing a reinforced concrete structure, the engineer uses the *specified compressive strength* of the concrete. However, the strength of concrete in a structure is variable and is more accurately described by some type of probability density function. In North American practice, the specified strength is generally taken to represent the strength that is expected to be exceeded with about 90% probability, i.e., if 10 random samples were taken from the structure, 9 of them would be expected to exceed the specified

strength. The specified strength is also called the *characteristic strength*, and this term will be used in subsequent discussion.

One of the objectives of in-place testing during construction is to assure, with a high degree of confidence, that the concrete in the structure is sufficiently strong to resist construction loads. To have a safety margin during construction that is consistent with that under service conditions, one needs to know the in-place characteristic strength at critical stages of construction. How can we be assured of a reliable estimate of the in-place characteristic strength? The answer is by using statistical principles to account for the various sources of uncertainty.

The application of in-place testing for monitoring strength development during construction involves the following steps:

- Establish a relationship between the in-place test result and compressive strength.
- Perform the in-place tests prior to critical stages of construction.
- Analyze the test results to obtain a reliable estimate of the in-place characteristic strength.

The statistical principles to be considered during these steps are discussed.

THE STRENGTH RELATIONSHIP

Some manufacturers of in-place testing equipment provide with their devices one or more strength relationships to estimate compressive strength based on the in-place test results. However, the ASTM standards [6] and the ACI report [7] recommend that a correlation should be established for the specific test instrument using concrete materials that are similar to those to be used in actual construction. The following questions must be answered to develop a reliable strength relationship:

- How many test points (i.e., strength levels) are needed?
- How many replicate tests should be performed at each strength level?
- How should the data be analyzed?

Number of test points

The usual procedure is to perform replicate in-place tests and replicate standard compression tests^c at various strength levels. The average values of

^cCompressive strength is considered in this discussion, but correlation could also be established between in-place test results and other standard strength properties, such as flexural strength or indirect tensile strength.