MISCELLANEOUS PAPER C-70-18

PORTLAND - CEMENT CONCRETE RESEARCH, TESTING, AND PERFORMANCE

by

Bryant Mather

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ARMY-MRC VICKSBURG, MISS.

FOREWORD

The Board of Directors of the American Society for Testing and Materials (ASTM) selected Mr. Bryant Mather, Chief, Concrete Division, U. S. Army Engineer Waterways Experiment Station (WES), to prepare and present the 44th Edgar Marburg Lecture at the annual meeting of ASTM in Toronto, Ontario, Canada, on 23 June 1970 in the Ballroom of the Royal York Hotel.

A draft of the lecture was submitted to the Office, Chief of Engineers, and was cleared for presentation and publication. A slightly modified version, including reference to a number of matters that came to the author's attention later, was the basis of the presentation and the version submitted to ASTM for publication.

Directors of the WES during preparation and publication of this paper were COL Levi A. Brown, CE, and COL Ernest D. Peixotto, CE. Technical Director was Mr. F. R. Brown.

Bryant Mather

Portland-Cement Concrete; Research, Testing, and Performance

ABSTRACT: A critical review is made of selected aspects of the state-of-the-art of the prediction of performance of portland-cement concrete in service from the results of tests. The role of research in evaluating performance and in guiding the development of tests is discussed. It is concluded that while remarkable progress has been made, much remains to be done to provide basic and fundamental knowledge of the phenomena, the substances, and the environment of service. The critical needs are for better understanding of the nature and formation processes of the bonds that as formed give concrete strength, the processes by which these bonds become broken, and the critical levels of interacting environmental factors that produce irreversible changes in concrete in service. Such research results will permit the planning of experiments to yield data to establish relations between levels of relevant properties and performance in levels of environmental influences. From such relations, performance may be predicted. From such predictions, test methods and specifications may be established.

KEY WORDS: portland cements, cements, concretes, hydraulic cements, specifications, standards, tests, admixtures

This is, according to my count, the 44th Edgar Marburg Lecture. This lecturer felt very humble as he read the names of previous lecturers. I expect all future lecturers will have similar feelings. This lecture honors Edgar Marburg, the first secretary-treasurer of ASTM who served in that capacity from 1902 to 1918. I suggest that it is appropriate that this 1970 lecture also should honor, by extension, Mr. Marburg's most recent distinguished successor, Tom Marshall, who served as ASTM's Managing Director until his recent untimely death on April 9th of this year. ASTM has been fortunate in the caliber and competence of men who have served it as Chiefs of Staff; and we can well use this vehicle to express our appreciation of all who have so served all of us.

I should also like to call to your attention the fact that the first Edgar Marburg Lecture, 44 years ago, in 1926, was presented by Arthur Newell Talbot who took as his title "Research and Reinforced Concrete as an Engineering Material." There are men in the Talbot Laboratory at the University of Illinois today who could speak as authoritatively on the current status of research in reinforced concrete as could Professor Talbot in his day, and who continue to contribute to the work of ASTM especially in Committee C-9 on Concrete and Concrete Aggregates and Committee A-1 on Steel.

Almost exactly 30 years ago--to be precise, on 26 June 1940, the then Chairman of ASTM Committee C-1 on Cement,--who was, like the present Chairman, a federal bureaucrat, appeared before this Society to present the 15th Edgar Marburg Lecture. The title of P. H. Bates's monumental work is "Portland Cement: Theories (Proven and Otherwise) and Specifications."

Mr. Bates died in 1968 and at this meeting Committee C-1 is inaugurating an award created to honor his memory. Mr. Bates graduated from the University of Pennsylvania in 1902, the year that Edgar Marburg, who was also head of the Department of Civil Engineering there, became secretary-treasurer of ASTM. After Mr. Bates's graduation he became associated with the Pennsylvania Railroad where he worked with the first president of ASTM, Charles B. Dudley, until 1906. Mr. Bates's Marburg lecture occupies 32 printed pages in the Proceedings. Professor Thompson's 1969 lecture occupies 8 pages in the Journal of Materials. Today's lecture will be brief. I hope that these introductory reflections will have indicated to you why I feel that it is fitting that in 1970 there again be a discussion of cement and concrete presented to this society as a Marburg Lecture.

The purpose of making tests is to obtain information to predict performance. Research provides information on the composition, constitution, properties, and evolution, of the substances of interest. The information provided by research permits the selection of testing procedures and provides the basis for evaluating results of tests so as to predict performance. Much has been learned about cement and concrete, more is being learned every day. However, many unanswered questions remain and much of the testing that is now done is based on empirical relationships that have little rationale in terms of prediction of performance. The phenomena by which a suspension of particles of portland cement in water evolves into the solid cement paste binder of mortar or concrete, and by which this binder may be modified by interaction with environmental factors, are still poorly understood. The critical needs include a better understanding of the nature and processes of formation of the bonds that give strength to cement paste, and hence to mortar and concrete; the processes by which these bonds may become broken; and the critical levels of interacting environmental influences that produce irreversible changes in cement paste--and hence in mortar and concrete--in service.

The purpose of ASTM is to advance knowledge of materials and to conduct standardization activities relating to materials. All thoughtful people--and especially all ASTM members--should appreciate that standardization, to be effective and meaningful, must be based on knowledge of materials performance. I intend to call attention here to some areas in which knowledge is needed in order for standardization to evolve into more effective and meaningful terms. I will take portland cement and concrete as examples.

Portland cement concrete is a composite material that develops most of its relevant properties after it has been manufactured, transported to the place where it is to be used, deposited in the mold or forms or space that it is to fill and that is to give it its final shape. It is a composite of at least three and usually four distinct categories of ingredients: cement, aggregates, and water, plus one or more members of the category known by the rather indefinite designation "admixture." All of these, except water, are themselves usually multicomponent materials. All may be and usually are processed prior to use but only the cement is necessarily manufactured.

Portland cement and concrete are made and sold because they can serve some needs of mankind more economically and more satisfactorily than competitive products. There is, however, virtually no end product in which cement is used that could not be replaced by one containing no cement, if some other more economical and more satisfactory material were available. Concrete dams, concrete buildings, concrete roads, concrete wharves, concrete tanks, concrete bridges, exist not because there is no other way to provide these structures, but because an engineering and economic conclusion was reached that concrete was the most economical and satisfactory material to employ.

The material concrete--the product that forms itself from an assembly of portland cement, aggregates, and water--possesses many properties that can be measured, and the results of the measurements reveal that concrete can be formulated to possess these properties in a very wide range of levels. Concrete can be of nearly any color from white to black. Committee C-9 has a task group currently working on specifications and methods of testing coloring materials for concrete. Concrete can be of a wide range of unit weights--the specific gravity can be as low as 0.3 (20 lb per cu ft) to 4.0 or more (250 lb per cu ft). Committee C-9 has a task group on foaming agents for production of cellular concrete and subcommittees on lightweight concrete and on high-density concrete. Concrete can be so soft it can be excavated by a teaspoon or a fingernail or it can be so hard that diamond tipped tools cut it only with difficulty. It can be produced so that under quite small loads, less than 100 psi, it will deform so as to be reduced in volume to half, or it can resist very large loads--20,000 psi or more--with little deformation. It can be produced so it will be destroyed at relatively low temperatures or be highly refractory. It can be made to be a rather good electrical or heat conductor or a very effective electrical insulator or thermal insulator. It can be provided with great chemical resistance to many varieties of aggressive influences or it can be quickly destroyed by these same influences. It can be highly permeable or nearly impermeable. It can be provided with surfaces of great smoothness or great roughness; and this catalog could be extended.

When concrete performs unsatisfactorily it is because the particular concrete provided for the particular use in the specific location did not develop the proper levels of all the relevant properties that it should have developed to make it perform satisfactorily. This regrettable result, when it occurs--and fortunately it occurs only rarely--is a consequence of one, or both, of only two possible errors: either the concrete that was used failed to meet the specifications under which it was purchased or the specifications under which it was purchased failed to require appropriate levels of all relevant properties. Either you didn't get what you ordered or you didn't order what you needed.

It is the responsibility of ASTM--and of Committees C-1 and C-9 in particular--to contribute to knowledge of portland cement, concrete aggregates, admixtures, other materials used in making concrete, and concrete, so that knowledge will be available on what properties are relevant and what levels of these properties are needed for concrete to perform satisfactorily in any given use and environment. With this knowledge, standards may be developed that will contain meaningful requirements and refer to effective methods of testing cement and other concrete materials and concrete.

A great deal of progress has been made. Today, if it is required, as a part of the specifications for concrete, that all the ingredients used in its production comply with the current ASTM specifications, that the concrete--if it is itself ordered as an over-the-counter product--meets the ASTM specifications, and proper controls are in effect to insure that these requirements are complied with, the results will be satisfactory in virtually all instances. Much more than 90% of the cases of unsatisfactory performance result from failure to comply with published standards of good practice. We need research and development to deal with the remaining few cases, where concrete has been produced to the current standards of good practice and has failed to give satisfactory service. These cases, when adequately studied, reveal either that some particular combination of ingredients at particular levels in certain critical properties in a particular environment of use have interacted to produce instability; or some particular feature of the environment has interacted with the concrete to produce deterioration. The knowledge resulting from such studies has been evaluated and revisions have been made in specifications and, as needed, new or modified methods of testing have been developed and standardized.

The most difficult problem arising from activities of the sort just mentioned is the development and evaluation of the relevant knowledge. It may have been quite conclusively shown that cement containing quantities of a given ingredient at levels as high as were present in the cement used, employed together with a certain aggregate containing quantities of a given ingredient at levels as high as were present in the aggregate used, should not have been used in concrete of the proportions used in the environment in which it was placed, without some precaution having been taken to inhibit or mitigate the effects of the interaction that produced the instability that lead to the deterioration of the concrete and ultimately to the unhappiness of and expense to the owner. But how should ASTM proceed? Committee C-1 could, in effect, pick a number, significantly lower than the level of that of the cement that was used, and write into the ASTM specifications for cement that there shall be no more than this much of that ingredient. But how shall it select the number, how long can it, in good conscience, wait to receive results of experiments before taking some action to protect other users from the trouble that was caused the unhappy owner mentioned? Committee C-9 can, of course, simultaneously be considering a limit on the allowable amount of the "offending" aggregate constituent. Both committees may well be hearing about other ingredients that could have been added to the concrete that would have prevented the difficulty. And meanwhile in the Highway Research Board, in the American Concrete Institute, in the Portland Cement Association, and at other research and development centers and technical societies throughout the world the matter will be under study. Until rather recently, little of this activity will have been directed to quantification and evaluation of the relevant properties of the environment in which the misbehavior took place. Now this too is being studied in a most significant way.

We have learned much about the levels of properties concretes can be provided with. We are learning much about how to insure that a concrete has the levels of the presumably relevant properties that are mentioned in specifications. We are making progress in learning which properties are relevant to performance of different concretes for different uses in different environments. We have a long way to go to learn precisely what levels of what relevant properties are critical to concrete for each particular use in each particular environment. Yet, as was stated earlier, very very little concrete fails to give satisfactory service. This excellent record of performance results from two causes. The current standards of good practice, although they are based only on fragmentary bits of quantified relevant data, nevertheless reflect the empirical awareness of generations of competent practioners who, through experience, learned what to do and what not to do to stay out of most kinds of trouble. Their wisdom was great. Their rules, reflected in our standards, keep us out of most kinds of trouble. But they don't do it efficiently and they don't apply perfectly--especially to novel formulations of ingredients and mixtures, and to extreme environmental conditions. If we are to know how to use old materials efficiently and economically and to use new materials as well or better than we now know how to use old ones, we need to know why we do what we do, and how quantitatively to relate our selection of relevant properties and levels to the use and environment of use of the concretes we are to make in the future.

Today, too often, we require certain levels of chemical properties or particle size distribution or abrasion resistance--primarily because sometime in the past some body of data showed that a group of tested samples meeting these levels of these properties were associated with better performance than other samples not meeting these levels. Often the original body of supporting data failed to provide even a speculative chemical or mechanical mechanism to explain why this relationship of improved performance should be causally connected with an increase or decrease in the level of the property in question. Too often the data failed even to refer to a level of a property--being expressed only as a level in the result of a testing procedure. The limit remains in the specifications today. Its perpetuation is considered justified by those who defend such perpetuation by citing the fact that materials meeting the specifications containing the limit have given good service and it cannot be stated with equal assurance that other materials rejected by the application of this limit would have performed as well.

Today we have many tools not widely available in the past. X-ray diffraction permits rapid differentiation of materials that have similar chemical composition but which actually are different substances; a variety of spectroscopic instruments and procedures allow rapid, accurate, analysis of smaller samples and assessment of the quantities of constituents present in very small amounts; nondestructive testing techniques allow the changes in samples--and structures--to be followed through time and evaluated for relevant properties of the hidden interior portions; modern mechanical testing equipment permits studies to be made with greater precision and accuracy on a greater range of specimen sizes at a greater range of levels of properties and with better control of environment over greater ranges of environmental parameters. Today we also have the tools of statistical experimental design and electronic data processing which, when properly employed, are of invaluable and unique assistance, respectively, in guiding us to a reasonable choice of what to do in our experiments, and to what can be learned from the results of our experiments.

With these tools at our command, with the progress that has been made, with an awareness of the defects in our present formulation of the standards of good practice, with the knowledge that a costly wasteful crash program is not needed to keep concrete structures from falling down, we can and should mount an orderly, well planned attack on improving the state-of-the-art in cement and concrete testing and specification to the end that the future standards of good practice can be based on an understanding of relevant physical and chemical mechanisms, on the quantified relations of these mechanisms to levels of properties, to an understanding of the relevance of properties to performance, and to the interaction of properties with environment in producing performance. Such an attack cannot fail to provide a basis for modifying present requirements. I confidently predict that these modifications will necessarily make future requirements for cement and concrete more restrictive for certain uses in certain environments and less restrictive for other uses in other environments. I also confidently predict, that of the total concrete market, vastly more would fall in the category properly subjected to more relaxed requirements in the future than to that properly subjected to more stringent requirements. Thus, this attack will widen the market for cement and concrete and improve their competitive position; it will permit the use of aggregates not now acceptable; it will permit the production of much cement at lower production cost; and will, at the same time, raise the cost of cement and concrete in a few uses in a few environments but thereby reduce the greater costs of later repair or replacement that would otherwise be required had the more stringent requirements not been invoked at the time of construction.

Mr. Bates, in his 1940 lecture, provided a discussion of the problems encountered in defining portland cement. These problems still exist. There are constitutents of portland cement clinker which today are still inadequately understood and there are current problems in defining the calcium sulfate that is nearly always an essential ingredient of portland cement. He then presented a most interesting summary of the history of portland cement. Some notable additions to this history have been made in the ensuing years and today we see compositions including exotic ingredients whose inclusion permits production of portland cements that have unusual levels in the properties of volume change or setting time. He discussed the reactions of cement with water. Today we are witnessing a major development of new understanding of the nature and structure of the products of this reaction. This development is characterized by some controversy especially regarding the interpretation of the information on structure. As data are derived--and, more importantly, are understood--by the use of electron microscopy and the electron probe, these matters will not only be better understood, but the knowledge so gained will allow cement to be better used. Mr. Bates referred to the fact that at the meeting at which he spoke, the Society was "considering the acceptance of tentative specifications for five types of cement in which chemical requirements are so outstanding and physical requirements so dimly visible." He referred to these specifications as being "as good as an outline of research, through their inadequacies, as they are good purchase specifications." The specifications have been revised many times since 1940 and have been improved. But today, I believe they are better as an outline of research than they are as purchase specifications. Cement and concrete obtained by the intelligent use of current standards will yield--together with competent structural design and construction practice--structures that will in nearly all cases serve well their intended purposes. However, the current specifications for portland cement of any given type allow products of an amazingly wide variation in levels of relevant properties to be offerred in terms that would lead to very substantial difficulties if they were substituted one for another as sometimes is attempted.

In a letter received this spring from a distinguished engineer, a past president of the American Concrete Institute, I found these comments. "I have observed considerable variation in the quality of concrete produced by various brands of cement... The cement industry is suffering serious economic problems throughout the country... The depressed condition of the cement industry, in my opinion, can be attributed to the attitude of the consumers of cement, and this sad state of affairs will continue as long as low quality standards prevail, with the price per barrel as the yardstick for marketing. In our area, all brands are priced equally. We have measured the quality of the cements by their performance in producing high quality concrete for us. Naturally, if Brand X can achieve our objectives with 25 lb less per cubic yard than Brands Y or Z, we buy Brand X. If the choice of brand is left to the contractor, he will buy the cheapest, which encourages low cost rather than high quality. I am not sure that the Present ASTM tests are the best way to measure quality. In our experience, the most successful measure is the quality of the concrete, as made with our aggregates. The cement industry needs incentives for innovation and technological breakthroughs. It must shift its emphasis from price to technical excellence. To do this the customer should provide the rewards."

Mr. Edward Cohen, vice-president of the American Concrete Institute and chairman of its Building Code Committee, writing in the February 1970 issue of Materials Research and Standards, speaking as a designer of concrete structures, wrote "more research is needed to incorporate the variety of cement properties into the art of cement production. It is common knowledge that cements coming from certain areas of the country are preferable to others... the designer should be given the opportunity to specify that type of cement which best meets his structural and economical requirements."

The project manager for the contractor on the largest Corps of Engineers construction job, now going on, speaking in March 1970 at the Engineering Foundation Conference on Rapid Construction of Concrete Dams, noted as the first item in a list of "most promising areas" for cost reduction in construction of dams, "Better control and raising of strength requirements of cement--and optimization of SO_3 content and/or any other component to insure maximum response to admixtures to aid in better utilization of strength properties of portland cement concrete." In 1940, Mr. Bates, speaking of admixtures, said "As a red flag is purported to be to a bull, so were admixtures to some cement producers... Until very recently anyone who would dare propose the use of admixtures with portland cement to improve any somewhat lacking property was immediately figuratively killed with anathemas hurled by some producing interests... There never have been any logical reasons for this peculiar adverse attitude... Let us bear in mind that the setting and hardening of cement is a chemical reaction and one which takes place very slowly... It does not take much of an imagination to conclude that there are likely to be a host of materials which will speed up the reaction tremendously, possibly to the extent that within a day we may have the strength usually attained at the end of a year... It is curious that so much time has been spent in developing different kinds of cement and so little on developing very promptly by means of admixtures the full inherent qualities of the cements already at hand... The use of admixtures should not be frowned upon or scorned. On the contrary, their development and study should be highly commended and fostered." In 1970 a very large proportion of all the concrete made in the United States--and elsewhere--contains, in addition to portland cement, aggregates, and water, one or more admixtures. In 1964, the Director of Research of the Portland Cement Association, Mr. Hubert Woods, speaking before the convention of the National Ready-Mixed Concrete Association, said "The impression seems to be fairly widespread that the PCA is against admixtures of every kind. This is simply not so. For nearly two decades we have been advocating air-entrained concrete... air-entraining admixtures are an indispensible part of modern concrete technology... There are circumstances under which accelerators or retarders or water reducers or other admixtures may usefully be employed... We do not recommend indiscriminate use of admixtures... which renders the concrete less than adequate for its intended purpose... Use without adequate accuracy in batching, without adequate understanding of use and function... will lead to inadequate concrete." Even in 1970 not everyone concerned with cement has become as enlightened as Mr. Woods was in 1964 or as Mr. Bates was in 1940. Nevertheless, I believe that the next two major areas for development, innovation, and improvement in specifications for portland cement will be to provide assurance of greater uniformity of behavior and to provide assurance that the cement will perform more uniformly in concrete with the selected kinds of admixtures with which it is used.

Mr. Bates closed his 1940 lecture by expressing the wish that all engineers using cement could reach the degree of enlightenment of realizing that cement technology was not yet firmly founded on the doctrine of uncertainty. He stated that such recognition "would surely lead to more determined and more effective efforts to secure the results needed to change uncertainty to certainty... But the fact that it is certain that there are still many uncertainties regarding the true nature of portland cement, how it reacts with water, and how it will deport itself under certain trying conditions, in no way detracts from the proven findings of its tremendous use that 'the results are startlingly satisfactory'." The uncertainties of 1970 are not exactly the same ones that were those of 1940, but the challenge remains as does the opportunity.