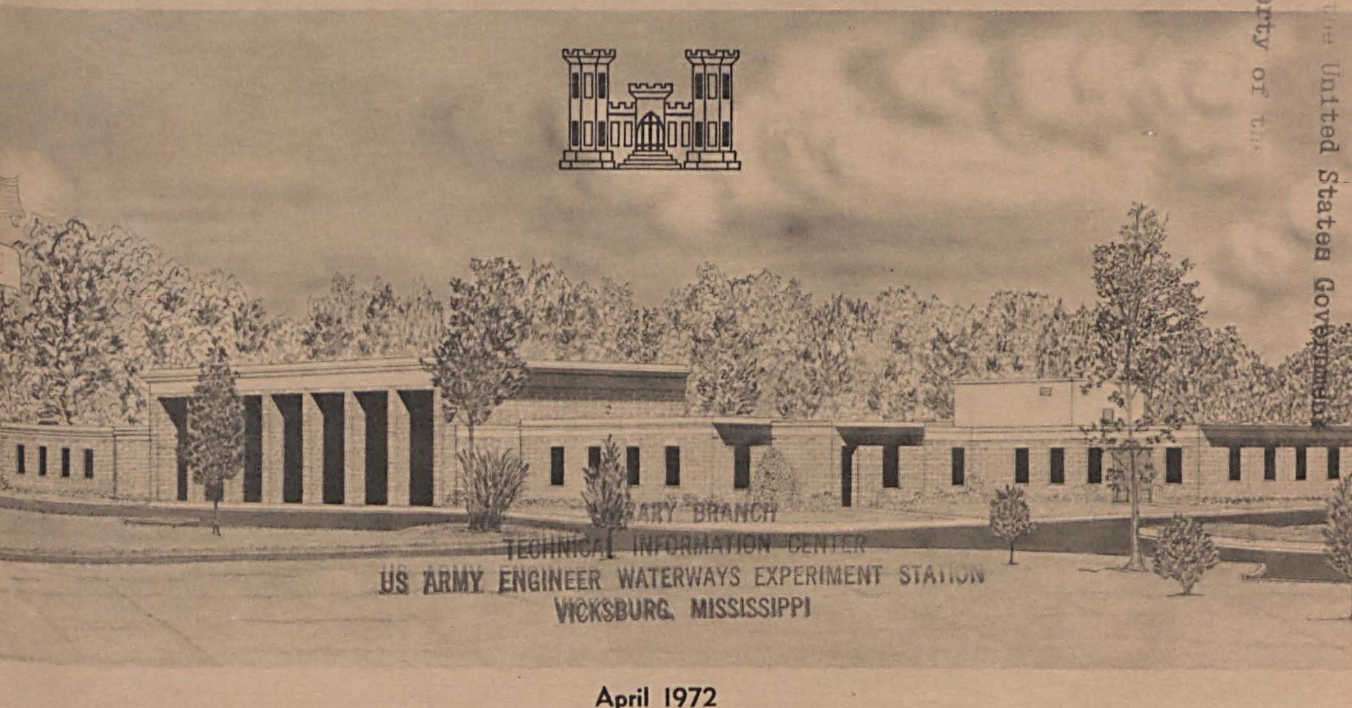
MISCELLANEOUS PAPER C-72-7

RELATING MATERIALS QUALITY TO MATERIALS PERFORMANCE TO STRUCTURAL PERFORMANCE OF CONCRETE

by

B. Mather



April 1972

Conducted by U. S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi

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Foreword

On 13 January 1971, Mr. J. R. Wright, Chief, Building Research Division, National Bureau of Standards, who also is RILEM* Delegate to the United States and Vice Chairman, U. S. National Committee, Conseil International du Batiment (CIB), invited Mr. Bryant Mather to submit an abstract of a paper for consideration for inclusion in the RILEM-ASTM-CIB Symposium on the Performance Concept in Buildings to be held in Philadelphia, Pa., 2-5 May 1972. Under date of 23 August 1971 word was received that the abstract submitted on 3 February 1971 was accepted and the paper should be submitted. On 27 August 1971 the manuscript was submitted concurrently to NBS and OCE. It was cleared by OCE on 17 September 1971 and was returned by NBS on 2 November 1971 approved subject to certain suggestions by reviewers. A revised "camera-ready" manuscript was sent to NBS on 18 November 1971.

Director of the WES during preparation of this manuscript was COL Ernest D. Peixotto, CE. Technical Director was Mr. F. R. Brown.

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* International Union of Testing and Research Laboratories for Materials and Structures.

Relating Materials Quality to Materials Performance to Structural Performance of Concrete

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Portland cement, aggregates for portland-cement concrete, admixtures for concrete, and curing materials for concrete are usually procured for use in construction under specifications that stipulate levels of quality as indicated by the results of standardized tests of samples. The information obtained from these tests is believed to be related directly or indirectly to levels of performance of the material itself, the composite of which it is a constituent, the structural element of which it is a component, and the structural system of which it is an element. The testing is limited to determinations that can be completed in the time available for testing and at an appropriate cost. The levels of quality are selected to be few for simplicity and are frequently higher than needed to insure adequacy of performance in the specific situation; rarely lower. Attention has primarily been directed to those few cases where less than adequate performance has resulted. Greater economies and more prudent utilization of natural resources will result if attention were directed to those much more numerous cases where stipulated levels of quality are higher than needed.

[1] Chief, Concrete Division

Key words: Aggregates; cement; concrete; concrete quality; materials; performance; portland cement; structural performance.

1. Introduction

This symposium on "The Performance Concept in Buildings" provides a most appropriate forum in which to re-examine the validity of the implicit assumption that the levels of quality of materials required by purchase specifications do insure the appropriate levels of performance of these materials in the composite of which they form a part, of that composite in the structural element of which it is a component, and of that element in the structural system or building of which it is an element. Other contributors to this symposium will review the criteria upon which structural systems or buildings are planned, designed, and specified to have the selected dimensions, location, orientation, and other features generally related to user needs. This paper addresses the criteria upon which the concrete that will be used in a structural system or building is selected and specified.

2. Aggregates for Concrete

Typically, as indicated for example by Section 403 of the 1963 ACI Building Code (1)[2], aggregates for concrete for reinforced concrete buildings are required to conform to a general specification, in the example ASTM C 33, Specifications for Concrete Aggregates (2). However, Section 403 provides an escape clause reading "except that aggregates failing to meet these specifications but which have been shown by special test or actual service to produce concrete of adequate strength and durability may be used...where authorized by the Building Official." These statements are not changed in the 1971 Code (3).

ASTM C 33 includes a note to its scope, which note reads "This specification is regarded as adequate to ensure satisfactory materials for most concrete. It is recognized that, for certain work or in certain regions, they may be either more or less restrictive than needed." Much of the concrete in buildings does not need to resist the action of freezing and thawing when in a wet condition; in fact, relatively very little concrete in buildings must be able to resist such an exposure in order to provide satisfactory performance. Nevertheless, ASTM C 33-71 requires (Section 5) that fine aggregate must be tested by the sulfate soundness procedure and not exhibit more than a stipulated amount of degradation--or have a satisfactory service record--or perform satisfactorily in a freezing and thawing test. No option is given, other than through the general note to the scope, for waiving the soundness provisions when they are inapplicable.

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[2] Figures in parentheses indicate the literature references at the end of this paper.

The criteria for selection of aggregates for concrete need to be revised so that the levels of "quality" as measured by standard tests and the tests selected for such measurement are varied to relate to the performance required of the concrete in the service environment of the building in which the concrete is used. This concept was stated by ACI Committee 621 in 1961 (4) in these words: "In selecting an aggregate it is economical to require only those properties pertinent to its use in a particular project." This is not the practice today.

3. Cement

The purchase specifications for portland cement were referred to by P. H. Bates in 1940 as being "as good as an outline of research, through their inadequacies, as they are good purchase specifications" (4). Mr. Bates spoke of the activities of the user of cement in these terms: "He must determine which type (of cement) he should use in any case by studying the conditions under which he will use the cement, the conditions during its later life, and the requirements in the standard wherein the nature of the several types is given. In many cases the choice is simple and can be quickly made. A high-early-strength cement would hardly be selected if there is no need for haste in construction or in placing the finished structure in use. A low-heat or sulfate resisting cement would hardly be selected for a reinforced concrete frame building to be covered with brick or stone" (4). This, I suggest, is the performance concept in building--related, more than 30 years ago, to the purchase specifications for cement. Yet, today the degree to which we are able to employ this concept efficiently is not very great. In 1970, I wrote the following: (5)

"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, current specifications for portland cement of any given type allow products of an amazingly wide variation in levels of relevant properties to be offered in terms that could lead to substantial difficulties if they were substituted one for another as is sometimes attempted.

"In a letter received this spring from a distinguished engineer and 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.... 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.

"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 as a designer of concrete structures, said, '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 project 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 or any other component to ensure maximum responce to admixtures to aid in better utilization of strength properties of portland cement concrete.'"

4. Concrete

If the environment of service imposes tensile stresses on the concrete that exceed its tensile strength, one or more cracks will form. If a given crack is one that interferes with the rendering of satisfactory service by the concrete, it is desirable that there be an investigation to establish whether the error that was made that allowed the conditions to develop that required the crack to form was in (a) estimating the stresses that would be imposed, (b) estimating the strength that would be required, (c) selecting concrete materials and proportions to give the strength estimated to be required, or (d) producing concrete having the strength estimated to be required. Note that there are four stages where error can occur; stated more generally these are:

1. Evaluating the environmental severity.

2. Selecting the quality level of relevant properties appropriate to the environmental severity.

3. Selecting materials and proportions to yield concrete of the appropriate quality level of relevant properties.

4. Getting concrete of the desired quality.

Stated bluntly, when concrete fails to behave properly, the questions are: (a) Did you order what you should have ordered? (b) Did you get what you ordered? i.e., should you properly blame yourself or the contractor for the trouble you are in?

Figure 1 was prepared to show the relationship between concrete properties and concrete behavior. It assumes that concrete, a material, is an element of a system such as a building. It further assumes that the concrete is desired to behave in a given manner if the performance of the system of which it is a part will be satisfactory. Thus starting in the center of the botton of the diagram with "performance of the system," we assume that from the criteria applicable thereto one can establish what performance is desired of the concrete. Knowing the desired level of performance, we should be able to establish the desired--and needed--level of relevant properties, provided we also know the level of the environmental influences that will act upon it. When the desired levels of relevant properties are established, the specification requirements for materials properties, materials proportions, and construction practices may be set. Once these requirements have been stipulated, and enforced, the result will be the production of concrete having such levels of appropriate properties that, as the concrete interacts with the environment, its behavior in service will be such that its achieved performance will equal the desired performance and the performance of the system of which it is a portion will be satisfactory.

In the present state-of-the-art of concrete making, it is not possible to state, without reservation, that a particular concrete mixture is uniquely the most economical that could be specified and produced at a given time in a given place, to be placed at a given location in a particular structure. The techniques for evaluating the environment conditions to which that concrete will be subjected during its service life do not permit precise calculations. We can estimate dead loads rather accurately; live loads somewhat less accurately. Earthquake forces are becoming better understood. Foundation interactions are often quite poorly predictable. Chemical attack and weather severity are evaluated generally only in qualitative terms. Since we cannot evaluate environmental conditions with precision, we could not select appropriate levels of quality to match environmental severity even if we had a perfectly precise basis for relating concrete quality levels to degrees of combined and classified environmental severity. We are in better shape when it comes to selecting materials and their proportions to yield predictable quality levels of concrete properties, but in some areas even here we can only deal in qualitative terms. Finally, there is quality control and inspection; the point at which we try to have assurance that we are getting within proper limits, what we ordered and are paying for. A great deal of progress has been made in this area rather recently (6).

Milo Ketchum commented on the relation of concrete strength and building performance in part as follows (7):

"High strength, alone, has very little advantage for ordinary reinforced concrete buildings. If proper production control could be maintained, a nominal cylinder strength of 2500 psi (at 28 days) should be satisfactory for most concrete structures, and this can be achieved with a minimum cement content. High strength, however, is a symbol for other desirable properties and a pledge that the concrete will have enough cement. Ultimate strength design for sections of concrete members has demonstrated to the design profession that concrete seldom fails in compression. We specify the higher strength because of the non-uniformity of test results and because it is insurance against concrete that would have to be removed from the structure. Considering the thousands of concrete cylinders made every day, there is remarkably little concrete removed from buildings because of low strength. Even though the specifications call for removal for understrength, it is difficult to enforce this clause and in most cases some compromise is made that satisfies everyone without having to remove the concrete.

"It would make more sense to me if we were able to forget strength and were able to control the deflection properties of concrete by some kind of field test or procedure. The apparent modulus of elasticity is usually unimportant, but plastic flow of concrete is a serious problem in selecting structural systems. Almost every engineer can report examples of excessive deflections due to plastic flow or shrinkage."

This strongly suggests not only that concrete strength, specified at current levels of "quality" has little relation to significant problems of buildings performance with regard to strength but that other properties, not specified, are more significant to performance. It has been suggested that the sorts of safety factors that are currently employed to obtain specified levels of strength also add unnecessarily to cost. I suggest that a proper element in the "performance concept in buildings" is avoidance of unnecessarily high costs. Here my example is taken from a discussion of an arch dam, but I feel sure similar considerations could be developed for buildings. Wengler (8) showed that it was customary to build arch dams with a safety factor of 4 as the ratio of concrete strength to design stress. He showed, for a specific example, that by reducing the concrete strength from 4800 to 2400 psi, keeping the working stress at 1200 psi, i.e., reducing the safety factor from 4 to 2, the cement content could have been reduced from 3.5 bags/cy to 2.0 and the cost of the job by 8 percent or by nearly $2 million. By keeping the originally specified concrete strength, increasing the allowable working stress from 1200 to 2400 psi, i.e., reducing the safety factor from 4 to 2 by another route, a saving of $5.4 million or 22 percent was calculated.

5. Concluding Statement

The foregoing discussion has, I trust, suggested that, with regard to the concrete used in the construction of buildings, there are substantial benefits that may be realized if one were to start with a proper consideration of the performance of the building system in going through the process of obtaining the appropriate concrete for use therein. If one were to catalog and quantify the elements of performance of the system that are needed for structural and aesthetic success, were to relate these in turn to the elements needed for satisfactory performance of concrete, in the environment of service, one could select the appropriate quality levels of materials properties, the appropriate mixture proportions and construction practices, specify as needed, and enforce the specifications. The result would be, in so far as the concrete is concerned, concrete appropriate to its intended use. Such concrete could often be made using materials not now allowed by specifications, using concrete mixtures containing smaller quantities of more costly ingredients, and often in sections of smaller dimensions. In some cases, the reverse would be the case; in these cases the structure would be made safe and satisfactory where under current practices these results are not assured. On balance there would be a general reduction in cost and a conservation of natural resources.

6. References

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(4) Bates, P. H., "Portland Cement - Theories (Proven and Otherwise) and Specifications," Proc, ASTM, Vol 40, 1940, pages 469-500

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(8) Wengler, Roman P., Effect of Safety Factor on Cost of Arch Dams in Rapid Construction of Concrete Dams, ASCE 1970, pages 249-262

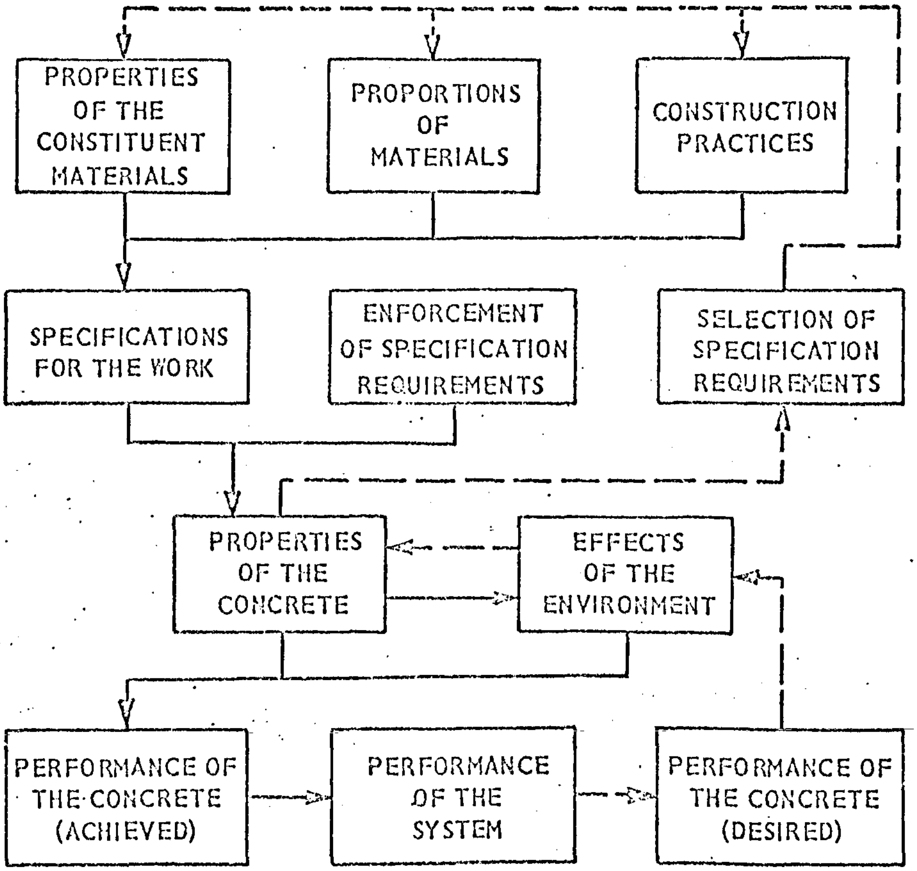
PROPERTIES OF THE CONSTITUENT MATERIALS
PROPORTIONS OF MATERIALS
CONSTRUCTION PRACTICES
SPECIFICATIONS FOR THE WORK
ENFORCEMENT OF SPECIFICATION REQUIREMENTS
SELECTION OF SPECIFICATION REQUIREMENTS
PROPERTIES OF THE CONCRETE
EFFECTS OF THE ENVIRONMENT
PERFORMANCE OF THE CONCRETE (ACHIEVED)
PERFORMANCE OF THE SYSTEM
PERFORMANCE OF THE CONCRETE (DESIRED)

Fig. 1

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13. ABSTRACT

Portland cement, aggregates for portland-cement concrete, admixtures for concrete, and curing materials for concrete are usually procured for use in construction under specifications that stipulate levels of quality as indicated by the results of standardized tests of samples. The information obtained from these tests is believed to be related directly or indirectly to levels of performance of the material itself, the composite of which it is a constituent, the structural element of which it is a component, and the structural system of which it is an element. The testing is limited to determinations that can be completed in the time available for testing and at an appropriate cost. The levels of quality are selected to be few for simplicity and are frequently higher than needed to insure adequacy of performance in the specific situation; rarely lower. Attention has primarily been directed to those few cases where less than adequate performance has resulted. Greater economies and more prudent utilization of natural resources will result if attention were directed to those much more numerous cases where stipulated levels of quality are higher than needed.

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Aggregates						
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Structural performance						