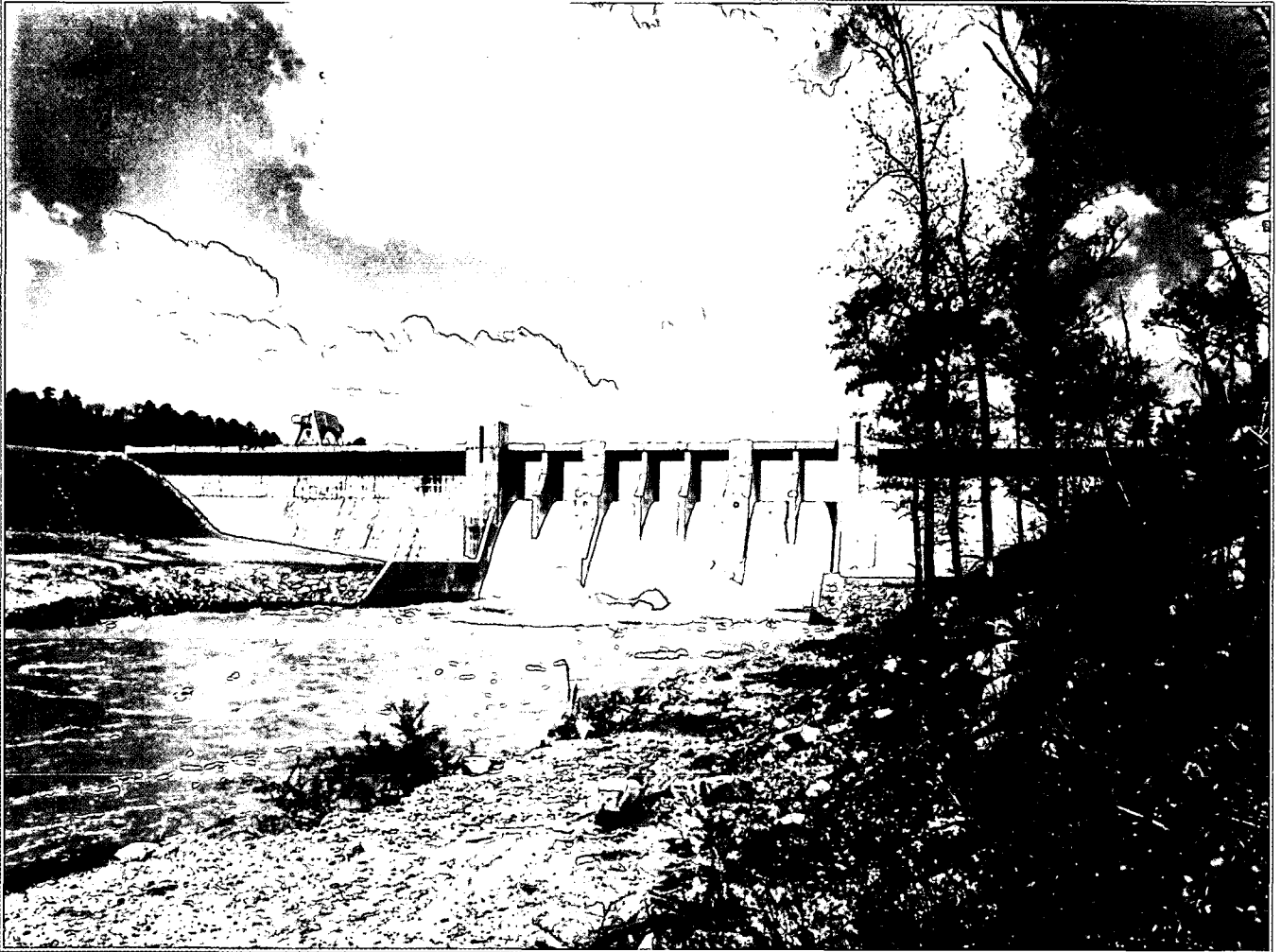


# Investigating Concrete:

## Selected Works of Bryant and Katharine Mather



*Together, Katharine and Bryant Mather have contributed over 100 years of scientific work for concrete research and development activity for the U.S. Army Corps of Engineers and have participated in many technical organizations, such as the American Concrete Institute (ACI), the American Society for Testing and Materials (ASTM), the Transportation Research Board (TRB), and others.*

**Editors:**  
**Celik Ozyildirim**  
**Shuaib Ahmad**



**American Concrete Institute®**  
*Advancing concrete knowledge*  
**SP-223**



**ACI Special Publication**

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**ACI SP-223**

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This commemorative publication is the result of contributions from a number of individuals. Ed Nawy originated the idea of commemorative compilations to honor individuals who have made significant contributions to concrete technology through their distinguished work and contributions. The idea was embraced by the Technical Activities Committee (TAC) of ACI. For this commemorative publication, Bryant Mather worked with Celik Ozyildirim and Shuaib Ahmad to compile a list of Bryant and Katharine's publications. This was a daunting task.

Gratitude and appreciation are extended to external reviewers Richard Gaynor, Terence Holland, Steven Kosmatka, Joseph Lamond, and James Pierce, who offered very valuable comments and suggestions.

The editors express their deep appreciation to Shannon Banchero of the *Engineering Staff at ACI* for working with various publishers and compiling the selected papers for this book. Her meticulous work is greatly appreciated.

Finally, appreciation is extended to all those publishers and organizations that permitted ACI to reproduce the original papers and articles of Katharine and Bryant Mather in this book. They are as follows: American Society for Testing and Materials, Elsevier, Transportation Research Board, National Ready-Mixed Concrete Association, RILEM, and Thomas Telford.



## FOREWORD

In October 2000, the American Concrete Institute's Technical Activities Committee approved publication of a commemorative compilation honoring Bryant Mather for his significant contributions to concrete technology. This publication, *Investigating Concrete—Selected Works of Bryant and Katharine Mather*, is the result of a cooperative effort by Mather, Celik Ozyildirim, and ACI Chief Engineer Shuaib Ahmad.

It is divided into seven parts: potential of concrete; cementitious materials; aggregates; durability of concrete; petrographic examination of aggregates and concrete; specifications for use of concrete in transportation structures; and research and emerging technologies. This publication also includes an appendix with a bibliography of selected works of Bryant and Katharine Mather. Bryant helped in developing a comprehensive list of their publications. Per Bryant's request, Katharine was added to the title and several of her papers were added to this publication. The total number of publications was in excess of 800. The list was reduced to 400 by identifying papers dealing with concrete materials only. Bryant, Celik Ozyildirim, and Shuaib Ahmad met at ACI Headquarters to further reduce the list to a more manageable 164 publications. This reduced list of 164 citations is included in the appendix of this publication.

Together, Katharine and Bryant Mather have contributed over 100 years of scientific work for concrete research and development activity for the U.S. Army Corps of Engineers and have participated in many technical organizations, such as the American Society for Testing and Materials (ASTM), Transportation Research Board (TRB), American Concrete Institute (ACI), and others. Their work has significantly contributed to the advancement and better understanding of concrete. On September 25, 2001, the U.S. Army Engineer Research and Development Center renamed its structures laboratory building the Katharine and Bryant Mather Building.

Bryant started his career in August 1941, when he accepted a job as a junior geologist with the Central Concrete Laboratory at the U.S. Military Academy at West Point, N.Y. Not long thereafter, Bryant began to examine aggregate to associate rock types with "soundness."

Katharine started her career at the same laboratory in April 1942. She also had assignments performing microscopic petrography. She, like Bryant, had more semester hours of petrography during her graduate work at Johns Hopkins University than any other geological specialty. Both Bryant and Katharine were assigned to work on the preparation of the *Handbook for Concrete and Cement*—a compilation of test methods, specifications, terminology, and standards in concrete technology developed or modified and adopted for use by the Corps of Engineers.

Throughout their careers, Bryant and Katharine made important contributions to concrete petrography. They co-authored a paper on petrographic methods for concrete aggregates, which was the basis for ASTM C 295, adopted in 1954. As of 2002, ASTM C 295 still cites this paper as its first reference. Katharine Mather compiled the contributions made by the use of light microscopy to concrete research, which was published as part of a symposium, sponsored by the ASTM committee on microscopy. The paper was selected by ASTM Committee C 09, Concrete and Concrete Aggregates, to receive the Sanford E. Thompson Award for 1961.

Katharine later collaborated with Tom Kennedy to produce petrographic data on concrete exposed to freezing and thawing at Treat Island, Maine. She compared the data with specimens of the same batches subjected to freezing and thawing in the laboratory. This paper was published in the *ACI Journal* and was selected for the Wason Medal in 1955.

When the Mathers joined the Corps of Engineers' Concrete Laboratory in 1941, the principal research effort at the laboratory was the Cement Durability Program, in which durability primarily referred to resistance to freezing and thawing.

Bryant further discussed the subject of freezing and thawing in his paper "How to Make Concrete That Will be Immune to the Effects of Freezing and Thawing," which was published in ACI SP-122, *Paul Klieger Symposium on Performance of Concrete*.

Over the last 50 years, the contributions of Bryant and Katharine have been recognized in many ways by various organizations, including ACI, ASTM, and TRB.

The Proceedings of the *Katharine and Bryant Mather International Conference* co-sponsored by the American Concrete Institute and published as ACI SP-100, *Concrete Durability: Katharine and Bryant Mather International Conference*, consists of two volumes totaling 2,179 pages. One of Bryant's last contributions to the concrete industry was his tireless work on the revision of ACI SP-1, *Concrete Primer*, which was published by the American Concrete Institute in 2002.

The editors hope that this commemorative publication to honor Katharine and Bryant Mather is well received and provides a good comprehensive overview of their distinguished contribution to the concrete industry.

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## PART I — POTENTIAL OF CONCRETE

Bryant's vision of concrete materials and their potential did not have limits. He believed that concrete was the choice material for construction. To help realize the potential of concrete as a construction material, he considered the ethical, social, and environmental issues. He worked endlessly to teach the professionals of the concrete community that concrete is made from local materials and local know-how and therefore has infinite variability. He also stressed that if certain factors are carefully considered, concrete with very uniform characteristics can be achieved and can be made to last as long as one desires it to last.

Bryant's paper, *Realizing the Potential of Concrete as a Construction Material*, articulates the potential of concrete in a unique fashion. In this paper, Bryant concluded that the potential of concrete as a construction material will be better realized when in his words:

1. We improve our procedures for describing what we want so we don't pay for behavior we don't need and can't use, i.e., we learn to specify intelligently.
2. We employ readily available procedures for describing, understanding, and controlling variability of concrete.
3. We consider the ethical aspects of construction and especially the environmental aspects of concrete production and use.
4. We find out and act to alleviate the real-life problems of the people who are out there trying to make good concrete.



## REALIZING THE POTENTIAL OF CONCRETE AS A CONSTRUCTION MATERIAL

by Bryant Mather<sup>1</sup>

### ABSTRACT

Concrete is international, but made locally; has infinite variability, but can be made very uniform; and can be made to last as long as you want it to. Therefore, what is needed to more fully realize its potential as a construction material is to understand what we want it to do, learn how to make it so it will do so, use available methods to restrict undesired variability, consider the ethical and environmental aspects of its use, and help the people who are making it to do it better.

### Keywords

Concrete; Durability; Environment; Ethics; Service life; Specification overkill; Statistical methods; Uniformity; Variability

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### INTRODUCTION

When the question of “realizing the potential of concrete as a construction material” was suggested to me as the subject of these remarks, my first reaction was, what is there that has been built using construction materials that hasn’t been built using concrete? What unrealized potential does concrete have as a construction material? Or perhaps one first needs to define “construction” — and then “construction material.” Stein (1993) includes in “Construction Categories” a list of building types and uses ranging from “Animal Clinic,” “Bank,” “Dog Kennel,” “Factory,” “Garage,” “Jail,” “Museum,” “Roundhouse,” “Stable,” and “Theater,” to “Warehouse.” I believe that examples of all of these have been built using concrete.

I therefore concluded that perhaps the opportunity presented by this title is not so much to talk about how to construct some category of construction that has never before been produced using concrete, but rather describing how to do concrete work of the kind that the human race has been engaged in to some degree or other for the past eight millennia (Malinowski and Friefelt 1993) but doing it better so as to serve better, at lower social cost. We need, inter alia, to learn how to better realize the potential of concrete as a construction material by producing it with the use of less energy and smaller emissions of greenhouse gases.

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Even as was the case with these remarks, in 1987 the organizers of the First International Conference on Concrete Durability invited Katharine Mather and me to speak at the opening session. On that occasion, the version that was published had the title “Reflections on Concrete Durability and on International Conferences on Concrete Durability” (Mather and Mather 1987). In it, we reiterated a number of well-known relevant facts about concrete. I restate them in slightly revised form as an introduction.

Concrete is international and as we have air to breathe, water to drink, earth to grow plants in; it provides for all that which the 1976 National Ready Mixed Concrete Association’s U.S. Bicentennial bumper sticker said: — “Concrete — the Foundation of America,” and that can now be expanded to “Concrete — the Foundation of Civilization.”

**Concrete is made locally**—The mixing water, with negligible exceptions (perhaps when concrete is made on the moon); the aggregates usually; the cement often, are or are made from one or more locally available natural raw materials, after various degrees of processing.

**Concrete has infinite variability**—The varieties of concrete that are intentionally produced are more numerous than the known varieties of natural sedimentary rocks. Concretes have been — and will be — required to be produced having densities from as low as  $160 \text{ kg/m}^3$  ( $10 \text{ lb mass/ft}^3$ ) to as high as  $4800 \text{ kg/m}^3$  ( $300 \text{ lb mass/ft}^3$ ); that have unconfined compressive strengths from as low as  $0.35 \text{ MPa}$  ( $50 \text{ psi}$ ) to as high as  $275 \text{ MPa}$  ( $40,000 \text{ psi}$ ); that are of any color — white, black, pink, turquoise, chartreuse, or as one Corps of Engineers officer demanded, “sand tan;” we await the demand for “olive drab.”

**Concrete can be made to be very uniform**—ACI Committee 214 was organized in 1946. It told concrete makers and users how to use strength tests to measure uniformity of concrete as produced and still does. In 1979, ASTM Standard Method C 917 for Evaluation of Cement Strength Uniformity was adopted. For many years ASTM Specification C 33 has put rather restrictive limits on uniformity of grading of fine aggregate in terms of fineness modulus. There are uniformity requirements on pozzolans given in ASTM Specification C 618.

**Concrete can be made to last as long as you want it to**—Even as some relatively fragile sedimentary rocks exist that have survived some hundreds of millions of years, so there are concretes that, if they remain in relatively mild environments, could last forever or at least as close to forever as we can measure. The duration of the life of a concrete with its relevant properties not sufficiently degraded so as to impair or jeopardize its ability to serve its intended purpose, is not usually a function of the absolute level of any universally relevant property of the concrete such as slump, density, strength, modulus of elasticity, or color but is almost always a function of the interaction of some property or properties, the required levels of which depend on the severity of the environment to which the concrete will be exposed in service. One need not worry much about resistance to freezing and thawing in the tropics, except in facilities using refrigeration; or at the poles, except in facilities using intermittent heating. One need not worry about acid attack, abrasion attack, sulfate attack, attack by boring or burrowing molluscs, or any of the myriad hazards described by Kleinlogel (1950), Biczok (1976), or others except where they exist and impact the concrete of interest. And where these potentially destructive influences can be and are brought to bear on the concrete, if their action and its intensity and duration are properly anticipated, the concrete can be rendered adequately resistant so as to merit the designation durable, even when as demanded of us by authorities dealing with the storage of nuclear waste, means not significantly degraded for many centuries or in some cases hundreds of centuries.

With these considerations in mind, what is there to say about the unrealized potential of concrete as a construction material? In my view, several things: First, what do we need to do that we are not doing that, if we did it, would greatly reduce the number of cases of premature degradation of concrete in service. Too much concrete that should last at least 50 or 100 years with minimal damage is showing serious damage in a tenth or less of that time. And, next, what do we need to do that we are not doing that if we did it, would greatly reduce the cost of concrete by not paying extra to provide resistance to aggressive influences that have negligible likelihood of being encountered by the concrete in its intended service life. We now, often, pay a lot to provide frost-resistant concrete for use in regions where natural freezing has not taken place for millions of years. If we only ordered what we need and can benefit from, we'd have fewer things to look out for through quality control and quality assurance, and that, too, would contribute to lowering the cost.

One important matter, therefore, is to know how properly to assess the nature and severity of the environment of service; to get a reasonable estimate of intended service life; to get a reasonable assessment of how much degradation is tolerable structurally and, when relevant, aesthetically. One must then, from these and known relationships of environmental influences and concrete composition and constitution, have and use procedures and criteria by which to select materials, proportions, and construction practices that will, with reasonable probability of success and compliance with the owner's budget for the work, give concrete that will not prematurely deteriorate.

Most of the knowledge to do this exists, some in relatively quite refined states. But the manner in which this knowledge is used in an attempt to make it an effective tool for makers and users of concrete is primitive. Today we talk about reactive vs. non-reactive aggregate and high-alkali vs. not high-alkali cement as if all structures, in all environments, involving all ambient temperatures and temperature ranges, in all degrees of moistness or dryness needed the same level of protection. There is no relaxation of the specified limit of 0.60 percent equivalent  $\text{Na}_2\text{O}$  maximum on cement as a function of environmental severity, degree of reactivity of aggregate, or anticipated level of permeability of concrete. An aggregate is either reactive or not; if not, nothing need be done, no precautions taken; if reactive, then the precautions must be taken without reference to degree of reactivity or degree of severity of exposure.

Today we talk about need for resistance to freezing and thawing. If the concrete will ever likely freeze when any of the spaces in it that can hold freezable water are more than 91 percent water filled, we need air-entrainment, sound aggregate, and protection against freezing until moderate maturity is achieved. And, air-entrainment means an air content that will give an air-void system with a bubble-spacing factor,  $\bar{L}$ , less than 0.2 mm (0.008 in.) regardless of whether we have one or one hundred cycles of freezing and thawing per year and regardless of whether the rate of freezing is fast or slow or whether the minimum temperature achieved 10 mm below the exposed concrete surface is minus 5 °C or minus 50 °C.

In 1987 (Mather and Mather), we decided to refer to these sorts of approaches as specification overkill. It involves, much of the time, paying more than needs to be paid to buy a level of protection that, in many cases, cannot ever be needed and from which no good can ever be derived. Ever in the preceding sentence means not more often than once in a million years. Today we have computers that can be run by most bright junior-high-school scientists that could be used to take the knowledge that does exist and derive from it reasonable criteria for matching degree of precautions needed or degree of restriction required of the contractor in his exercise of choice among materials, mixture proportions, and practices,

so that only limited precautions and light restrictions are called for when the nature and intensity of the anticipated environmental hazards and insults the concrete must resist are slight or of short duration in time. We can then reserve the levels of precautions we now take for all levels of severity for those cases where the hazard is really very severe and protection is needed for a very long time. We might well, by so limiting these requirements in their applicability, be able to increase their degree of protection so as further to minimize the probability that they will ever be less effective than needed. My challenge therefore is: Because concrete need not deteriorate, ensure that it doesn't, but do so without raising the cost more than necessary; stamp out specification overkill.

## VARIABILITY

Another area in which there is significant room for improvement in concrete technology in practice in the degree to which we realize the potential of concrete as a construction material is the application of the theory of probability to the understanding of, specification of, and interpretation of test data on the measured properties of concrete. The application of the theory of probability to the ready-mixed concrete industry was described by Stanton Walker (1944, 1944a) in a section of the publication *Control of Quality of Ready-Mixed Concrete* entitled "Over-Design to Meet Specifications." Tables were given showing the average strength required for operations with different coefficients of variation so that there will be nine chances out of 10 or 99 chances out of 100 that no test will fall below the specified strength. He remarked that these relations "demonstrate forcibly that investment in good control is self-liquidating." In 1946, the ACI Advisory Committee, under his chairmanship, recommended the formation of a new technical committee entitled, "Evaluation of Results of Compression Tests of Field Concrete." The mission of the committee was stated as follows: The assignment is to analyze data of compressive tests of samples of concrete taken in the field to determine the nature and extent of variations in them for different job conditions and to develop measures of the reliability of such tests as bases for the design of concrete proportions. (Taken from a letter from Stanton Walker to Harvey Whipple, November 27, 1946.)

The committee produced a standard which as of 1965 was called "ACI Standard Recommended Practice for Evaluation of Compression Test Results of Field Concrete" (ACI 214-65), which had as its abstract:

"Statistical methods provide valuable tools for assessing results of strength tests, and such information is also of value in refining design criteria and specifications. The report discusses briefly the numerous variations that occur in the strength of concrete and presents statistical methods that are useful in interpreting these variations. Criteria are offered that can be used to establish specifications and maintain required uniformity. An appendix presents a simplified version of statistical quality-control procedures."

In 1973 ACI SP 37, "Realism in the Application of ACI Standard 214-65," was published. The preface to this SP included the following:

Standard ACI 214, since its first promulgation, has produced something of a revolution in the field of evaluation of concrete strength tests, and, when applied properly, has resulted in considerable improvement in the quality, and especially the uniformity, of the concrete on projects where it was used. For reasons that are explored in some of the papers in this symposium, however, acceptance of the ideas

and techniques contained in the Standard has been slow and reluctant in some quarters. This situation has been the subject of much discussion at meetings of Committee ACI 214 in recent years.

At the meeting in Denver, in March 1971, the conclusion was reached that what was needed was a strong program of education. As a first step in this direction, the decision was made to hold a symposium at the fall meeting. A committee consisting of Howard T. Arni, Federal Highway Administration, Co-chairman; Edward A. Abdun-Nur, Consulting Engineer, Co-chairman; Francis J. Principe, Principe-Dana, Incorporated; and V. M. Malhotra, Canada Department of Energy, Mines, and Resources, was appointed to organize the symposium.

The Symposium was held on November 4, 1971, in Buffalo, New York.

Mr. Abdun-Nur's two papers, "Control of Concrete Mixes," which was co-authored by Joseph J. Waddell and appeared in the March 1959 *ACI Journal*, and "How Good Is Good Enough?" in the January 1962 *ACI Journal*, have become classics in the field of evaluation of strength tests and are still extremely helpful to those who wish to make use of Standard ACI 214. The committee hopes that the inclusion of these two papers and of Standard ACI 214 itself as Appendices along with the other papers will make this volume a very useful guide to those who are involved in problems of evaluation of strength tests of concrete.

Regrettably, much of what was said in 1973 about the application of probability is still true. What was said about what was needed is...education is still true — and always will be true. We could all benefit from reading Ed Abdun-Nur's paper on "How Good Is Good Enough?" again (Abdun-Nur 1962).

In 1993 I was invited to write a Foreword to a book called *Concrete Mix Design, Quality Control and Specification* by Ken Day (1995); in it I said:

"I was once required to attend night courses at the laboratory in which the Director, Mr. Charles E. Wuerpel, taught a course in concrete mix design. I failed to learn to do it — too much arithmetic. This was in 1942. This book, I believe, tells the reader that there is a great deal more arithmetic now than then, but don't worry; the computer will take care of getting it done, provided you instruct the computer properly.

"Somewhat later I became convinced that most of the time one could make concrete of appropriate quality for a given use with locally available materials. I once upset some nuclear physicists by suggesting that 'sidewalk' concrete from the local neighborhood ready-mix plant, if uniform, would make just as good a biological shield around a nuclear reactor as concrete with high-density aggregate imported from a thousand miles away. I suggested that the extra volume needed would cost less than the shipping cost of a smaller volume of expensive aggregates. Ken Day understands this (section 1.2).

"It has been one of my theses that properly proportioned concrete cannot be over vibrated — but one needs to proportion concrete for 'excessive' vibration if one

wants to vibrate it excessively. Ken knows this too (section 1.3). I have also argued that one can design structures (including pavements) for whatever loading is relevant and then select a design concrete strength for that loading (compressive, flexural, or whatever) and proportion a mixture to achieve it; but having done so, it is dumb not to use compressive strength for routine control testing; Ken says this (section 1.7). He knows that hot weather does not directly increase water demand, he just implies it like everybody else. Unlike everybody else, however, he has a proposal ('equivalent slump,' section 12.1) to get to the truth of the matter, as I have been urging for many years.

"The concept of distinguishing acceptable non-conforming concrete from unacceptable non-conforming concrete that Ken calls 'structurally defective' and 'contractually defective' needs more emphasis; and this book provides it.

"It is good to be reminded of the fact that when worrying about the 'actual' strength of concrete in a structure it is quite proper to worry about its present strength under some conditions and its eventual strength under others (section 5.15). It is also good to read in section 6. 1: 'Fortunately the pressure to specify minimum cement contents was resisted.' We had the battle of New Orleans about this in the ACI and a rule was made that if there were to be a minimum cement content there must also be an alternative performance requirement that if met would obviate the need for the prescriptive one.

"I was very happy to see 'Waterproofers' put into quotation marks, because the term implies doing something that is not possible.

"For these and other reasons I am pleased to commend this book to its readers, in spite of my belief that, in concrete technology, mix should only be used as a verb and design should only refer to selection of properties of concrete structural elements and hence the title should have been 'Concrete Mixture Proportioning.'"

I am told that a new edition of this may appear in 1999.

## SOCIAL/ETHICAL ISSUES

In April 1995 the Netherlands Cement industry in its magazine *Cement* included the following: "Does the future of concrete have anything to do with ethics? Any human activity has an ethical dimension. This is true of science and technology, as therefore for civil engineering too. The future of concrete will not be affected so much by ethical considerations, but mainly by technical, economic, social, and ecological developments. Nevertheless ethical guidelines can contribute to the attitudes adopted. If the construction industry acts responsibly, with a keen realization of the contribution it can make, concrete as a construction material will have an important role in the future. At the beginning of any technical venture all those involved should ask themselves in principle: 'Will this do more harm than good?' In the many cases where those involved do not consider it incumbent upon them to stand on the sidelines, they should follow some ethical guidelines, which apply to all areas of science and technology."

Among the questions that are properly asked about concrete as a construction material, in addition to the questions about whether what it is to be used to build will do more harm than good — e.g., ICBMS, nuclear power plants, gambling casinos, etc. — is the question of whether concrete or some alternative construction material does more harm to the environment in its production and use. In the United States, there has been created an Environmental Council of Concrete Organizations (ECCO) with its headquarters at the Portland Cement Association. It has produced a folder called “The Surprising Environmental Benefits of Cement” which points out that unlike building materials that rely on scarce or non-renewable resources, concrete is made from three abundant, readily available ingredients: (1) water, (2) aggregate (stone, sand, and gravel, and (3) portland cement (a fine gray powder made from abundant natural materials). A growing list of recycled materials supplements these three basic ingredients. In addition to stone, sand, and gravel, aggregate may contain some recycled materials, such as slag, a by-product of steel-making. And part of the portland cement can be replaced by other materials, such as fly ash, a by-product of coal-burning power plants.

Even the actual process of making cement uses recycled materials. High-energy wastes such as old tyres can be safely recycled as fuel for the cement-making process. Each year, a single cement kiln can recycle one million tyres, conserving fossil fuels and placing less demand on landfill space. It then points out that when you consider that concrete is strong; adaptable; and resistant to fire, water, and weather; there’s little wonder it has a longer service life than wood, steel, asphalt, and other construction products. Concrete’s durability conserves resources by reducing maintenance and the need for reconstruction. And at the end of its initial service life, concrete can be crushed and reused as aggregate for new concrete, continuing the cycle of environmental benefits. The folder also notes that the thermal mass of concrete buildings saves energy year-round by reducing temperature swings.

During the cooling season, the building will require cooling mainly at night — an off-peak time when electric companies can produce power more efficiently and conserve fossil fuels. During the heating season, a concrete building will cost less to heat than a comparable structure made of different materials. And these benefits last as long as the building itself — which in the case of concrete structures is a very long time.

It is concluded that concrete is one of the single most environmentally friendly construction products currently available.

In another connection, I was once asked to speak to the question of whether or not I was aware of any structure built of concrete by the Corps of Engineers that would have been less of an insult to its environment had it been built of a different construction material. After deliberation and consultation, I concluded that no Corps of Engineers concrete structure I could think of would have been more environmentally friendly if made of some other construction material. When I made this point in a talk, a member of the audience told me of a concrete repair to the tailrace from a penstock at a hydroelectric power dam where when the repair was completed it was noted that fish tended to assemble close to the new concrete surface. I have not been given any explanation of this, but I regard it as tending to validate my conclusion. I suggest that considering ethical, social, environmental (“green”) issues will, to an increasing degree, help in the realization of the potential of concrete as a construction material.

## PROBLEMS

In 1997 the National Ready Mixed Concrete Association surveyed its membership on technical and production-related problems. Highly rated problems were several quality assurance issues, including improperly conducted fresh and hardened concrete testing and obtaining reports from commercial laboratories. Problems relating to materials listed aggregates and cements as being variable and a lack of communication by the material suppliers when the characteristics of these materials changed. Other highly rated problems related to controlling air content and slump, primarily due to changing compatibility of cements and admixtures. On specification issues, a significant problem was dealing with unreasonable requirements, such as inconsistent prescription and performance requirements.

When asked to describe a recent technical or production problem, about 40% indicated that they were dealing with variations in materials and mixture performance, such as setting time, slump, strength, and air content. Another 30% were dealing with customer complaints regarding concrete flatwork and finishing problems, often related to improper concreting practices. About 20% of the responses related to complying with unreasonable and conflicting specification requirements, such as specifications for specific brand materials, significantly over-designed mixtures, and other durability-related test qualification.

About 30% of production problems related to improper functioning of plant and truck equipment and control systems. Obtaining and retaining trained plant personnel and truck drivers was cited as one of the primary problems. About 10% of the comments related to compliance with environmental regulations and the problems with handling returned concrete, wash water, and storm water.

When asked about how things could be improved, 40% indicated that there needs to be some means to educate and inform engineers, architects, and other specifiers about following national standards while allowing flexibility for local conditions and materials; standardize the submittal process; move toward performance-based specifications; and promote the use of concrete. About 20% indicated that testing issues should be addressed by improving and informing about standard procedures and the qualification of testing personnel. More educational and training programs for ready-mixed concrete producers, including sales training; dealing with material variability; mix designs for high-performance concrete; and other quality-control functions were stressed by about 15% of the responses. Addressing durability issues such as scaling and other flatwork problems; alkali-silica reactivity; and concrete permeability specifications were also mentioned. About 9% also indicated that contractor and customer education should be made available, while another 9% indicated that effort should be expended toward updating guides and standards in ACI, ASTM, and other organizations.

## CONCLUSIONS

The potential of concrete as a construction material will be better realized when:

1. We improve our procedures for describing what we want so we don't pay for behavior we don't need and can't use, i.e., we learn to specify intelligently.
2. We employ readily available procedures for describing, understanding, and controlling variability of concrete.
3. We consider the ethical aspects of construction and especially the environmental aspects of concrete production and use.

4. We find out and act to alleviate the real life problems of the people who are out there trying to make good concrete.

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## PART II — CEMENTITIOUS MATERIALS

Cementitious materials are an integral component of concrete. The properties of cementitious materials influence the service life of concrete and, therefore, the service life of concrete structures.

Bryant had a keen and passionate interest in extending the service life of concrete structures. One of the areas of his interest was alkali-aggregate reaction. He authored numerous publications dealing with various aspects on use of pozzolans and slag related to alkali-silica reaction.

In 1959, he published a classic paper *Effectiveness of Mineral Admixtures in Preventing Excessive Expansion of Concrete Due to Alkali-Aggregate Reaction* that has been selected to be reproduced in this publication. In this paper he described the effectiveness of pozzolans or slag in preventing excessive expansion of concrete due to alkali-silica reaction. He stated that a reduction in expansion will occur if sufficient amounts of pozzolans are used in the concrete mixture.

The main conclusions drawn in the above-mentioned paper were:

1. The synthetic silica glass was found to be the most active admixture, only 10% replacement by volume is needed to reduce the percentage expansion by 75% in two weeks; next the calcined shales, requiring 19 to 29% replacement; the uncalcined diatomite, requiring 22%; the volcanic glasses, requiring 32 to 36%; and lastly, the slags and fly ashes, requiring 39 to 45%.
2. It is evident from this investigation that no current chemical test could be used, with reliance, to evaluate the effectiveness of an admixture in preventing excessive expansion. Further work may develop a reliable chemical test, because a relation was found between minimum percentage replacement value, fineness of the material, reactive silica, and the amount of alkalies retained by the reaction product.
3. The mortar-bar test requires improvement to increase the precision for both intra- and interlaboratory testing. Andreasen and Christensen\* have noted that the finer fractions (passing a No. 125 sieve) in the Pyrex aggregate may act as admixtures, and have stressed the importance of removing these finer fractions by washing the aggregate. Other differences in testing conditions and procedures between laboratories should be resolved.
4. Specifications for evaluating admixtures for effectiveness in preventing excessive expansion due to the alkali-aggregate reaction require the material to be tested at one percentage replacement, generally 25% by volume.

\* A. H. M. Andreasen and K. E. Hauland Christensen, "Investigation of the Effect of Some Pozzolans on Alkali Reactions in Concrete," Progress Report L 1, Committee on Alkali Reactions in Concrete, Danish National Institute of Building Research and Academy of Technical Sciences, Copenhagen (1957).



## **EFFECTIVENESS OF MINERAL ADMIXTURES IN PREVENTING EXCESSIVE EXPANSION OF CONCRETE DUE TO ALKALI-AGGREGATE REACTION\*\***

**by Leonard Pepper and Bryant Mather<sup>1</sup>**

### **SYNOPSIS**

Twenty materials, representing eight different classes of mineral admixtures, were evaluated, using both chemical and mortar-bar test methods, for their effectiveness in preventing excessive expansion of concrete due to alkali-aggregate reaction. It was found that the chemical tests cannot be used with reliance to evaluate effectiveness. Each of the replacement materials evaluated will prevent excessive expansion if a sufficient quantity is used. Correlations were found between effectiveness and: fineness, dissolved silica, and percentage of alkali retained by reaction product.

Five of the materials tested (a fly ash, a tuff, a calcined shale, a calcined diatomite, and an uncalcined diatomite) showed a reduction in alkalinity of 40 percent or more when tested by the quick chemical test. All of these except the fly ash met the requirement proposed by Moran and Gilliland for the relationship between reduction in alkalinity and silica solubility.

Six of the materials tested (two slags, a fly ash, a pumicite, and two calcined shales) reduced mortar-bar expansion at least 75 percent with high-alkali cement and Pyrex glass aggregates when used as 50, 45, 35, and 30 percent replacements of the cement.

Calculations were made that suggest that the minimum quantity of each material required for effective prevention of excessive expansion ranged from 10 percent for the synthetic silica glass to 45 percent for one of the slags. By groups, these calculated minimum percentages were: calcined shales, 19 to 29; uncalcined diatomite, 22; volcanic glasses, 32 to 36; slags, 39 to 45; and fly ashes, 40 to 44.

The investigation of mineral ad-mixtures as cement-replacement materials was initiated by the Office of the Chief of Engineers in 1950 as part of the Civil Works Investigations Program with the purpose of ascertaining the degree to which portland cement may be advantageously replaced by other materials, considering cost and the quality of the resulting concrete. This paper deals with that part of the investigation that was concerned with the ability of these materials to prevent excessive expansion of concrete due to alkali-aggregate reaction.

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\* Presented at the Sixty-second Annual Meeting of the Society, June 21-26, 1959.

<sup>+</sup> This paper is based on Technical Report No 6-481, U. S. Army Engineer Waterways Experiment Station, July, 1958.

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Many tests to determine pozzolanic activity of mineral admixtures have been described (2, 6, 7).<sup>2</sup> In some, only the mineral admixture is involved; in others, the admixture is mixed with either lime or portland cement. Several tests to evaluate the effectiveness of mineral admixtures in preventing excessive expansion due to the alkali-aggregate reaction have been proposed. These tests, as well as those for determination of alkali release and fineness, were selected for use in this investigation. The tests used were evaluated for reliability, and the minimum percentage of the replacement material that would effectively reduce the expansion was determined.

## MATERIALS

### Portland Cements

Three portland cements were used in this investigation: two type I cements, one of high alkali content (1.07 percent alkalies calculated as soda) and one of low alkali content (0.37 percent); and one type II cement of medium alkali content (0.68 percent). The results of tests of these cements are given for in Table I.

### Replacement Materials

The 20 replacement materials studied represent eight classes. The classes, the specific materials tested, and the abbreviations for the materials used herein, are as follows:

| Class of Material                 | Material                                                                                  |
|-----------------------------------|-------------------------------------------------------------------------------------------|
| 1. Granulated blast-furnace slags | Slag I<br>Slag II                                                                         |
| 2. Natural cements                | Natural I (Nat I)<br>Natural II (Nat II)                                                  |
| 3. Fly Ashes                      | Fly Ash I (FA I)<br>Fly Ash II (FA II)<br>Fly Ash III (FA III)<br>Fly Ash IV (FA IV)      |
| 4. Natural Volcanic Gases         | Pumicite (Pum F)<br>Pumicite (Pum L)<br>Tuff<br>Obsidian (Obs)                            |
| 5. Calcined opaline shales        | Calcined Shale (C Sh M)<br>Calcined Shale (C Sh N)<br>Calcined diatomaceous earth (Cal D) |
| 6. Uncalcined Diatomite           | Uncalcined diatomaceous earth(Unc D)                                                      |
| 7. Uncalcined Quart               | Silica Flour<br>Air Float<br>Ad-mix                                                       |
| 8. Glass                          | Synthetic, pure silica glass (SS glass)                                                   |

<sup>2</sup> The boldface numbers in parentheses refer to the list of references appended to this paper.

The 16 materials in the first six classes were also used in the general investigation of cement-replacement materials. The methods of processing these materials and data on their use in concrete are given in report I of that investigation, (11) Classes 7 and 8 consist of four materials, all of which may be regarded as essentially pure silica. The three materials in class 7 are quartz and the one in class 8 is an amorphous silica. The results of tests of all 20 materials are given in Table II.

### Hydrated Lime

Some of the tests required the admixtures to be reacted with hydrated lime. The lime selected conformed to ASTM Specifications C 6 for Normal Finishing Hydrated Lime and, in addition, it was required that it contain not less than 75 percent CaO nor more than 5 percent MgO based on the non-volatile portion, and that not more than 5 percent be retained on the No. 325 sieve. The properties of the lime are given in Table II.

### Aggregates

Three aggregate conditions were used in making 1 by 1 by 11-in. bars for expansion tests: Pyrex glass, Sioux quartzite, and a Sioux-Klufa opaline quartzite combination, all previously described in Waterways Experiment Station reports (10, 12). Both the reactive aggregate (Pyrex glass) and the innocuous aggregate (Sioux quartzite) were graded as required by CRD-C 123 (9). The combination of 90 percent Sioux quartzite and 10 percent Klufa opaline quartzite has been found (12) to be more reactive than any other combination of these materials. This combination was graded as follows:

| Sieve             | Percentage Retained |       |
|-------------------|---------------------|-------|
|                   | Sioux               | Klufa |
| 3/8 in. to No. 4  | 2.5                 | —     |
| No. 4 to No. 8    | 7.5                 | —     |
| No. 8 to No. 16   | 10.0                | —     |
| No. 16 to No. 30  | 32.0                | 3.0   |
| No. 30 to No. 50  | 25.6                | 4.9   |
| No. 50 to No. 100 | 9.0                 | 2.0   |
| Passing No. 100   | 3.5                 | —     |
| Total             | 90.1                | 9.9   |

## TESTS AND RESULTS

### Test for Reactivity with Sodium Hydroxide (NaOH):

*Test Method*—To evaluate admixtures for their effectiveness in preventing excessive expansion of concrete, an adaptation of the quick chemical test for reactivity of aggregate with sodium hydroxide has been used. Since some materials will harden when 25 g of the admixture is reacted with 25 ml of 1N

NaOH, it was necessary to reduce the weight of admixture used to 12.5 g. In all other respects the test is the same as described in the Corps of Engineers version of the quick chemical test (CRD-C 128) (9).

*Tests of Individual Materials and Blends*—Each of the 19 admixtures in classes 1 through 7 and the two type I portland cements were tested alone. The twentieth admixture, synthetic pure silica glass, was not tested because its great absorptive capacity precluded testing without further modification of the test method. Each material was tested in either duplicate or triplicate.

The average results of the tests of each of the admixtures and the portland cements are given in Table III. The two type I cements gave values for dissolved silica ( $S_c$ ) of zero and for reduction in alkalinity ( $R_c$ ) of 187 and 137. The 19 admixtures gave results for  $S_c$  ranging from 0 to 883 and for  $R_c$  ranging from 65 to 545. The utility of this test would be greatly enhanced if either or both of the determined functions ( $S_c$ ,  $R_c$ ) were additive. However, the results obtained from a series of tests definitely indicate that neither function is additive and, therefore, the performance of a given blend cannot be predicted.

*Discussion of Results*—Two criteria have been applied to the test to determine the effectiveness of admixtures in reducing expansion due to alkali-aggregate reaction. The Davis Dam specification (8) required a minimum reduction in alkalinity ( $R_a$ ) of 40 percent for a material to be regarded as effective. Of the materials tested in this investigation, the data in Table III show that only five meet this requirement: fly ash I, tuff, calcined shale M, calcined diatomite, and uncalcined diatomite, with  $R_a$  values of 46, 41, 52, 55, and 44 percent, respectively. Calcined shale N, with an  $R_a$  value of 39 percent, may be regarded as borderline. The second criterion was proposed by Moran and Gilliland (7) who plotted the  $S_c$  and  $R_c$  values for a number of materials and found that those that will reduce mortar expansions 75 percent or more in two weeks at 20 percent replacement by weight (25 percent by volume) will fall above or to the right of a line having the equation  $R_c + 2/3 = 630$ . The test results in Table III have been graphically represented in Fig. 1. It is evident that calcined diatomite, calcined shale M, tuff, uncalcined diatomite, and calcined shale N meet this requirement. Although fly ash I met the Davis Dam specifications, it does not conform to this requirement. Table IV summarizes these data as well as the data obtained by other methods used in this investigation to test the effectiveness of mineral admixtures in preventing expansion due to alkali-aggregate reaction.

### Modified Test for Reactivity with NaOH:

*Modified Method* — The Bureau of Reclamation used the quick chemical test for some time to assist in the evaluation of admixtures (8). However, it did not prove to be completely satisfactory, and in 1952, a description of a modified version of the reactivity test (6) was published. The modified test assumes an admixture-to-cement ratio of 1 to 3 by weight and a tricalcium silicate ( $C_3S$ ) content of cement of 40 percent. Therefore, 25 ml of 0.5N NaOH (instead of 25 ml of 1N NaOH) are reacted with 4.0 g of admixture and 1.5 g of calcium hydroxide ( $Ca(OH)_2$ ). The reaction container, the reaction time, and the temperature are the same as for the original method. The containers are, however, agitated throughout the reaction period by an end-over-end rotation at 30 rpm. In addition to the determination of  $S_c$  and  $R_{OH}$ <sup>4</sup> on the filtrate, the net reduction in concentration of sodium (Na) and potassium (K) was determined and also the concentration of alumina ( $Al_2O_3$ ).

*Criteria* — The paper by Mielenz et al (6) correlated graphically the reduction in alkalis ( $R_a$ ) and the reduction in alkalinity ( $R_{OH}$ ) of 63 admixtures representing a wide variety of materials, with the reduction in expansion ( $R_c$ ) of mortar bars containing Pyrex aggregate, high-alkali cement, and the tested admixture at ages of 14 days, 2 months, and 1 year. The correlations were found to be satisfactory for all three ages, but best at 14 days; therefore, only the 14-day correlations were shown. Admixtures that reduced expansion by 75 percent in the mortar-bar test were generally regarded as effective. The value of 75 percent reduction was, therefore, used to determine the criteria for the chemical tests. The values of 180 or greater for reduction in alkalis and 201 or greater for reduction in alkalinity were apparently selected from the graph as being those that will

<sup>4</sup> In this paper, the reduction in alkalinity as determined in the modified test is designated  $R_{OH}$  rather than  $R_c$ .

most efficiently separate admixtures that will reduce mortar-bar expansion by 75 percent or more from those that will reduce expansion by less than 75 percent.

*Statistical Determination of Criteria* — The published data did not include the line of best fit, which may substantiate the criteria. As part of this investigation, the equations of these lines, the correlation coefficients, and the standard errors of estimate (4) were calculated and are:

| Determination            | Test Age | Equation of Regression Line, <sup>a</sup> R <sub>e</sub> | Correlation Coefficient | Standard Error of Estimate | Value Corresponding to 75 percent Reduction in Expansion |
|--------------------------|----------|----------------------------------------------------------|-------------------------|----------------------------|----------------------------------------------------------|
| Net reduction of alkalis | 14 days  | 0.162 R <sub>A</sub> + 41.0                              | 0.84                    | 12.5                       | 209.7                                                    |
|                          | 2 months | 0.161 R <sub>A</sub> + 41.0                              | 0.79                    | 15.3                       | 211.3                                                    |
|                          | 1 year   | 0.165 R <sub>A</sub> + 33.2                              | 0.78                    | 16.6                       | 253.1                                                    |
| Reduction in alkalinity  | 14 days  | 0.154 R <sub>OH</sub> + 38.2                             | 0.84                    | 12.4                       | 238.6                                                    |
|                          | 2 months | 0.256 R <sub>OH</sub> + 37.6                             | 0.82                    | 14.3                       | 239.7                                                    |
|                          | 1 year   | 0.165 R <sub>OH</sub> + 29.4                             | 0.82                    | 15.3                       | 276.5                                                    |

<sup>a</sup> R<sub>A</sub> = reduction in alkalis, milliequivalents per liter, R<sub>OH</sub> = reduction in alkalinity, milliequivalents per liter, and R<sub>e</sub> = percent reduction in mortar expansion.

The difference between the equations for the three test ages and between the corresponding correlation coefficients are not significant. The magnitude of the correlation coefficients indicates that the regression lines are not due to random chance. Information concerning the reproducibility of the test was included with the published data. The standard deviation for reduction in alkalis was found to vary between 7.4 and 14.5. The criterion specified for reduction in alkalis is two to three standard deviations less than the values found by use of the regression line to correspond to a 75 percent reduction in expansion both at 14 days and 2 months. The criterion for reduction in alkalis, and probably for reduction in alkalinity, is too low in that many admixtures that will reduce expansion by only 70 percent in 14 days will be evaluated as effective along with most if not all admixtures that will reduce expansion by 75 percent or more. The criteria apparently take into account the lack of precision of the chemical test without considering the lack of precision in the mortar-bar test.

*Additional Modification of the Test* — An additional series of tests was made in which the mixtures of replacement material and calcium hydroxide that were reacted with NaOH were proportioned to represent specific admixture-to-cement ratios by solid volume and specific calculated C<sub>3</sub>S contents rather than the assumed value of 40 percent. In this series, the SiO<sub>2</sub> and Al<sub>2</sub>O<sub>3</sub> determinations were omitted and the double end point titration was used.

*Blends Tested* — The reactivity of admixture-calcium hydroxide mixtures representing the following blends was determined by the procedure just as described.

| Class | Replacement Material | Replacement, Solid Volume <sup>a</sup> , percent |                   |
|-------|----------------------|--------------------------------------------------|-------------------|
|       |                      | Type I High-Alkali                               | Type I Low-Alkali |
| 1     | Slag I               | 30, 50, 70                                       | 50                |
|       | Slag II              | 50                                               | —                 |
| 2     | Nat I                | 20, 35, 50                                       | 35                |
|       | Nat II               | 35                                               | —                 |
| 3     | FA I                 | 30, 45, 60                                       | 45                |
|       | FA II                | 45                                               | —                 |
|       | FA III               | 45                                               | —                 |
|       | FA IV                | 45                                               | —                 |
| 4     | Pum F                | 25, 35, 45                                       | 35                |
|       | Pum L                | 35                                               | —                 |
|       | Tuff                 | 35                                               | —                 |
|       | Obs                  | 35                                               | —                 |
| 5     | C Sh M               | 20, 30, 40                                       | 30                |
|       | C Sh N               | 30                                               | —                 |
|       | Cal D                | 30                                               | —                 |
| 6     | Unc D                | 8, 12, 16                                        | 12                |

<sup>a</sup> Values taken from reference (11).

**Test Results** — Test results obtained for these blends and for the lime substituting for the two cements are shown in Table V. All the results shown were obtained from duplicate determinations.

The following blends, of all those tested, were found to meet both published criteria (6) when tested with the calcium hydroxide ratio representing the high-alkali cement: 45 percent pumicite F, 35 percent tuff, 30 and 40 percent calcined shale M, 30 percent calcined shale N, and calcined diatomite. None of the blends made with uncalcined diatomite were found to meet the requirements; undoubtedly, the percentage of uncalcined diatomite used was too low. Some anomalies were also observed. The 35 percent blend of pumicite L with high-alkali cement gave results greater than 210 for reduction in alkalinity but the results for reduction in alkalies were less than 180; this was also found for the 45 and 60 percent of fly ash I with high-alkali cement and the 45 percent blend with low-alkali cement. The 30 percent blend of fly ash I with high-alkali cement met the 210 criteria only when the double end point titration was used. Only the 45 percent blend of pumicite F with high-alkali cement would be affected if the criteria were changed to those derived from the regression line. The other blends (35 percent tuff, 30 and 40 percent calcined shale M, 30 percent calcined shale N, 30 percent calcined diatomite, all with high-alkali cement) would still be regarded as effective inhibitors. The following general observations were apparent from this test:

- The amount of replacement material used must exceed a given minimum before expansion can be effectively reduced and, for the materials tested, the minimum replacement was never lower than 30 percent.
- The values for reduction in alkalies ( $R_A$ ) and alkalinity ( $R_{OH}$ ) generally increased with increasing replacement.
- Blends made with low-alkali cement will not necessarily give results similar to those obtained with blends made with high-alkali cement.

- (d) Changing the numerical values of the criteria does not materially affect the interpretation of the results.

### Mortar-Bar Test

*Mortars* — The only direct method available for determining the degree of expansion caused by alkali-aggregate reaction is the mortar-bar test. Similarly, the only direct method available for determining the effectiveness of an admixture in preventing excessive expansion due to the reaction is to compare the expansion of bars made with the admixture and a reactive aggregate with bars made without the admixture (control bars), all other conditions being the same. For this phase of the investigation, each of the 14 materials in classes 1 and 3 through 6 and, the one admixture in class 8 were used both at the assumed optimum and at one half the assumed optimum percentages by solid volume (the class 8 material was, in addition, used at one fourth optimum) with the type I, high-alkali portland cement. Three sets of three bars each, each set made on a different date, were made for each blend with Pyrex glass as the aggregate. The bars were fabricated in accordance with CRD-C 123 (9) except that:

- The water content of the mortar was adjusted for a flow of 110  $\pm$  5 percent by ten ½-in. drops in 6 sec.
- The quantity of cementing material used per batch did not equal 450 g; however, the volume of cementing material used per batch did equal that of 450 g of portland cement.

Method CRD-C 123 (9), with the exceptions noted above, differs from ASTM Method C 227 from which mortar-bar methods used by other laboratories were derived in the following essential respects:

- The grading of the Pyrex aggregates differs as follows:

| Sieve Size |          | Percentage Used |            |
|------------|----------|-----------------|------------|
| Passing    | Retained | CRD-C 123       | ASTM C 227 |
| 3/8-in.    | No. 4    | 2.5             | 0          |
| No. 4      | No. 8    | 7.5             | 20         |
| No. 8      | No. 16   | 10.0            | 20         |
| No. 16     | No. 30   | 35.0            | 20         |
| No. 30     | No. 50   | 30.5            | 20         |
| No. 50     | No. 100  | 11.0            | 20         |
| No. 100    | Pan      | 3.5             | 0          |

- CRD-C 123 provides for stripping bars from molds at an age of 44  $\pm$  4 hr while ASTM Method C 227 provides for stripping at 24  $\pm$  2 hr.

In addition three sets of bars were made with the first admixture in each of the above classes at the assumed optimum (11) percentage only (class 8 material was also blended at one half optimum percentage), blended with the type I high-alkali cement and with the Sioux-Klufa combination as the aggregate. Finally, these same admixtures at the same percentage replacement were blended with the type II medium-alkali cement, and bars were made with Pyrex glass as the aggregate. The following control mixtures were used, each represented by three sets of three bars.

- Type I high-alkali cement, Pyrex glass.
- Type I high-alkali cement, Sioux-Klufa combination.

- (e) Type I high-alkali cement, Sioux quartzite.
- (f) Type II medium-alkali cement, Pyrex glass.
- (g) Type II medium-alkali cement, Sioux-Klufa combination.

*Tests and Results* — The bars were stored for a period of 1 yr. Their length change was determined at 14 days, 6 months, and 1 yr according to Method CRD-C 123. The percentage reduction in expansion was calculated by the following equation:

$$R_e = \frac{E_r - E_t}{E_r} \times 100$$

where:

$R_e$  = reduction in mortar expansion, percent,

$E_t$  = average expansion of bars containing the admixture, percent, and

$E_r$  = average expansion of the applicable control bars, percent.

The average results of all these tests are shown in Table VI both as percentage expansion and percentage reduction in expansion at bar ages of 14 days, 6 months, and 1 year.

*Discussion of Test Results* — The expansion due to alkali-aggregate reaction was reduced for every combination tested except in three cases: the bars made from mortars containing blends of high-alkali cement, both 2.5 and 5.0 percent of the synthetic silica glass with Pyrex glass aggregate (1/4 and 1/2 optimum percentages of the admixtures), and the blend of 12 percent uncalcined diatomite with the Sioux-Klufa aggregate. The degree of reduction of the expansion was increased by increasing the percentages of admixture in the mortar. Maximum reduction of expansion for bars made with Pyrex glass aggregate was found for the blend of 30 percent calcined shale with high-alkali cement. For mortars made with the Sioux-Klufa combination as the aggregate, the maximum reduction in expansion was found for the blend containing the synthetic silica glass at its optimum percentage. Three of the mortars made with the medium-alkali cement showed shrinkage at the age of 1 yr: those containing calcined shale M, slag 1, and synthetic silica glass at their optimum percentages.

The following materials may be regarded as effective at a test age of 14 days, using the criterion of a reduction in expansion of at least 75 percent when tested in mortars made with high-alkali cement and Pyrex glass: slags I and II, fly ash IV, pumicite L, calcined shale M, calcined shale N, and synthetic silica glass at their optimum percentage replacements. At test ages of 6 months and 1 yr, all the admixtures tested (at their optimum percentage replacement), except uncalcined diatomite, caused reduction in expansion of 75 percent or more. When the Sioux-Klufa combination was used as the aggregate, slag I, calcined shale M, and synthetic silica caused reduction in expansion of 75 percent or more at all three ages and pumicite F at a test age of 14 days. All the admixtures tested with the medium-alkali cement (Pyrex glass-aggregate) caused a reduction in expansion of 75 percent or greater at all three ages.

*Petrographic Examination of Bars* — After expansion measurements were completed, condition of the bars was determined by examination of the exterior and interior surfaces, both visually and with a stereoscopic microscope. Each bar was rated numerically on a condition scale depending on the presence and amount of (a) external signs of reaction such as warping, surface gel, and surface cracking and (b) internal signs of reaction, such as gel and reacted aggregate. The scale is as follows:

- 0 = No signs of reaction, bar as cast
- 1 = Slight evidence of reaction
- 2 = Slight evidence of reaction, signs are more abundant
- 3 = Moderate reaction, some damage
- 4 = Intermediate between conditions 3 and 5
- 5 = Severe reaction, damage, and deterioration

The numerical ratings of the bars are given in Table VI. The observations are summarized below:

- (a) The general observations included the following:
  1. There was a definite over-all relationship between the observed condition and the expansion of the bars examined. The actual relationship was that the observable signs of alkali-aggregate reaction increased as the expansion increased.
  2. Every bar examined showed some evidence of alkali-aggregate reaction.
  3. Calcium sulfoaluminate was not found in any of the bars.
  4. All bars containing slag had the typical blue-green color in the interior and across the bottom of the bar as cast. The area covered by the color varied directly with the slag content. The color faded on exposure to air, but was still quite apparent after two months exposure. In a previous investigation of portland blast-furnace slag cements (13), the blue-green color was found to fade more rapidly than it did in these bars.
- (b) Specific relationships observed were:
  1. All the bars made with Pyrex glass as the aggregate were rated as being of condition 1 or 2. Of the 14 admixtures in classes 1 and 3 through 6, 10 had the same rating at both the optimum and half optimum percentages replacement. The other four were rated as showing more reaction with increasing expansion.
  2. The bars made with the Sioux-Klufa combination, as the aggregate show, in general, have higher expansion and higher ratings, varying from 2 to 5, than those made with Pyrex glass aggregate.
  3. Both the condition scale rating and the expansion indicate that uncalcined diatomite is not effective when used as a 12 percent replacement of high-alkali cement with the Sioux-Klufa combination aggregate.
  4. All the bars made with the synthetic silica glass required such large amounts of water in mixing that they were abnormally weak. This made it impossible to use bar strength, which normally diminishes with increased reaction, in arriving at rating conditions.

### Rate of Alkali Release

In addition to the other chemical tests described previously, the rate of alkali release of the replacement materials in the presence of lime and water was determined by the method described in Appendix B of the paper by Moran and Gilliland (7). The concentration of the alkalies in solution was determined at 0, 2, 7, 28, and 90 days for each of the 16 materials in classes 1 to 6 and for the 4 materials in classes 7 and 8 at 28 days only. The alkali content of each material was also determined in accordance with CRD-C 244 (9) as well as the water-soluble alkalies as directed in CRD-C 209 (9).

The results of all these analyses are shown in Table VII. The alkali content of the solution at various test ages is reported in terms of total alkali, as  $\text{Na}_2\text{O}$ , as percentage of the replacement material, and also as a percentage of the alkali content of the material. The rate of release curves are similar for both sets of data and are shown in Fig. 2, based on the alkali content. The rate of alkali release of the majority of the admixtures increased after the second day, becoming zero or decreasing after 28 days. The diatomites ceased releasing alkali after 7 days, and calcined shale N absorbed alkali at a

uniform rate after 7 days. For slags I, II, and calcined shale M, the rate of release was constant up to 28 days and then became negative. Tuff stopped releasing alkali after the second day. The amount of alkali released, as a percentage of alkali content, was greatest for the natural cements, then the fly ashes, followed by the slags and volcanic glasses. The calcined earths released the least alkali. As a percentage of the replacement material, the greatest amount of alkali was released by the volcanic glasses and fly ash I. The least amount was released by the calcined earths and the slags.

### Mean Particle Diameter

In addition to the determination of particle size by microscopic methods (Table 11), the mean particle diameter for each of the replacement materials was calculated as described in ASTM Specification C 402 - 58 T, Section 8(b).<sup>\*</sup> The calculated values are shown in Tables II and VIII and correspond very well to the microscopic results.

### Autoclave Expansion

Pastes containing the type II cement and the replacement materials in classes 1, and 2 through 8, in the proportion of 4 to 1 were tested for autoclave expansion. All ten bars tested were sound; the maximum expansion was 0.13 percent for pumicite L.

## COMPARISON OF TEST RESULTS AND CORRELATIONS

### Comparison of Chemical and Mortar-Bar Test Results

Most of the results of the various tests previously described are compared in Table IV. Only the results concerning materials in classes 1 and 3 through 6 are shown. For those tests involving blends of an admixture and a cement or an admixture in a mortar, only the high-alkali cement and the Pyrex glass aggregate results are shown. In addition, the criteria were rigidly interpreted to determine whether a material would be effective; that is, when a test result was found to be one unit less than the criterion, the admixture was judged to be noneffective. As can be seen from the table, complete agreement between the methods was obtained only for calcined shale M, which is effective as a replacement of 25 percent by volume or greater. If it is assumed that the percentage replacement used for uncalcined diatomite was too low, the methods agree and uncalcined diatomite will not be effective as replacements of 16 percent or less. It was noted previously and is also evident in Table IV that all the materials tested, except uncalcined diatomite, caused reduction in expansion of 75 percent or greater at test ages of 6 months and 1 yr when used at their "optimum" percentage replacement. If the 6-month and 1-yr test results are not considered, agreement between the methods was also obtained for fly ash II, fly ash III, obsidian (all noneffective at their optimum percentage replacement or lower), pumicite F (effective at 45 percent replacement but not at the optimum or lower), and calcined shale N (found effective at optimum percentage replacement but disagreement was found between the two criteria for reactivity with NaOH at 25 percent replacement). Slags I and II and fly ash IV were found effective at their optimum percentage replacement by the mortar-bar test but ineffective by any of the chemical tests. Tuff and calcined diatomite were found to be effective by the chemical tests at their optimum percentage replacement but ineffective by the mortar-bar tests at 14-day test age. The lack of agreement in the results for fly ash I and pumicite L is between the chemical methods.

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<sup>\*</sup> *Tentative Specifications for Raw or Calcined Natural Pozzolans for Use as Admixtures in Portland Cement Concrete (C 402-58T)*, 1958, Book of ASTM Standards, Part 4, p. 519.

## MINIMUM PERCENTAGES OF REPLACEMENT FOR EFFECTIVENESS

For the proper employment of a criterion of effectiveness based on the ability of an admixture to reduce expansion by a given proportion, or to a given proportion, of that which takes place when no admixture is used, it is necessary that the control condition be one in which substantial expansion takes place. It further follows that the effectiveness of the admixture must be evaluated under conditions in which it serves a function other than that of a mere diluent. It has been shown for a given case studied by U. W. Stoll at the U. S. Naval Civil Engineering Laboratories that, for a reactive aggregate used with a cement of 1.2 percent alkalis calculated as soda, substitution of a cement having 0.50 percent alkalis would result in 75 percent less expansion and that replacement of 60 percent of the cement of 1.2 percent alkali content with an inert diluent should be expected to produce the same reduction in expansion.

Effective admixtures should exhibit some beneficial effect in addition to that of dilution. To determine the extent of this additional beneficial effect, the applicable data in Table V and VI were plotted in Fig. 3. The curves were interpolated (or extrapolated) to determine the percentage replacement that corresponded to the appropriate criteria for effectiveness. The interpolated values are shown in Table IX.

All the admixtures tested do have some additional beneficial effect other than dilution of cement. Some effects are manifested at different levels of replacement ranging from a minimum of 10 percent for synthetic silica glass at both 14 days and 6 months to 52 percent for fly ash III at 14 days. The agreement between the results obtained for the two test methods is very good considering that these are interpolated results.

The minimum percentage replacement values may also be used to compare admixtures with each other. The lower the minimum replacement value, the more effectively the admixture will prevent expansion due to the alkali-aggregate reaction. This comparison is made in Table VIII. The admixtures are listed in ascending order of the average minimum replacement values. The average of the 14-day and 6-month values was used. The changes in the order would not be significant if either the 14-day or 6-month values were used. The synthetic silica glass heads the list as most effective, followed by the calcined shales and uncalcined diatomite, then the natural glasses, and finally the blast-furnace slags and fly ashes.

## CORRELATION OF MINIMUM REPLACEMENT VALUES WITH FINENESS, ALKALI RELEASE, AND DISSOLVED SILICA

The relation between the interpolated minimum replacement value for each admixture and the fineness of the admixture (mean particle diameter), the rate of alkali release at 28 and 90 days, and the amount of silica dissolved in the quick chemical test is indicated in Table VIII. The minimum replacement value did not correlate with the 0, 2, and 7-day alkali-release data. Figure 4 gives the curves of best fit, the equations of these curves, the correlation indices or coefficient, and the standard errors of estimate. The correlations, with due considerations of the small sample, are not due to random chance. Since evidence of correlation between the independent variables was not found, a multiple linear regression curve for the data in Table VIII was calculated with the following results:

$$R = 27.3 - 0.0158 S_c + 1.6 \ln D + 3.5 \ln A_{90}$$

where: multiple correlation coefficient = 0.951, standard error of estimate = 2.50, and beta coefficient for  $S_c = 0.542$ ,  $A_{90} = 0.366$ ,  $D = 0.109$ .

The sample size is too small for a sound opinion to be formed regarding the multiple correlation, although it appears to be a good correlation. The beta coefficients indicate that the  $S_c$  value of an admixture has the greatest effect on the minimum percentage replacement value and the mean particle diameter the least. Other correlations were attempted including silica content, alkali content, alkali release as a percentage of the amount of admixture used, all versus the minimum replacement value, but without success. The correlations and also the lack of correlations indicate to some extent the factors that are necessary for effective reduction of expansion due to the alkali-aggregate reaction. Further work is necessary to determine the relative effect of lime on the reactions. The multiple correlation does not suggest the mechanism of the reaction but rather serves to evaluate the relative effect of the factors, when considered together, on the reaction.

## REACTIONS INVOLVED IN PREVENTING EXCESSIVE EXPANSION

Many hypotheses have been advanced to explain alkali-aggregate reaction and the effectiveness of measures to prevent its causing excessive expansion in concrete; however, a great deal of work still remains to be done to provide a basis for an adequate hypothesis. With the thought that some benefits might be derived from simplification of what appears to be a complex reaction, a summary of an hypothesis concerning the reactions involved was prepared, part of which has been published (1). It proposes a working hypothesis concerning phenomena involved in pozzolanic reaction, alkali-aggregate reaction, and prevention of excessive expansion of concrete due to alkali-aggregate reaction. The hypothesis was based on the assumption that all three phenomena are fundamentally the same: the reaction of calcium, alkalies, and hydroxide ions with soluble silica. The degree of reaction was thought to depend on the silica content, the metastability of the silica, and the fineness of the material. This investigation substantiates part of the working hypotheses. Since precise knowledge of the actual reactions that will cause the phenomena is lacking, the hypothesis will certainly aid in determining the type of chemical test needed to evaluate materials with respect to the phenomena. A chemical test to evaluate effectiveness of admixtures will have to determine, in the presence of lime, the reactive (glassy or noncrystalline) silica content of the material, and the alkalies that will be removed from solution. The chemical tests used in this investigation do not fulfill these requirements since:

- (a) The quick chemical test does not evaluate the reductions in alkalies directly, nor does the reaction take place in the presence of lime.
- (b) The modified quick chemical test does not correlate the effects of dissolved silica and reduction of alkalies with effectiveness in preventing excessive expansion. In addition, both tests lack the precision normally desired in chemical tests. The precision of the quick chemical test has been previously examined and reported (10).

## CONCLUSIONS

All the materials tested in this study will effectively reduce expansion if sufficient amounts are employed in the mixture. All the materials exhibit a beneficial effect with regard to expansion other than by dilution. The synthetic silica glass was found to be the most active admixture, only 10

percent replacement by volume is needed to reduce the percentage expansion by 75 percent in two weeks; next the calcined shales, requiring 19 to 29 percent replacement; the uncalcined diatomite, requiring 22 percent; the volcanic glasses, requiring 32 to 36 percent; and lastly, the slags and fly ashes, requiring 39 to 45 percent.

It is evident from this investigation that neither chemical test can be used, with reliance, to evaluate the effectiveness of an admixture in preventing excessive expansion. Further work may develop a reliable chemical test, since a relation was found between minimum percentage replacement value, fineness of the material, reactive silica, and the amount of alkalis retained by the reaction product. The mortar-bar test requires improvement to increase the precision for both intra- and interlaboratory testing. Andreasen and Christensen (3) have noted that the finer fractions (passing a No. 125 sieve) in the Pyrex aggregate may act as admixtures, and have stressed the importance of removing these finer fractions by washing the aggregate. Other differences in testing conditions and procedures between laboratories should be resolved.

Specifications for evaluating admixtures for effectiveness in preventing excessive expansion due to the alkali-aggregate reaction require the material to be tested at one percentage replacement, generally 25 percent by volume. As indicated in this study, materials may be more effectively evaluated and compared if they are tested at two or three different percentage replacements. The minimum percentage replacement for effectiveness may then be determined by interpolation.

Pending additional development work, the criteria and procedures set forth in Specifications CRD-C 262 and Methods 263 - 577 appear to be the most reasonable means of establishing the effectiveness of a material in preventing excessive expansion due to alkali-aggregate reaction.

## ACKNOWLEDGMENTS

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## DISCUSSION

*MR. T. C. POWERS*<sup>1</sup>— I have not read this paper, hence this question. Do these correlations, pertaining to soluble silica, pertain to all the materials you described at first, or only to the selected four that you described later?

*MR. BRYANT MATHER* (author) — It pertained to the 14 of the 20 materials that belong to classes 1 and 3 through 6, as indicated by the values in Table VIII.

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*MR. A. D. CONROW*<sup>2</sup> — What is the author's opinion of Pyrex glass as a material to represent a reactive aggregate in and the reliability of results obtained with its use as a means for judging performance if common aggregates are used?

*MR. MATHER* — I believe that Pyrex glass provides the most standardizable reactive aggregate to use as a representative of extreme reactivity. I do not envision the case where a mineral admixture would be effective in reducing expansion of a high-alkali cement — Pyrex glass mortar and fail to be effective in the field where the potential expansion was due to alkali-aggregate reaction. There are expansions in the field, as is well known, which have not been proved to be due to alkali-aggregate reaction. Pyrex glass with high-alkali cement would not provide a controlled situation for testing for some other kind of expansion and the ability of something to prevent or reduce it.

*MR. RAYMOND E. DAVIS*<sup>3</sup> — I am wondering if the results of the Pyrex glass test do not give an exaggerated idea of the quantity of pozzolan required to reduce the alkali aggregate expansion as compared with the results that we get with most of the reactive aggregates.

*MR. MATHER* — I am sure that the results do tend to give such an exaggerated idea. It will be recalled that ASTM Specifications C 402 - 58 T provide alternative requirements for the ability of a mineral admixture to deal with alkali reaction expansion. The test with Pyrex glass and high-alkali cement and the requirement that a 75 percent reduction in expansion be obtained at 14 days when 25 percent by weight of the cement is replaced by the mineral admixture is the less desirable alternative. The preferable alternative is the test with Pyrex glass and job cement and the requirement that the 14-day expansion not exceed 0.020 percent when the amount of admixture to be used on the job is used in the mortar. This latter approach not only allows the severity of the test to be reduced proportionately to the degree to which the job cement has less than a maximum alkali content but also permits the cement:admixture ratio to be that which will actually be employed. Whether we can and should also employ a less reactive aggregate than Pyrex glass is debatable. If we could be sure that the accelerated test gave in 14 days an expansion proportional to the ultimate expansion of the test combination in service and could also be sure that the test aggregate represented the most reactive condition to be encountered, then such a test aggregate — less reactive than Pyrex — would be desirable. Obviously an admixture should not be rejected for use because tests with a cement of 1.0 percent alkalis as  $\text{Na}_2\text{O}$ , Pyrex glass, and a cement:admixture ratio of 4: 1 showed less than 75 percent reduction in expansion when it is certain that the cement will never contain more than say 0.7 percent alkalis as  $\text{Na}_2\text{O}$ , the aggregates are only mildly reactive, and the cement: admixture ratio will be 3: 1 rather than 4: 1.

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**Table I — Results of Tests of Portland Cements**

| Test result                                                    | Type I Cement |            | Type II Cement |
|----------------------------------------------------------------|---------------|------------|----------------|
|                                                                | High-alkali   | Low-alkali | Medium-alkali  |
| <b>Chemical Data</b>                                           |               |            |                |
| Major components:                                              |               |            |                |
| SiO <sub>2</sub> , percent                                     | 20.6          | 20.1       | 23.1           |
| Al <sub>2</sub> O <sub>3</sub> , percent                       | 5.4           | 6.6        | 5.0            |
| Fe <sub>2</sub> O <sub>3</sub> , percent                       | 3.9           | 3.1        | 3.9            |
| CaO, percent                                                   | 61.0          | 65.5       | 61.1           |
| MgO, percent                                                   | 3.9           | 1.2        | 2.8            |
| SO <sub>3</sub> , percent                                      | 2.1           | 2.0        | 2.0            |
| Loss on ignition, percent                                      | 1.9           | 0.97       | 1.6            |
| Minor components:                                              |               |            |                |
| Na <sub>2</sub> O, percent                                     | 0.62          | 0.11       | 0.23           |
| K <sub>2</sub> O, percent                                      | 0.68          | 0.39       | 0.69           |
| Total as Na <sub>2</sub> O, percent                            | 1.07          | 0.37       | 0.68           |
| P <sub>2</sub> O <sub>5</sub> , percent                        | 0.13          | 0.20       | ...            |
| Mn <sub>2</sub> O <sub>3</sub> , percent                       | 0.07          | 0.12       | ...            |
| Separate determinations:                                       |               |            |                |
| Insoluble residue, percent                                     | 0.54          | 0.12       | 0.23           |
| Chloroform solubility, percent                                 | 0.002         | 0.004      | ...            |
| Moisture content, percent                                      | 0.36          | 0.19       | ...            |
| Calculated compounds:                                          |               |            |                |
| C <sub>3</sub> S, percent                                      | 44            | 56         | 29             |
| C <sub>2</sub> S, percent                                      | 26            | 16         | 44             |
| C <sub>3</sub> A, percent                                      | 8             | 12         | 7              |
| C <sub>4</sub> AF, percent                                     | 12            | 9          | 12             |
| CaSO <sub>4</sub> , percent                                    | 4             | 3          | 3              |
| <b>Physical Data</b>                                           |               |            |                |
| Fineness, passing No. 325 sieve, percent                       | 90.1          | 93.2       | 94.8           |
| Fineness, Blaine, sq cm per g                                  | 3765          | 3450       | 3590           |
| Specific gravity                                               | 3.11          | 3.15       | 3.17           |
| Time of setting (Gillmore):                                    |               |            |                |
| Initial, hr:min                                                | 2:50          | 2:45       | 5:30           |
| Final, hr:min                                                  | 4:20          | 5:45       | 8:00           |
| Autoclave expansion, percent                                   | 0.28          | 0.14       | 0.10           |
| Normal consistency, percent                                    | 24.0          | 27.2       | 24.6           |
| Air in mortar, percent                                         | 10.2          | 7.6        | 8.8            |
| Comprehensive strength, psi:                                   |               |            |                |
| 3 days                                                         | 1510          | 2600       | 1745           |
| 7 days                                                         | 2065          | 3900       | 2665           |
| 28 days                                                        | 3065          | 5565       | 5140           |
| Heat of hydration, cal per g (70 F water-cement ratio = 0.40): |               |            |                |
| 3 days                                                         |               |            |                |
| 7 days                                                         | 56            | 66         | —              |
| 28 days                                                        | 65            | 84         | 71             |
| 6 months                                                       | 71            | 99         | 82             |
| 1 yr                                                           | 86            | 106        | —              |
| Bleeding (water-cement ratio = 0.4):                           | 86            | 111        | 89             |
| Rate, ml per sq cm per sec X 10 <sup>6</sup>                   |               |            |                |
| Capacity, ml per cc X 10 <sup>3</sup>                          | 64            | 59         | 37             |
| Bleeding (water-cement ratio = 0.45):                          |               |            |                |
| Rate                                                           | 114           | —          | 37             |
| Capacity                                                       | 29            | —          | 7              |



Table II — Results of test of replacement materials and hydrated lime, continued

| Test result                          | Natural volcanic glass                            |               |          |                |        |         |                   |          |          |           |               |           |           |         |             |                   |                              |                 |              |        |                        |                     |
|--------------------------------------|---------------------------------------------------|---------------|----------|----------------|--------|---------|-------------------|----------|----------|-----------|---------------|-----------|-----------|---------|-------------|-------------------|------------------------------|-----------------|--------------|--------|------------------------|---------------------|
|                                      | Granulated water-quenched iron blast-furnace slag |               |          | Natural cement |        | Fly ash |                   | Pumicite |          |           | Calced shales |           |           |         |             | Uncalcined quartz |                              |                 |              |        | Syn silica glass AD-34 | Hydrated lime AD-31 |
|                                      | I RC-198                                          | II RC-216 (B) | I RC-214 | II RC-215      | I AC-3 | II AD-7 | III AD-8          | IV AD-9  | (F) Ad-6 | (L) AD-10 | Tuff AD-11    | Obs AD-12 | C sh AD-5 | N AD-13 | Cal D AD-14 | Unc D AD-15       | SiO <sub>2</sub> flour AD-35 | Air float AD-36 | Ad-mix AD-37 |        |                        |                     |
| Sulfide sulfur, %                    | 0.86                                              | 1.34          | 0.06     | 0.02           | 0.05   | 0.00    | 0.13              | 0.04     | 0.00     | 0.00      | 0.00          | 0.00      | 0.00      | 0.00    | 0.00        | 0.10              | 0.09                         | —               | —            | —      | —                      |                     |
| Total carbon, %                      | 0.45                                              | 0.53          | —        | —              | 0.43   | 3.17    | 11.1 <sub>3</sub> | 7.22     | 0.02     | 0.04      | 0.08          | 0.04      | 1.10      | 0.07    | 0.30        | 0.15              | —                            | —               | —            | —      | —                      |                     |
| Physical data                        |                                                   |               |          |                |        |         |                   |          |          |           |               |           |           |         |             |                   |                              |                 |              |        |                        |                     |
| Fineness                             | 95.8                                              | 98.8          | 87.9     | 96.5           | 95.5   | 92.8    | 93.6              | 85.1     | 98.6     | 90.8      | 86.2          | 66.9      | 98.1      | 70.5    | 98.8        | 68.5              | —                            | —               | —            | —      | 100.0                  |                     |
| Passing No. 200 sieve, dry, %        | 90.2                                              | 97.2          | 91.0     | 93.2           | 93.5   | 87.7    | 85.8              | 81.5     | 98.1     | 91.4      | 85.5          | 67.2      | 96.8      | 71.5    | 98.6        | 93.0              | 96.9                         | 96.0            | 99.9         | 96.7   | 98.0                   |                     |
| Passing No. 325 sieve, wet, %        | 90.2                                              | 97.2          | 91.0     | 93.2           | 93.5   | 87.7    | 85.8              | 81.5     | 98.1     | 91.4      | 85.5          | 67.2      | 96.8      | 71.5    | 98.6        | 93.0              | 96.9                         | 96.0            | 99.9         | 96.7   | 98.0                   |                     |
| Specific surface, cm <sup>2</sup> /g | 360                                               | 3695          | 11,260   | 6420           | 3565   | 2940    | 2945              | 4205     | 4410     | 8340      | 10460         | 3415      | 13685     | 11770   | 10450       | 12125             | 4425                         | 5500            | 4125         | 476000 | —                      |                     |
| Blaine air permeability              | 341                                               | 3390          | 9790     | 5830           | 3335   | 2855    | 2715              | 3960     | 4640     | 8230      | 13215         | 3850      | 12921     | 15020   | 12195       | 15345             | 4545                         | 5130            | 4075         | —      | —                      |                     |
| Fisher air permeability              | 279                                               | 4615          | 3835     | 1475           | 7030   | 5960    | 5050              | 5045     | 4505     | 6670      | 9850          | 4085      | 3360      | 7600    | 6485        | 12445             | 2595                         | 2790            | 3745         | —      | —                      |                     |
| Klein hydro-meter                    | 0                                                 | —             | —        | —              | —      | —       | —                 | —        | —        | —         | —             | —         | —         | —       | —           | —                 | —                            | —               | —            | —      | —                      |                     |

**Table II — Results of test of replacement materials and hydrated lime, continued**

| Test result                      | Natural volcanic glass                            |               |          |                |        |         |          |         |          |           |            |           |                 |              |             |                   |                              | Syn silica glass AD-34 |                 |              |
|----------------------------------|---------------------------------------------------|---------------|----------|----------------|--------|---------|----------|---------|----------|-----------|------------|-----------|-----------------|--------------|-------------|-------------------|------------------------------|------------------------|-----------------|--------------|
|                                  | Granulated water-quenched iron blast-furnace slag |               |          | Natural cement |        |         | Fly ash  |         |          | Pumicite  |            |           | Calcined shales |              |             | Uncalcined quartz |                              |                        |                 |              |
|                                  | I RC-198                                          | II RC-216 (B) | I RC-214 | II RC-215      | I AC-3 | II AD-7 | III AD-8 | IV AD-9 | (F) AD-6 | (L) AD-10 | Tuff AD-11 | Obs AD-12 | C sh AD-5       | M C sh AD-13 | Cal D AD-14 | Unc D AD-15       | SiO <sub>2</sub> flour AD-35 |                        | Air float AD-36 | Ad-mix AD-37 |
| Nitrogen adsorption <sup>b</sup> | 950                                               | 8100          | 4680     | 2620           | 7900   | 1600    | 2470     | 30,200  | 7990     | 6040      | 2593       | 8000      | 2423            | 1360         | 179,0       | 25950             | —                            | —                      | —               | —            |
|                                  | 0                                                 | 0             | 0        | 0              | 0      | 0       | 00       | 00      | 0        | 0         | 00         | 0         | 00              | 00           | 0           | 0                 | 0                            | —                      | —               | —            |
| Particle size (microscope)       |                                                   |               |          |                |        |         |          |         |          |           |            |           |                 |              |             |                   |                              |                        |                 |              |
| Minimum, $\mu$                   | 0.5                                               | 0.5           | -0.5     | -0.5           | 0.5    | 0.5     | 1        | 1       | 1        | 0.5       | -0.5       | -0.5      | 0.5             | -0.5         | -0.5        | -0.5              | -0.5                         | 0.2                    | <0.4            | 0.2          |
| Maximum, $\mu$                   | 270                                               | 400           | 350      | 250            | 1000   | 1000    | 2000     | 3000    | 250      | 500       | 450        | 1000      | 200             | 300          | 400         | 2000              | 100                          | 4                      | 60              | —            |
| Predominant range, $\mu$         | 2-9                                               | 2-15          | 0.5-3    | 0.5-3          | 1-10   | 3-13    | 4-20     | 3-14    | 2-20     | 2-14      | 2-8        | 6-15      | 2-6             | 1-7          | 2-10        | 0.5-1             | —                            | —                      | 0.4-0.8         | —            |
| Mean diameter, $\mu$             | 4.8                                               | 4.7           | —        | —              | 5.3    | 7.1     | 6.9      | 5.2     | 4.8      | 2.5       | 2.1        | 6.1       | 1.6             | 1.8          | 2.0         | 1.8               | 4.1                          | 2.0                    | 2.2             | 0.5          |
| Specific gravity                 | 2.84                                              | 2.87          | 2.85     | 2.89           | 2.48   | 2.36    | 2.43     | 2.26    | 2.35     | 2.39      | 2.27       | 2.36      | 2.51            | 2.35         | 2.45        | 2.30              | 2.64                         | 2.60                   | 2.63            | 2.20         |
| Normal consistency               | 30.4                                              | 26.2          | 38.4     | 36.0           | 21.8   | 33.2    | 47.2     | 48.0    | 44.0     | 43.6      | 50.8       | 23.0      | 25.6            | 67.0         | 62.0        | 36.4              | <i>c</i>                     | <i>c</i>               | <i>c</i>        | <i>d</i>     |

Table II — Results of test of replacement materials and hydrated lime, continued

| Test result                                   | Natural volcanic glass                            |               |          |                |        |         |          |         |          |           |
|-----------------------------------------------|---------------------------------------------------|---------------|----------|----------------|--------|---------|----------|---------|----------|-----------|
|                                               | Granulated water-quenched iron blast-furnace slag |               |          | Natural cement |        |         | Fly ash  |         | Pumicite |           |
|                                               |                                                   |               |          |                |        |         |          |         |          |           |
| Air content of mortar, %                      | I RC-198                                          | II RC-216 (B) | I RC-214 | II RC-215      | I AC-3 | II AD-7 | III AD-8 | IV AD-9 | (F) Ad-6 | (L) AD-10 |
|                                               | 2.8                                               | 7.5           | 4.9      | 9.6            | 4.9    | 2.6     | 2.7      | 2.8     | 2.7      | 1.7       |
|                                               | 0.00                                              | 0.0001        | 0.0      | 0.000          | e      | 0.000   | f        | f       | f        | f         |
|                                               | 0.12                                              | 17            |          | 0.18           |        | 119     |          |         |          |           |
|                                               | 3                                                 |               |          |                |        |         |          |         |          |           |
|                                               |                                                   |               |          |                |        |         |          |         |          |           |
|                                               |                                                   |               |          |                |        |         |          |         |          |           |
|                                               |                                                   |               |          |                |        |         |          |         |          |           |
|                                               |                                                   |               |          |                |        |         |          |         |          |           |
|                                               |                                                   |               |          |                |        |         |          |         |          |           |
| Bleeding of paste Rate, ml/cm <sup>2</sup> /g |                                                   |               |          |                |        |         |          |         |          |           |
|                                               |                                                   |               |          |                |        |         |          |         |          |           |
|                                               |                                                   |               |          |                |        |         |          |         |          |           |
|                                               |                                                   |               |          |                |        |         |          |         |          |           |
|                                               |                                                   |               |          |                |        |         |          |         |          |           |
|                                               |                                                   |               |          |                |        |         |          |         |          |           |
|                                               |                                                   |               |          |                |        |         |          |         |          |           |
|                                               |                                                   |               |          |                |        |         |          |         |          |           |
|                                               |                                                   |               |          |                |        |         |          |         |          |           |
|                                               |                                                   |               |          |                |        |         |          |         |          |           |
| Capacity, ml/ml                               |                                                   |               |          |                |        |         |          |         |          |           |
|                                               |                                                   |               |          |                |        |         |          |         |          |           |
|                                               |                                                   |               |          |                |        |         |          |         |          |           |
|                                               |                                                   |               |          |                |        |         |          |         |          |           |
|                                               |                                                   |               |          |                |        |         |          |         |          |           |
|                                               |                                                   |               |          |                |        |         |          |         |          |           |
|                                               |                                                   |               |          |                |        |         |          |         |          |           |
|                                               |                                                   |               |          |                |        |         |          |         |          |           |
|                                               |                                                   |               |          |                |        |         |          |         |          |           |
|                                               |                                                   |               |          |                |        |         |          |         |          |           |
| Hydrated lime AD-31                           |                                                   |               |          |                |        |         |          |         |          |           |
|                                               |                                                   |               |          |                |        |         |          |         |          |           |
|                                               |                                                   |               |          |                |        |         |          |         |          |           |
|                                               |                                                   |               |          |                |        |         |          |         |          |           |
|                                               |                                                   |               |          |                |        |         |          |         |          |           |
|                                               |                                                   |               |          |                |        |         |          |         |          |           |
|                                               |                                                   |               |          |                |        |         |          |         |          |           |
|                                               |                                                   |               |          |                |        |         |          |         |          |           |
|                                               |                                                   |               |          |                |        |         |          |         |          |           |
|                                               |                                                   |               |          |                |        |         |          |         |          |           |

<sup>a</sup> Values corrected for sulfur.

<sup>b</sup> Tests conducted by National Bureau of Standards.

<sup>c</sup> Insufficient quantity of material to complete all tests.

<sup>d</sup> Material is hygroscopic and gelled.

<sup>e</sup> Accurate bleeding results could not be obtained.

<sup>f</sup> Using the specified proportions of water to solids, resultant pastes were too dry to test.

<sup>g</sup> Bleeding was too great to be measured with available apparatus.



**Table III – Results of Quick Chemical Test**

| Material                      | Cements and Replacement Materials Alone      |                                                      |                                        |
|-------------------------------|----------------------------------------------|------------------------------------------------------|----------------------------------------|
|                               | Dissolved Silica $S_c$ , milimoles per liter | Reduction in Alkalinity, $R_c$ , milimoles per liter | Reduction in Alkalinity, $R_a$ percent |
| Type I cement, low alkali     | 0                                            | 187                                                  | 18                                     |
| Type I cement, high alkali    | 0                                            | 137                                                  | 14                                     |
| Slag I                        | 0                                            | 74                                                   | 8                                      |
| Slag II                       | 0                                            | 68                                                   | 7                                      |
| Natural cement I              | 1                                            | 119                                                  | 12                                     |
| Natural cement II             | 0                                            | 113                                                  | 11                                     |
| Fly Ash I                     | 44                                           | 456                                                  | 46                                     |
| Fly Ash II                    | 158                                          | 280                                                  | 28                                     |
| Fly Ash III                   | 33                                           | 352                                                  | 36                                     |
| Fly Ash IV                    | 151                                          | 246                                                  | 25                                     |
| Pumicite F                    | 270                                          | 167                                                  | 17                                     |
| Pumicite L                    | 359                                          | 188                                                  | 19                                     |
| Tuff                          | 450                                          | 406                                                  | 41                                     |
| Obsidian                      | 204                                          | 65                                                   | 7                                      |
| Calcined Shale M              | 405                                          | 510                                                  | 52                                     |
| Calcined Shale N              | 883                                          | 390                                                  | 39                                     |
| Calcined diatomaceous earth   | 382                                          | 545                                                  | 55                                     |
| Uncalcined diatomaceous earth | 810                                          | 430                                                  | 44                                     |
| SiO <sub>2</sub> flour        | 360                                          | 248                                                  | 28                                     |
| Air float                     | 39                                           | 351                                                  | 38                                     |
| Ad-mix                        | 82                                           | 85                                                   | 11.6                                   |

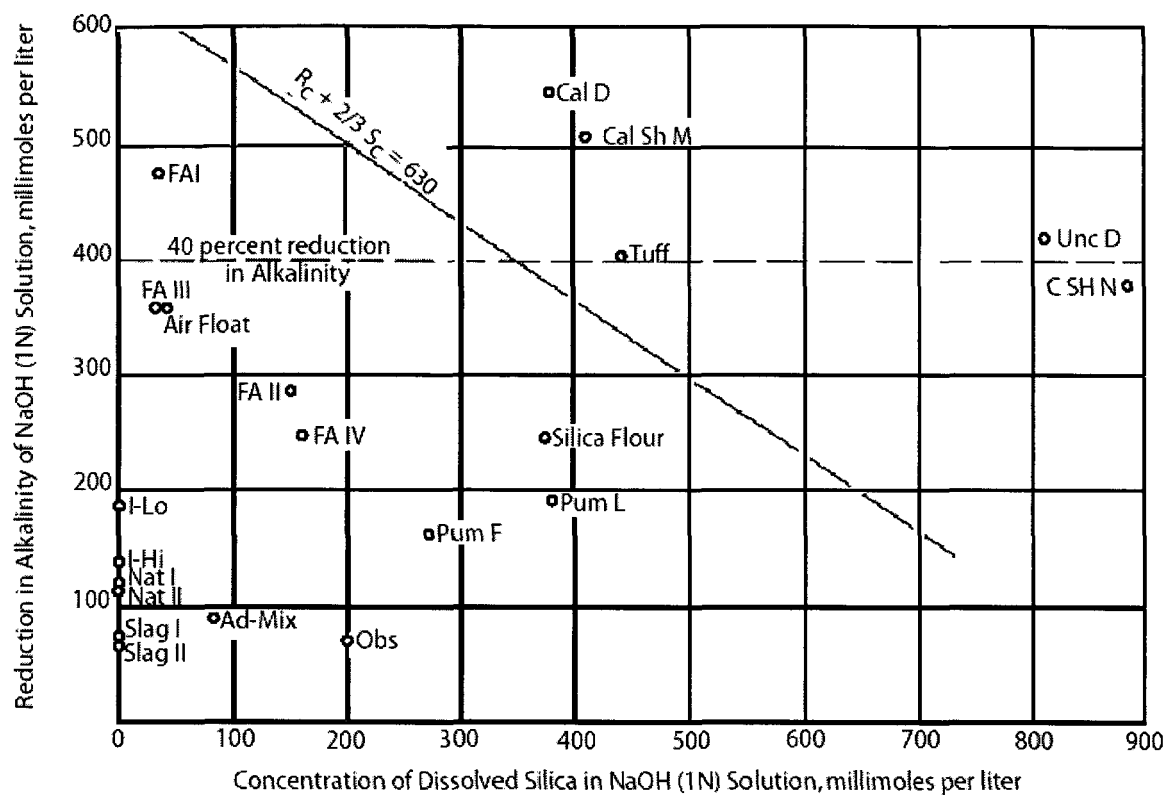


Fig. 1 — Reactivity of Materials with Sodium Hydroxide.

**Table IV — Summary of test results on effectiveness of admixtures**

| Admixture                     | Volume replacement material, percent | Reactivity with $\text{Na}^+$ ( $\text{OH}^-$ ) <sup>a</sup> |                      | Modified reactivity with NaOH                          |                                 |                        | Mortar-bar reduction in expansion > 75 percent |          |          |
|-------------------------------|--------------------------------------|--------------------------------------------------------------|----------------------|--------------------------------------------------------|---------------------------------|------------------------|------------------------------------------------|----------|----------|
|                               |                                      | $R_a \geq 40$ percent                                        | $R + 2/3 S \geq 630$ | $\text{Na}^+$ plus $\text{K}^+$ moles, per liter > 180 | OH <sup>-</sup> moles per liter |                        | 14 days                                        | 6 months | 1 year   |
|                               |                                      |                                                              |                      |                                                        | Single end point > 210          | Double end point > 210 |                                                |          |          |
| Slag I                        | 70                                   | —                                                            | —                    | <i>n</i>                                               | <i>n</i>                        | <i>n</i>               | —                                              | —        | —        |
|                               | 50                                   | —                                                            | —                    | <i>n</i>                                               | <i>n</i>                        | <i>n</i>               | <i>e</i>                                       | <i>e</i> | <i>e</i> |
|                               | 30                                   | —                                                            | —                    | <i>n</i>                                               | <i>n</i>                        | <i>n</i>               | —                                              | —        | —        |
|                               | 25                                   | <i>n</i>                                                     | <i>n</i>             | —                                                      | —                               | —                      | —                                              | <i>n</i> | <i>n</i> |
| Slag II                       | 50                                   | —                                                            | —                    | <i>n</i>                                               | <i>n</i>                        | <i>n</i>               | <i>e</i>                                       | <i>e</i> | <i>e</i> |
|                               | 25                                   | <i>n</i>                                                     | <i>n</i>             | —                                                      | —                               | —                      | <i>n</i>                                       | <i>n</i> | <i>n</i> |
| Fly ash I                     | 60                                   | —                                                            | —                    | <i>n</i>                                               | <i>e</i>                        | <i>e</i>               | —                                              | —        | —        |
|                               | 45                                   | —                                                            | —                    | <i>n</i>                                               | <i>e</i>                        | <i>e</i>               | <i>n</i>                                       | <i>e</i> | <i>e</i> |
|                               | 30                                   | —                                                            | —                    | <i>n</i>                                               | <i>n</i>                        | <i>e</i>               | —                                              | —        | —        |
|                               | 22.5                                 | <i>e</i>                                                     | <i>n</i>             | —                                                      | —                               | —                      | <i>n</i>                                       | <i>n</i> | <i>n</i> |
| Fly ash II                    | 45                                   | —                                                            | —                    | —                                                      | <i>n</i>                        | <i>n</i>               | <i>n</i>                                       | <i>e</i> | <i>e</i> |
|                               | 22.5                                 | <i>n</i>                                                     | <i>n</i>             | —                                                      | —                               | —                      | <i>n</i>                                       | <i>n</i> | <i>n</i> |
| Fly ash III                   | 45                                   | —                                                            | —                    | <i>n</i>                                               | <i>n</i>                        | <i>n</i>               | <i>n</i>                                       | <i>e</i> | <i>e</i> |
|                               | 22.5                                 | <i>n</i>                                                     | <i>n</i>             | —                                                      | —                               | —                      | <i>n</i>                                       | <i>n</i> | <i>n</i> |
| Fly ash IV                    | 45                                   | —                                                            | —                    | <i>n</i>                                               | <i>n</i>                        | <i>n</i>               | <i>e</i>                                       | <i>e</i> | <i>e</i> |
|                               | 22.5                                 | <i>n</i>                                                     | <i>n</i>             | —                                                      | —                               | —                      | <i>n</i>                                       | <i>n</i> | <i>n</i> |
| Pumicite F                    | 45                                   | —                                                            | —                    | <i>e</i>                                               | <i>e</i>                        | <i>e</i>               | —                                              | —        | —        |
|                               | 35                                   | —                                                            | —                    | <i>n</i>                                               | <i>n</i>                        | <i>n</i>               | <i>n</i>                                       | <i>e</i> | <i>e</i> |
|                               | 25                                   | <i>n</i>                                                     | <i>n</i>             | <i>n</i>                                               | <i>n</i>                        | <i>n</i>               | —                                              | —        | —        |
|                               | 17.5                                 | —                                                            | —                    | —                                                      | —                               | —                      | <i>n</i>                                       | <i>n</i> | <i>n</i> |
| Pumicite L                    | 35                                   | —                                                            | —                    | <i>n</i>                                               | <i>e</i>                        | <i>e</i>               | <i>e</i>                                       | <i>e</i> | <i>e</i> |
|                               | 17.5                                 | <i>n</i>                                                     | <i>n</i>             | —                                                      | —                               | —                      | <i>n</i>                                       | <i>n</i> | <i>n</i> |
| Tuff                          | 35                                   | —                                                            | —                    | <i>e</i>                                               | <i>e</i>                        | <i>e</i>               | <i>n</i>                                       | <i>e</i> | <i>n</i> |
|                               | 17.5                                 | <i>e</i>                                                     | <i>e</i>             | —                                                      | —                               | —                      | <i>n</i>                                       | <i>n</i> | <i>n</i> |
| Obsidian                      | 35                                   | —                                                            | —                    | <i>n</i>                                               | <i>n</i>                        | <i>n</i>               | <i>n</i>                                       | <i>e</i> | <i>e</i> |
|                               | 17.5                                 | <i>n</i>                                                     | <i>n</i>             | —                                                      | —                               | —                      | <i>n</i>                                       | <i>n</i> | <i>n</i> |
| Calcined shale M              | 40                                   | —                                                            | —                    | <i>e</i>                                               | <i>e</i>                        | <i>e</i>               | —                                              | —        | —        |
|                               | 30                                   | <i>e</i>                                                     | <i>e</i>             | <i>e</i>                                               | <i>e</i>                        | <i>e</i>               | <i>e</i>                                       | <i>e</i> | <i>e</i> |
|                               | 20                                   | —                                                            | —                    | <i>n</i>                                               | <i>n</i>                        | <i>n</i>               | —                                              | —        | —        |
|                               | 15                                   | —                                                            | —                    | —                                                      | —                               | —                      | <i>n</i>                                       | <i>n</i> | <i>n</i> |
| Calcined shale N              | 30                                   | <i>n</i>                                                     | <i>e</i>             | <i>e</i>                                               | <i>e</i>                        | <i>e</i>               | <i>e</i>                                       | <i>e</i> | <i>e</i> |
|                               | 15                                   | —                                                            | —                    | —                                                      | —                               | —                      | <i>n</i>                                       | <i>n</i> | <i>n</i> |
| Calcined diatomaceous earth   | 30                                   | <i>e</i>                                                     | <i>e</i>             | <i>e</i>                                               | <i>e</i>                        | <i>e</i>               | <i>n</i>                                       | <i>e</i> | <i>e</i> |
|                               | 15                                   | —                                                            | —                    | —                                                      | —                               | —                      | <i>n</i>                                       | <i>n</i> | <i>n</i> |
| Uncalcined diatomaceous earth | 16                                   | <i>e</i>                                                     | <i>e</i>             | <i>n</i>                                               | <i>n</i>                        | <i>n</i>               | —                                              | —        | —        |
|                               | 12                                   | —                                                            | —                    | <i>n</i>                                               | <i>n</i>                        | <i>n</i>               | <i>n</i>                                       | <i>n</i> | <i>n</i> |
|                               | 8                                    | —                                                            | —                    | <i>n</i>                                               | <i>n</i>                        | <i>n</i>               | —                                              | —        | —        |
|                               | 6                                    | —                                                            | —                    | —                                                      | —                               | —                      | <i>n</i>                                       | <i>n</i> | <i>n</i> |

<sup>a</sup> In this test, the admixture is used by itself. The criterion correlates the results with mortar-bar results in which 20 percent portland cement by weight (25 percent by volume) is replaced by the admixture.

Note: The letter *n* denotes that the admixture was found to be non-effective, the letter *e* that the admixture was found to be effective.

**Table V — Results of modified quick chemical test**

| Material                      | Replacement percent | Blends made with Ca(OH) <sub>2</sub> equivalent of Type I high-alkali cement, milliequivalents per liter |                         |                                                              |                                            |                  | Blends made with Ca(OH) <sub>2</sub> equivalent of Type I low-alkali cement, milliequivalents per liter |                         |                                                              |                                            |                  |
|-------------------------------|---------------------|----------------------------------------------------------------------------------------------------------|-------------------------|--------------------------------------------------------------|--------------------------------------------|------------------|---------------------------------------------------------------------------------------------------------|-------------------------|--------------------------------------------------------------|--------------------------------------------|------------------|
|                               |                     | Reduction in Na <sup>+</sup>                                                                             | K <sup>+</sup> released | Net reduction in alkali, (Na <sup>+</sup> + K <sup>+</sup> ) | Reduction in alkalinity (OH <sup>-</sup> ) |                  | Reduction in Na <sup>+</sup>                                                                            | K <sup>+</sup> released | Net reduction in alkali, (Na <sup>+</sup> + K <sup>+</sup> ) | Reduction in alkalinity (OH <sup>-</sup> ) |                  |
|                               |                     |                                                                                                          |                         |                                                              | Single end point                           | Double end point |                                                                                                         |                         |                                                              | Single end point                           | Double end point |
| Cement                        | 0                   | 6                                                                                                        | 0                       | 6                                                            | -2                                         | -4               | 5                                                                                                       | 0                       | 5                                                            | 5                                          | 1                |
| Slag                          | 30                  | 34                                                                                                       | 10                      | 24                                                           | 16                                         | 32               | -4                                                                                                      | 19                      | -23                                                          | 49                                         | 73               |
|                               | 50                  | 25                                                                                                       | 6                       | 19                                                           | 35                                         | 59               |                                                                                                         |                         |                                                              |                                            |                  |
|                               | 70                  | 10                                                                                                       | 13                      | -3                                                           | 90                                         | 142              |                                                                                                         |                         |                                                              |                                            |                  |
| Slag II                       | 50                  | 162                                                                                                      | 8                       | 154                                                          | 37                                         | 54               | —                                                                                                       | —                       | —                                                            | —                                          | —                |
| Natural cement I              | 20                  | 8                                                                                                        | 19                      | -11                                                          | -5                                         | -19              | -16                                                                                                     | 28                      | -44                                                          | 41                                         | 32               |
|                               | 35                  | 3                                                                                                        | 24                      | -21                                                          | 45                                         | 32               |                                                                                                         |                         |                                                              |                                            |                  |
|                               | 50                  | -19                                                                                                      | -39                     | -58                                                          | 70                                         | 73               |                                                                                                         |                         |                                                              |                                            |                  |
| Natural cement II             | 35                  | -12                                                                                                      | 21                      | -32                                                          | 35                                         | 31               | —                                                                                                       | —                       | —                                                            | —                                          | —                |
| Fly ash I                     | 30                  | 69                                                                                                       | 13                      | 56                                                           | 167                                        | 223              | 60                                                                                                      | 19                      | 41                                                           | 239                                        | 312              |
|                               | 45                  | 52                                                                                                       | 22                      | 30                                                           | 261                                        | 327              |                                                                                                         |                         |                                                              |                                            |                  |
|                               | 60                  | 87                                                                                                       | 13                      | 75                                                           | 295                                        | 376              |                                                                                                         |                         |                                                              |                                            |                  |
| Fly ash II                    | 45                  | 134                                                                                                      | 18                      | 116                                                          | 170                                        | 200              | —                                                                                                       | —                       | —                                                            | —                                          | —                |
| Fly ash III                   | 45                  | 52                                                                                                       | 11                      | 41                                                           | 148                                        | 182              | —                                                                                                       | —                       | —                                                            | —                                          | —                |
| Fly ash IV                    | 45                  | 110                                                                                                      | 15                      | 95                                                           | 146                                        | 198              | —                                                                                                       | —                       | —                                                            | —                                          | —                |
| Pumicite F                    | 25                  | 60                                                                                                       | 45                      | 15                                                           | 104                                        | 121              | 140                                                                                                     | 49                      | 91                                                           | 116                                        | 144              |
|                               | 35                  | 152                                                                                                      | 48                      | 104                                                          | 154                                        | 185              |                                                                                                         |                         |                                                              |                                            |                  |
|                               | 45                  | 220                                                                                                      | 26                      | 194                                                          | 227                                        | 256              |                                                                                                         |                         |                                                              |                                            |                  |
| Pumicite L                    | 35                  | 199                                                                                                      | 24                      | 175                                                          | 235                                        | 265              | —                                                                                                       | —                       | —                                                            | —                                          | —                |
| Tuff                          | 35                  | 224                                                                                                      | 16                      | 208                                                          | 257                                        | 293              | —                                                                                                       | —                       | —                                                            | —                                          | —                |
| Obsidian                      | 35                  | 47                                                                                                       | 33                      | 14                                                           | 50                                         | 73               | —                                                                                                       | —                       | —                                                            | —                                          | —                |
| Calcined Shale M              | 20                  | 50                                                                                                       | 2                       | 48                                                           | 68                                         | 72               | 151                                                                                                     | 6                       | 145                                                          | 175                                        | 172              |
|                               | 30                  | 216                                                                                                      | 0                       | 216                                                          | 238                                        | 243              |                                                                                                         |                         |                                                              |                                            |                  |
|                               | 40                  | 325                                                                                                      | -6                      | 331                                                          | 377                                        | 381              |                                                                                                         |                         |                                                              |                                            |                  |
| Calcined shale N              | 30                  | 356                                                                                                      | 0                       | 356                                                          | 386                                        | 390              | —                                                                                                       | —                       | —                                                            | —                                          | —                |
| Calcined diatomaceous earth   | 30                  | 258                                                                                                      | 6                       | 252                                                          | 355                                        | 362              | —                                                                                                       | —                       | —                                                            | —                                          | —                |
| Uncalcined diatomaceous earth | 8                   | 47                                                                                                       | 0                       | 47                                                           | -2                                         | -6               | -17                                                                                                     | 8                       | -25                                                          | 36                                         | 23               |
|                               | 12                  | 43                                                                                                       | 4                       | 39                                                           | 44                                         | 37               |                                                                                                         |                         |                                                              |                                            |                  |
|                               | 16                  | 95                                                                                                       | -2                      | 97                                                           | 53                                         | 72               |                                                                                                         |                         |                                                              |                                            |                  |

**Table VI—Results of Mortar-Bar Expansion Tests**

| Replacement material          |           | Expansion, % |       |       | Reduction in expansion, % |       |      | Warp, <sup>a</sup> % | Petrographic rating of bar condition |
|-------------------------------|-----------|--------------|-------|-------|---------------------------|-------|------|----------------------|--------------------------------------|
| Type                          | Volume, % | 14 days      | 6 mos | 1 yr  | 14 days                   | 6 mos | 1 yr | 1 yr                 |                                      |
| Type I High-alkali cement     |           |              |       |       |                           |       |      |                      |                                      |
| Pyrex aggregate               |           |              |       |       |                           |       |      |                      |                                      |
| None                          | —         | 0.106        | 0.221 | 0.230 | —                         | —     | —    | 0.05                 | 2                                    |
| Slag I                        | 50        | 0.008        | 0.011 | 0.014 | 92                        | 95    | 94   | 0.0                  | 1                                    |
|                               | 25        | 0.060        | 0.098 | 0.102 | 43                        | 56    | 56   | 0.03                 | 2                                    |
| Slag II                       | 50        | 0.021        | 0.025 | 0.028 | 80                        | 89    | 88   | 0.02                 | 2                                    |
|                               | 25        | 0.084        | 0.117 | 0.123 | 21                        | 47    | 47   | 0.04                 | 2                                    |
| Fly ash I                     | 45        | 0.028        | 0.033 | 0.035 | 74                        | 85    | 85   | 0.0                  | 1                                    |
|                               | 22.5      | 0.063        | 0.089 | 0.093 | 41                        | 60    | 60   | 0.0                  | 2                                    |
| Fly ash II                    | 45        | 0.031        | 0.032 | 0.037 | 71                        | 86    | 84   | 0.0                  | 1                                    |
|                               | 22.5      | 0.069        | 0.090 | 0.095 | 35                        | 59    | 59   | 0.0                  | 1                                    |
| Fly ash III                   | 45        | 0.034        | 0.035 | 0.037 | 68                        | 84    | 84   | 0.0                  | 1                                    |
|                               | 22.5      | 0.059        | 0.086 | 0.093 | 44                        | 61    | 60   | 0.0                  | 1                                    |
| Fly ash IV                    | 45        | 0.027        | 0.026 | 0.028 | 75                        | 88    | 88   | 0.0                  | 1                                    |
|                               | 22.5      | 0.063        | 0.083 | 0.091 | 41                        | 62    | 60   | 0.0                  | 1                                    |
| Pumicite F                    | 35        | 0.035        | 0.040 | 0.045 | 67                        | 82    | 80   | 0.0                  | 2                                    |
|                               | 17.5      | 0.059        | 0.082 | 0.087 | 44                        | 63    | 62   | 0.0                  | 2                                    |
| Pumicite L                    | 35        | 0.025        | 0.034 | 0.040 | 76                        | 85    | 83   | 0.0                  | 1                                    |
|                               | 17.5      | 0.065        | 0.088 | 0.094 | 39                        | 60    | 59   | 0.02                 | 1                                    |
| Tuff                          | 35        | 0.028        | 0.052 | 0.060 | 74                        | 76    | 74   | 0.0                  | 1                                    |
|                               | 17.5      | 0.072        | 0.155 | 0.170 | 32                        | 30    | 26   | 0.01                 | 2                                    |
| Obsidian                      | 35        | 0.036        | 0.046 | 0.053 | 66                        | 79    | 77   | 0.0                  | 1                                    |
|                               | 17.5      | 0.081        | 0.127 | 0.136 | 24                        | 43    | 41   | 0.03                 | 2                                    |
| Calcined shale M              | 30        | 0.018        | 0.021 | 0.029 | 83                        | 90    | 87   | 0.0                  | 1                                    |
|                               | 15        | 0.069        | 0.092 | 0.104 | 35                        | 58    | 55   | 0.0                  | 1                                    |
| Calcined shale N              | 30        | 0.004        | 0.002 | 0.009 | 96                        | 99    | 96   | 0.0                  | 1                                    |
|                               | 15        | 0.044        | 0.057 | 0.067 | 58                        | 74    | 71   | 0.02                 | 1                                    |
| Calcined diatomaceous earth   | 30        | 0.032        | 0.037 | 0.043 | 70                        | 83    | 81   | 0.0                  | 1                                    |
|                               | 15        | 0.071        | 0.104 | 0.110 | 33                        | 53    | 52   | 0.0                  | 1                                    |
| Uncalcined diatomaceous earth | 12        | 0.077        | 0.123 | 0.134 | 27                        | 44    | 42   | 0.03                 | 1                                    |
|                               | 6         | 0.101        | 0.185 | 0.198 | 5                         | 16    | 14   | 0.03                 | 1                                    |
| Synthetic silica glass        | 10        | 0.024        | 0.053 | 0.086 | 77                        | 76    | 63   | 0.03                 | 1                                    |
|                               | 5         | 0.059        | 0.182 | 0.236 | 44                        | 18    | -3   | 0.04                 | 1                                    |
|                               | 2.5       | 0.101        | 0.260 | 0.293 | 5                         | -18   | -27  | 0.05                 | 2                                    |

Table VI—continued

| Replacement material          |           | Expansion, % |        |        | Reduction in expansion, % |       |      | Warp, <sup>a</sup> % | Petrographic rating of bar condition |
|-------------------------------|-----------|--------------|--------|--------|---------------------------|-------|------|----------------------|--------------------------------------|
| Type                          | Volume, % | 14 days      | 6 mos  | 1 yr   | 14 days                   | 6 mos | 1 yr | 1 yr                 |                                      |
| Sioux-Klufa aggregate         |           |              |        |        |                           |       |      |                      |                                      |
| None                          | —         | 0.159        | 0.681  | 0.803  | —                         | —     | —    | 0.06                 | 5                                    |
| Slag I                        | 50        | 0.010        | 0.117  | 0.180  | 94                        | 83    | 78   | 0.0                  | 3                                    |
| Fly ash I                     | 22.5      | 0.065        | 0.381  | 0.464  | 59                        | 44    | 42   | 0.04                 | 3                                    |
| Pumicite F                    | 35        | 0.018        | 0.282  | 0.361  | 89                        | 59    | 55   | 0.04                 | 3                                    |
| Calcined shale M              | 30        | 0.018        | 0.051  | 0.102  | 89                        | 93    | 87   | 0.02                 | 3                                    |
| Uncalcined diatomaceous earth | 12        | 0.119        | 0.792  | 0.964  | 25                        | -16   | -20  | 0.05                 | 5                                    |
| Synthetic silica glass        | 10        | 0.021        | 0.044  | 0.059  | 87                        | 94    | 93   | 0.01                 | 2                                    |
|                               | 5         | 0.053        | 0.281  | 0.317  | 67                        | 59    | 61   | 0.03                 | 3                                    |
| Sioux aggregate               |           |              |        |        |                           |       |      |                      |                                      |
| None                          | —         | 0.004        | 0.027  | 0.057  | —                         | —     | —    | 0.0                  | 2                                    |
| Type II medium-alkali cement  |           |              |        |        |                           |       |      |                      |                                      |
| Pyrex aggregate               |           |              |        |        |                           |       |      |                      |                                      |
| None                          | —         | 0.046        | 0.068  | 0.075  | —                         | —     | —    | 0.0                  | 2                                    |
| Slag I                        | 50        | -0.003       | -0.009 | -0.005 | 107                       | 113   | 107  | 0.0                  | 1                                    |
| Fly ash I                     | 45        | 0.008        | 0.005  | 0.008  | 83                        | 93    | 89   | 0.0                  | 1                                    |
| Pumicite F                    | 35        | -0.002       | -0.004 | 0.003  | 104                       | 106   | 96   | 0.0                  | 1                                    |
| Calcined shale M              | 30        | 0.000        | -0.005 | -0.002 | 100                       | 107   | 103  | 0.0                  | 1                                    |
| Uncalcined diatomaceous earth | 12        | 0.001        | 0.002  | 0.004  | 98                        | 97    | 95   | 0.0                  | 1                                    |
| Synthetic silica glass        | 10        | 0.008        | -0.019 | -0.022 | 83                        | 128   | 129  | 0.0                  | 1                                    |
|                               | 5         | 0.006        | 0.004  | 0.016  | 87                        | 94    | 79   | 0.0                  | 1                                    |
| Sioux-Klufa aggregate         |           |              |        |        |                           |       |      |                      |                                      |
| None                          | —         | 0.100        | 0.454  | 0.537  | —                         | —     | —    | 0.02                 | 4                                    |

<sup>a</sup> Determined according to Method CRD-C123.