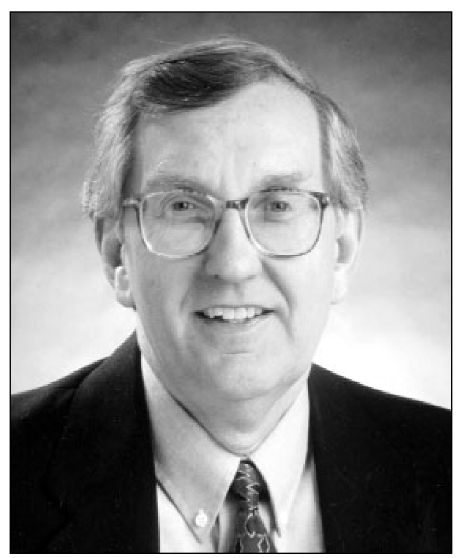
13. MATERIALS

13.1 CONSTRUCTION MATERIALS REFERENCE LABORATORIES

In the early part of the 20th century, there was concern about the inconsistency of testing of portland cement which was becoming an important material used in construction. In response, a number of organizations, including NIST, ASTM International, and the Portland Cement Association collaborated in studies directed towards improving standardized specifications and test methods for portland cement. This response lead to the formation of the Cement Reference Laboratory in 1929 as a research associate program at NIST, managed by NIST but under the sponsorship of ASTM Committee C01 on Hydraulic Cement [1]. In 1960, ASTM Committee C09 on Concrete and Concrete Aggregate was added as a sponsor, and the name was changed to the Cement and Concrete Reference Laboratory (CCRL). J. R. Dwyer who was actively involved with establishing CCRL was its Manager from 1929 to 1965. He was followed by John R. Dise in 1965 who added the title of Manager of AMRL and served as Secretary of ASTM Committee C01 for the whole of his time with CCRL. James H. Pielert became Manager of AMRL and CCRL in 1983, a position he still occupies. John Haverfield was the Assistant Manager of CCRL until 1985 when Raymond Kolos assumed the position.

The AASHTO Materials Reference Laboratory (AMRL) was established at NIST in 1965 under a similar arrangement with the sponsorship of the

James Pielert, leader of Construction Materials Reference Laboratories.



American Association of State Highway and Transportation Officials (AASHTO) [2]. This formation was in response to an investigation of the Interstate Highway System Program by Congressman Blatnick in the early 1960s, which identified problems with the consistency of testing of materials used in highways. NIST was selected because it was already hosting the CCRL, which became the model for AMRL, and because of its reputation, could provide an unbiased evaluation of laboratory performance. Oakley McIntosh was the Assistant Manager of AMRL until 1985 when Peter Spellerberg assumed the position.

The primary mission of AMRL and CCRL is to improve the quality of testing in laboratories that test construction materials. This is accomplished through on-site visits to laboratories, distributing proficiency samples to laboratories for testing, participating in the work of standards committees, and conducting research related to development of tests for construction materials. Construction materials covered include hydraulic cements, portland cement concrete, masonry materials, reinforcing steel, pozzolans, aggregates, soils, asphalt binders, hot-mixed asphalt, plastic pipe, and paints used in transportation systems.

The last quarter of the 20th century was a period of substantial change in AMRL and CCRL as, with the increasing emphasis on quality in construction, their programs gained increasing recognition by the construction community. The number of laboratories participating in AMRL and CCRL programs more than doubled during this period resulting in more than 1400 laboratories participating in 2003. This participation includes laboratories from all 50 of the United States and 20 other countries. New programs were added in masonry materials, pozzolans, blended cements, hot-mixed asphalts, and paints used in transportation systems.

The AMRL and CCRL Laboratory Assessment and Proficiency Sample Programs have become important components of the laboratory accreditation system in the United States [3]. AMRL and CCRL Proficiency Sample Programs are used by the three major accreditors of construction materials testing laboratories; the AASHTO Accreditation Program (AAP), the American Association for Laboratory Accreditation (A2LA), and the National Voluntary Laboratory Accreditation Program (NVLAP). AMRL and CCRL Laboratory Assessment programs are used by the AAP. Additionally, AMRL provides technical support to the AAP, which was established by AASHTO in 1988, and it currently has more than 800 laboratories accredited.

AMRL has had an important role in the implementation of technology resulting from the National Academies' Strategic Highway Research Program (SHRP). SHRP was established by Congress in 1987 as a five year, $150 million research program to improve the performance and durability of the nation's highways, and to make those highways safer for both motorists and highway workers [4]. At the time SHRP concluded in 1993, it had developed 130 products in support of its mission, and the implementation of SHRP technology became an important follow-up activity. AMRL supported the drafting of more than 70 standards resulting from this research, which are being processed through the AASHTO and ASTM standards process. The resulting standardized test methods and practices have been added to AMRL's Laboratory Assessment and Proficiency Sample Programs, and to the scope of AAP. In addition, AMRL has assembled a state-of-art liquid asphalt laboratory.

In the mid-1990s, AMRL had a lead role in the metrication of AASHTO's materials standards as part of the movement toward the use of the metric system of measurement in the United States.

Kathryn Tice, AMRL research associate, is preparing hot performance graded asphalt binder test samples for placement in a pressured aging vessel for optimizing use in highway construction.

The relationship between NIST, ASTM, and AASHTO on the AMRL and CCRL programs was strengthened in 1999 with the signing of a new Memorandum of Agreement calling for the development of a standards-oriented research component which would complement the BFRL research program. This will ensure the continued excellent relationship between the three parties to the agreement.

AMRL and CCRL have had a significant impact on the quality of testing of construction materials during their 70 year history. The increasing concern currently being expressed about quality on the international level indicates that the programs can still make a valuable contribution in promoting the quality of testing of construction materials. These programs are unique examples of Federal government, state government, and private sector cooperation in addressing a problem of common concern. Their customers were strong and effective proponents before Congress for the continued existence of CBT during the budget crisis of the 1980s.

The AMRL and CCRL have developed a large amount of data from the standard tests carried out by participants in the proficiency programs. The CCRL cement and concrete databases are of great value to BFRL's Virtual Cement and Concrete Testing Laboratory (VCCTL) program in which they are being used in testing the validity of VCCTL models for simulating performance of cement and concrete [5].

The strong leadership provided by Dwyer and Dise in the first half century of CCRL and AMRL's existence put these organizations in leadership positions in promoting the quality of laboratory testing. Through Pielert's thoughtful management, strong interpersonal skills, and interest in keeping up with technological developments and foreseeing future needs have led to increased professional stature and high morale for the research associates who staff the CMRL, good relations with sponsors in ASTM and AASHTO, and strong synergy with research activities in BFRL.

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13.2 SERVICE LIFE PREDICTION OF CONSTRUCTION MATERIALS

13.2.1 INTRODUCTION

Although most building and construction materials are expected to have service lives of several decades, no methods have been available for making reliable predictions of long service lives either from short-term tests or from first principles. The lack of generally-accepted methods for service life prediction has been a barrier to the most effective selection, use and maintenance of building and construction materials, and has been cited as an important contributor to premature failures. It is also a barrier to innovation since designers are reluctant to specify products for which evidence of performance over time is lacking. The need to reduce costs associated with repair, replacement and maintenance, and to assess the service lives of innovative materials without decades of testing led to the initiation, in 1973, of CBT's research program on service life prediction. In that year, Geoffrey Frohnsdorff joined CBT in 1973 as Chief of the Materials and Composites Section, at a time when the Section was heavily involved in durability studies in support of HUD's Operation Breakthrough. Larry Masters and Winfred Wolfe had prepared a report [1] on weather and climatological data to provide a basis for relating outdoor exposure tests performed at sites such as those used by NBS at the Roosevelt Roads Naval Base in Puerto Rico, and at Nellis Air Force Base in Nevada, as well as at the NBS site.

During the planning of a project to evaluate the durability of several types of adhesively-bonded sandwich panels, Frohnsdorff pointed out the need for a general methodology for service life prediction. He then obtained agreement from HUD that such a standard methodology should be developed, and he arranged for a new subcommittee, E-6.22, Durability Performance of Building Constructions, to be established in ASTM Committee E06, Performance of Buildings. As chairman of the new subcommittee, Frohnsdorff appointed Peter Sereda of the National Research Council of Canada (NRCC) as vice-chairman, and Masters was appointed chairman of a task group to develop the needed standard methodology. Frohnsdorff, Masters and Sereda shared the ambitious goal of developing a fundamental, science-based understanding of materials degradation that could provide the technical basis for a new generation of durability standards .

13.2.2 STANDARD PRACTICE FOR DEVELOPMENT OF ACCELERATED TESTS AND A NEW SYSTEM OF SERVICE LIFE PREDICTION STANDARDS

By 1978, Masters had the first of the needed service life prediction standards in place as ASTM E-632, Standard Practice for Developing Short-Term Accelerated Tests for Prediction of the Service Life of Building Materials and Components. Also in 1978, as a result of the collaboration between Frohnsdorff and Sereda in ASTM Committee E06, an International Conference on the Durability of Building Materials and Components was held in Ottawa with NRCC, NBS/NIST, ASTM, and RILEM as sponsors. A keynote paper [2] on “The Meaning of Durability and Durability Prediction” that Frohnsdorff and Masters presented at the conference suggested that the reliability approach might be brought in to service life predictions of building materials. That led to hiring Jonathan Martin, a reliabilist from the University of Washington. Thus, in 1978, three major seeds of what has become BFRL’s world-leading service life prediction program for building materials were planted - the hiring of Martin, the publication of ASTM E-632, and the holding of the International Conference; the conference became the first in the series of triennial International Conferences on the Durability of Building Materials and Components (DBMC) sponsored by NRCC, NBS/NIST, RILEM and CIB. The Second International Conference (2DBMC) was held at NBS in 1981 with Frohnsdorff as chairman. Subsequent conferences in the series have been held in Espoo, Finland; Singapore; Brighton, England; Tokyo; Stockholm; Vancouver; and Brisbane.

In 1980, for his achievement in leading the development of ASTM E-632, Masters received the Department of Commerce Bronze Medal. In the same year, Frohnsdorff was appointed to RILEM’s Research Advisory Group (RAG) and, in 1983, when he was chairman of the Advisory Group, Frohnsdorff arranged for the establishment of a RILEM Committee on Service Life Prediction, Committee 71-SLP, with Masters as chairman. The main products of this committee were Masters’ report [3] based on ASTM E-632, and a later report prepared by Masters and Erik Brandt, a guest researcher from Denmark. RILEM recognized the importance of the later report by giving it pre-standard status by designating it a RILEM Technical Recommendation [4]. It is noteworthy that both the Principal Guide to Service Life Planning [5] of the Architectural Institute of Japan and a key portion of British Standard BS 7543, Guide to Durability of Buildings, and Building Elements, Products and Components” [6] draw on ASTM E-632 or have portions patterned on it. The needs identified in Masters’ work provided the justification for the 1984 NATO Advanced Research Workshop on Problems in the Prediction of the Service Life of Building and Construction Materials [7] at which Masters brought together leading European and U.S. durability researchers.

CBT and other laboratories made many applications of the ASTM E-632 methodology during the 70s and 80s. For instance, CBT supported the Department of Energy and the emerging solar energy industry with studies and recommendations that provided the technical basis for many standards for the durability of materials used in solar energy systems [8]. CBT's knowledge on matters relating to durability and related aspects of performance of building materials was also applied on several projects of national importance. The work of Paul Campbell, Mary McKnight, and Larry Masters in providing detailed specifications for the restoration and maintenance for the paint on the White House was described [9] as one of the most sophisticated and professional paint studies ever conducted. Then, for a study concerning the possible use of stone preservative treatments in the restoration of the West Front of the United States Capitol [10], James Clifton received a National Historic Preservation Award in 1988; the citation for the award stated, "technically it has broken much new ground; it is a model for archival and curatorial work." For other durability-related studies, Mary McKnight received the Department of Commerce Bronze Medal in 1994 for contributions to improved coatings practices, and, for his work in modeling the degradation of coatings, Tinh Nguyen received the Bronze Medal in 1994.

In 1990, Frohnsdorff and Masters presented a paper [11], "Suggestions for a Logically-Consistent Structure for Service Life Prediction Standards," at the 5DBMC Conference. It recommended the development of a system of service life standards with three levels. The first level would consist of a single generic standard, such as ASTM E-632 or the RILEM Technical Recommendation, that outlined the methodology for predicting service life. The second level would consist of about six generic standards addressing topics called out in the standard in the first level including: characterization of service environments, characterization of materials and components, identification of degradation mechanisms, modeling the kinetics of degradation, determination of times-to-failure, and reporting of results. The third level would consist of an indefinite number of material- or product-specific standards that described how the generic standards in the two higher levels should be applied in predicting service lives of specific materials. This hierarchy has been adopted as a model for the development of international standards for service life prediction in cooperative activities involving the joint CIB/RILEM Committee on Service Life Prediction and ISO TC59/SC14 on Design Life (see next paragraph). The European Community is relying on the development of such standards for full implementation of its Construction Products Directive.

In 1993, Frohnsdorff proposed to ISO Technical Committee TC59, Building Construction, that it should establish a Working Group on Design Life of Buildings. The proposal was accepted and Working Group 9 was established in Subcommittee 3 of TC59, with Frohnsdorff as chairman. In 1997, in recognition of the progress made, Working Group 9 was elevated to subcommittee status as ISO TC59/SC14, Design Life of Buildings and Constructed Assets [12]. The Subcommittee is drafting an eight-part standard, ISO 15686, Buildings and Constructed Assets: Service Life Planning. Taken together, the parts will, for the first time, recommend that designers call for service life data, or standard service life predictions, for products to be used in their designs.

13.2.3 THE RELIABILITY-BASED APPROACH TO SERVICE LIFE PREDICTION

When Jonathan Martin joined CBT's materials research staff in 1978, he introduced the reliability-based approach to service life prediction. The reliability-based methodology [13], with its rigorous experimental procedure and strong scientific basis, had already had a long history of successful application in the electronics, aerospace, nuclear, and medical fields. In a reliability-based methodology, since weathering factors cannot be controlled, results of field exposure experiments are not the standard of performance -- however, they may be an important source of data if the weathering factors can be monitored just as they are in the laboratory. The standard of performance is now based on laboratory experiments that can be made repeatable and reproducible if the sources of experimental error are minimized; with proper design, the experiments can provide data from which service life under any expected conditions can be predicted. There is no longer a need to try to design laboratory experiments that simulate outdoor exposures since the laboratory experiments can cover the range of exposure conditions that a product will be exposed to in the field. With the paradigm shift accompanying adoption of the reliability-based methodology, laboratory accelerated aging and fundamental mechanistic experiments are, for all practical purposes, equivalent except for the number of experimental variables under investigation. For his leadership in developing the reliability-based approach to service life prediction of coatings and other polymeric building materials, Martin received the Department of Commerce Bronze Medal in 1996.

The industrial significance of Martin's work was first recognized by the coatings community. In 1994, a strong research consortium -- the Coatings Service Life Performance Consortium involving industry, government and academe -- was established. The consortium, managed by Martin, included several leading coatings manufacturers among its members. Its objective is to apply a reliability-based methodology in estimating the service life of a coating or other polymeric building material subjected to ultraviolet radiation and other weathering factors. Though initially established for a three-year period, the achievements of the consortium have been sufficiently encouraging that it has already been extended for two additional three-year periods. In view of the need to disseminate knowledge of the reliability approach, Martin, with David Bauer of the Ford Motor Company, initiated a series of international conferences, sponsored by the American Chemical Society, on prediction of service life of coatings, and on polymeric materials in general. The first two conferences were held in 1997 [14] and 1999 [15].

The reliability-based methodology requires the sets of data collected from the three primary sources of service life data (field, accelerated laboratory, and fundamental mechanistic studies) to have the same data elements and to be of comparable quality. Data is needed on the initial properties of a material, on changes in the properties of the material as functions of time, and on the weathering factors (i.e., degradative factors) in the exposure environment as functions of time. Data needed on the exposure environments, whether in the laboratory or field, are usually spectral irradiance, spectral distribution, specimen temperature, and specimen moisture content.

With the need for measurements to improve reliability-based service life predictions, Martin designed a completely new laboratory exposure device to minimize the temporal, spatial, systematic, equipment, and operational sources of error encountered in earlier devices. In the new device [16], each of 32 similar ports on the surface of a 2 m diameter integrating sphere opens into the sphere's interior. The interior is illuminated by an intense source of visible and ultraviolet radiation at the top of the sphere. The ports provide essentially-identical sources of radiation for exposure chambers attached to the ports through parabolic cone concentrators. Because of the uniformity of the radiation within the sphere, monitoring the radiation emitted from a single port is equivalent to monitoring the radiation emitted from every port. Conditions within any of the exposure chambers could be controlled for spectral radiation, temperature, and relative humidity, and for almost any other factor of interest; where necessary, mechanical loads could be applied to some specimens. Large numbers of small specimens can be exposed in each of the chambers, and the specimens can be easily removed for analysis to determine the degree of degradation. The ability to provide a variety of precisely-controlled exposures of large numbers of specimens greatly increases the power and practicality of applying the reliability approach to prediction of service lives under any specified conditions. In an ancilliary development, to provide for frequent analyses of the large number of specimens from the exposure chambers, the presentation of specimens for infra-red and ultraviolet spectrophotometric measurements was automated. One of the early findings from the reliability-based experiments was the unexpectedly strong dependence of rate of photodegradation on the moisture content within a coating [17].

The need for high-quality field data for use with data from the new exposure

Tinh Nguyen, physical scientist, is using a Fourier transform infrared microscope to study factors affecting the failure of organic protective coatings on steel.

device in predicting the service lives of materials in the field, was accompanied by a need for access to strategically-located, well-instrumented, field exposure sites. The establishment of eight such sites at widely-spaced locations within the U. S. was carried out as a cooperative project among four Federal Agencies with overlapping interests -- NIST, the Smithsonian Environmental Research Center (SERC), the USDA UV-B Network Program, and the Forest Products Laboratory (FPL) at Madison, WI [18]. With the establishment of these sites, NIST now has in place all the necessary components for development and demonstration of its world-leading capability to apply the reliability approach to the prediction of the service lives of polymeric building materials including paints and coatings, building joint sealants, and composites.

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13.3 CORROSION PROTECTION FOR REINFORCING STEEL

The deterioration of concrete highway bridge decks exposed to deicing salts was identified as a national problem by the mid 1960s. The lifetime of bridge decks was only 5 to 10 years in northern states where deicing salts were heavily used. The Federal Highway Administration (FHWA) estimated that $25 billion was needed over the next decade to repair the failing decks.

FHWA engaged CBT to develop performance criteria and test methods for organic coatings to protect reinforcing bars from corrosion while providing needed structural reinforcement. The research carried out by James Clifton, Robert Mathey, and Hugh Beeghly [1, 2] showed that only four of the forty eight coatings evaluated met the performance criteria. All four were spray-applied powdered epoxy resins.

Standards based on this research for epoxy-coated steel reinforcing bars were adopted by the American Association of State Highway and Transportation Officials, ASTM, and the Concrete Reinforcing Steel Institute [3, 4]. A new industry represented by the Fusion-Bonded Coaters Association developed to supply epoxy-coated reinforcing. Forty six states specify epoxy-coated reinforcing in bridge deck construction. By 1990, over 272.2 x 10^6 kg of epoxy-coated steel reinforcement, about 5.5 percent of all reinforcing bars, were used in the U.S. In recognition of the importance of their work, Clifton and Mathey received the Department of Commerce Silver Medal in 1975, and the Alfred E. Lindau Award from the American Concrete Institute in 1987.

Findings from FHWA indicate the coated reinforcing extends the life of a bridge deck exposed to deicing salts, from 5 to 10 years without coating, to more than 40 years. Considering the 25 percent additional cost of coated reinforcing to be insignificant compared to the total labor and material cost for a bridge deck replacement, the 1990s annual expenditure of $500 million for bridge deck replacement, and a discount rate of 7.6 percent, the annual present value savings by use of coated reinforcing to extend life from 10 years to 40 years is $745 million.

James Clifton, leader of inorganic building materials research.

James Clifton, who earned a Ph.D. in Inorganic Chemistry from Oregon State University, joined the Building Research Division in 1969 and led research in durability of inorganic building materials until his death in 1999. He was a quiet, cheerful man with endless enthusiasm for research and the accomplishments of his colleagues. Robert Mathey joined BRD in 1955, worked 14 years in structural research, and then in materials research until his retirement in 1991. His warmth, responsibility and cooperation were appreciated by colleagues in NBS, collaborating and sponsoring federal agencies and professional and standards committees. Hugh Beeghly worked for CBT for a few years in the 1970s following a long career in research in the steel industry.

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13.4 ROOFING RESEARCH

In 1969, C.W. Griffin [1] wrote that "the volume of built-up roofing annually installed in the United States totals 2 billion square feet… Probably 10 to 15 percent of the roofs ... fail prematurely." Statements such as Griffin's made it evident that the U.S. membrane roofing industry urgently needed to improve the performance of its products. One of the major problems of the era was poor characterization of the engineering properties of built-up-roofing (BUR) membranes. Consequently, specifications detailing the performance requirements for completed BUR membranes were non-existent. In contrast, prescriptive specifications indicating the type and number of reinforcing plies, and the type and amount of bitumen were the norm. A common result was that installed membranes had inadequate properties to perform satisfactorily.

This situation changed dramatically, when in 1974, Robert G. Mathey and William C. Cullen published Building Science Series (BSS) 55, Preliminary Performance Criteria for Bituminous Membrane Roofing [2]. For the first time, the U.S. membrane roofing industry had guidance for selecting membranes based on their performance properties. Mathey and Cullen identified 20 performance attributes considered important to the satisfactory performance of BUR membranes, and they suggested performance criteria for 10 of these attributes. The performance concept, applied to BUR membranes, was widely embraced by the industry. Specifiers selected membranes on the basis of their conformance to the criteria, manufacturers promoted (where appropriate) existing products, and developed new products, meeting the criteria. Consultants investigating performance problems with in-place membranes compared properties with the BSS 55 recommendations. Roofing contractors were perhaps the most vocal group of supporters and, in this regard, the National Roofing Contractors Association (NRCA) Manual incorporated recommendations that installed membranes have performance properties in accordance with BSS 55 criteria.

The impact of BSS 55 has been long lasting. By way of example, at an NRCA annual convention in the late 1980s, the Owens-Corning Company made a presentation on the history and performance of BUR systems in the U.S. The development of BSS 55 was recognized as a significant milestone in the industry's history, and a major driving force behind the significant improvements in BUR performance that occurred over the 15 year period after the report's publication.

Another major issue that faced the BUR industry in the early 1970s centered on restrictive requirements that severely limited the temperature to which asphalt could be heated during installation of built-up membranes. At the time, asphalt was classified into four Types, I, II, III & IV, based on the results of tests such as softening point and penetration. Although it was generally considered that the higher the type, the less likely the asphalt would flow at a given temperature, specifications for asphalt application did not usually recognize such differences. One consequence was that asphalt was often applied at temperatures too low for proper flow. Improper flow results in excessively thick, non-uniform asphalt layers that may contain voids and that may be inadequately adhered to membrane reinforcing felts. As a solution to this asphalt heating problem, industry task groups proposed the Equiviscous Temperature concept. According to this concept, asphalt was to be applied at a temperature at which it would flow sufficiently (i.e., have adequately low viscosity) to achieve well-adhered, uniformly thin, void-free layers between membrane plies. Equivalently said, the viscosity of the heated asphalt at application was proposed to be in the range of about 100 centistokes to 150 centistokes. In support of the industry efforts, Walter J. Rossiter and Mathey authored BSS 92, The Viscosities of Roofing Asphalts

Sampling built-up-roofing membranes for measuring its performance properties.

at Application Temperatures [3]. This report, which described a combined laboratory and field study, was a cornerstone of the technical foundation for the Equiviscous Temperature concept. In the laboratory, the viscosities of 20 typical roofing asphalts were measured over their application temperatures, and compared with softening points and penetrations. These data demonstrated that different asphalts had different viscosity-temperature relationships, and that asphalt application temperatures should be determined on the basis of viscosity. In the field, BUR membrane samples were prepared using typical roofing asphalts heated at different temperatures encompassing the range of application temperatures encountered in practice. These BUR samples were analyzed to relate the quality of the asphalt application to the application temperature and, in turn, the viscosity at application. The major recommendation was that the optimum viscosity of asphalt at the time of application should be within the range of 50 centistokes to 150 centistokes. Soon after publication of BSS 92, the industry adopted the Equiviscous Temperature concept which remains in use today.

As noted above in the quote from Griffin, at the beginning of the 1970s built-up roofing had a monopoly on the U.S membrane market. However, that monopoly was soon to be broken. Because of the all-too-frequent problems with BUR membranes in the early 1970s, many owners, architects, specifiers, and others responsible for roof system selection were eager to find alternative membrane materials. In response, material suppliers emerged who provided, at competitive costs, alternative systems based on elastomeric and thermoplastic polymeric membranes, and polymer-modified bituminous membranes. The growth in use of these products was explosive. Although their use was almost non-existent in the mid-1970s, by the end of the 1980s they accounted for about 70 percent of the membranes installed in the U.S. -- a figure that has remained reasonably constant through today. However, the growth in use was not problem free. These membranes had been introduced into the market without consensus standards to assist in their proper selection and use. Research was needed to understand better the performance of these systems, to develop solutions to the problems that were arising, and to contribute to the technical bases of the much needed consensus standards.

Of the new membrane materials that entered the market in the mid-1970s, EPDM (ethylene-propylene-diene terpolymer) rubber, manufactured as preformed single-ply sheets ready for field installation, experienced the most rapid growth. By the mid-1980s, it accounted for about 35 percent of the membrane market. EPDM is rather chemically inert rubber, which makes it attractive for outdoor use as a membrane material. However, this chemical inertness becomes a limitation when bonding adjacent sheets in the field to form the seams of a waterproofing membrane. At the time, these seams were typically fabricated with contact-type, polymer-based, liquid adhesives. In the mid-1980s, unsatisfactory seam performance accounted for about 50 percent of the EPDM membrane problems reported to the NRCA in surveys of member contractors. BFRL initiated research to elucidate the factors affecting performance and to develop solutions for improved performance.

Reports from NRCA indicated that many seam defects developed within the first three years of service.

Additionally, BFRL field inspections of EPDM roofing provided evidence of seams that were leak-free for 4 years to 5 years, at which time problems occurred. In these cases, disbonded seams were seen to be located at buckles and ripples in the EPDM membrane. BFRL researchers reasoned that many of these early failures were related to the rheological behavior of the adhesive and not to chemically-induced deterioration. Consequently, BFRL research staff in the Building Materials Division began studies to elucidate the major factors affecting the capability of seams to sustain loading. They developed creep-rupture test protocols, suitable to EPDM seams, in which joint specimens were stressed under constant load and the time over which they sustained the load was recorded. The better performing seams had longer times-to-failure. The factors investigated included material parameters such as the adhesive and its applied thickness, mechanical parameters such as the magnitude and type (i.e., peel and shear) of load, environmental parameters such as temperature, moisture and ozone, and application parameters such as the cleanness of the EPDM rubber surface.

Initial creep-rupture experiments and major findings were described in BSS 169, Strength and Creep-Rupture Properties of Adhesive-Bonded EPDM Joints Stressed in Peel, by Jonathan W. Martin, Edward Embree, Paul E. Stutzman, and J. A. Lechner [4]. Chief among the findings was that the thickness of the adhesive layer was an extremely important parameter affecting performance, as time-to-failure increased exponentially with adhesive thickness. Additionally, the cleanness of the EPDM rubber at the time of adhesive application was also shown to be significant. Although industry had always required that EPDM rubber was to be thoroughly cleaned before adhesive application, until BSS 169, the important influence of adhesive thickness on seam performance had been given little attention by practitioners. BFRL observations from field inspections showed, for example, that the thickness of adhesive layers often was less than EPDM manufacturers' recommendations. Although the relationship between adhesive thickness and seam performance was surprising to many, its implications were taken seriously. In 1991, the NRCA published [5], with BFRL assistance, a feature article entitled, "Is Your Adhesive Layer Thick Enough?" to alert contractors to the importance of adhesive thickness. At least one EPDM membrane manufacturer made available wet-film thickness gages to help ensure that the amount of applied adhesive was within prescribed limits.

BSS 169 demonstrated the importance of creep-rupture tests in evaluating seam performance. In 1993, ASTM issued Standard Test Method D5405, Conducting Time-to-Failure (Creep-Rupture) Tests of Joints Fabricated from Nonbituminous Organic Roof Membrane Material. This test method is based on BFRL seam research, and provides a sensitive procedure for investigating factors affecting seam performance under loading conditions that may lead to failure in the field.

As BFRL was completing its studies on liquid adhesives and ASTM Test Method D5405 was under development, EPDM roofing manufacturers introduced a new generation of adhesives based on preformed, polymer-based, tape adhesives. The introduction of tape adhesives was received with little enthusiasm by many practitioners, as they had become confident of the liquid adhesives being used at the time. On the other hand, proponents believed that tape adhesives had advantages over liquid adhesives such as enhanced seam performance, lessened environmental impact because they were solvent-free, and lower seam fabrication costs. In 1994, the EPDM industry formed a consortium with BFRL to conduct laboratory and field research to further the understanding of this innovative EPDM seam-adhesive technology. The consortium was comprised of three EPDM membrane material manufacturers, two tape adhesive manufacturers and two industry associations. The objectives were to:

- compare the creep-rupture performance of tape-bonded and liquid-adhesive-bonded seams of EPDM membranes, and
- recommend a test protocol for evaluating creep-rupture performance of such seams.

The results of the tape-bonded seam studies were published in BSS 175, BSS 176 and BSS 177 [6-8]. BFRL

Kevin Kraft and Edward Embry, BFRL materials staff, are examining the status of EPDM creep rupture experiment.

staff participating in the studies were Rossiter, Kevin Kraft, Embree, and James Seiler, who were assisted throughout by Mark Vangel of the NIST Statistical Engineering Division. Among the key findings, it was shown that tape-bonded seams had times-to-failure that were, in most cases, comparable to, or greater than, those of the liquid-adhesive-bonded seams. Moreover, the times-to-failure of tape-bonded specimens prepared with primed, clean EPDM were not affected by the application temperatures and pressures investigated. This finding was significant because application temperatures and pressures are difficult, if not practically impossible, to control in practice. Also, tape-bonded seams prepared with properly cleaned and primed EPDM rubber had longer times-to-failure than those fabricated without adequate cleaning and priming of the EPDM. This result, although not unexpected, emphasized to contractors in particular that proper application is a critical parameter affecting tape-bonded seam performance.

The consortium study hastened the acceptance of the innovative EPDM tape-bonded seam technology. In 1998, the NRCA marked the study conclusion in summarizing key findings and acclaimed its success in stating that "laboratory and field studies confirm the viability of tape-bonded seams" [9]. Additionally, the second study objective was successfully met, as the results provided the technical basis of ASTM Standard Practice D6383, Time-to-Failure (Creep-Rupture) of Adhesive Joints Fabricated from EPDM Roof Membrane Material. Among its benefits, this Standard Practice allows for evaluating the creep-rupture performance of newly developed adhesives for fabricating EPDM seams. The significance of this Standard Practice was made clear as the consortium study was concluding. At that time, two new tape adhesives for EPDM seams entered the market, which doubled the number available when the study began.

Throughout the 1970s, 80s, and 90s, BFRL staff played an important role in the dissemination of the results of roofing research to the U.S. roofing industry and in the development of the ASTM standards that were urgently needed by the roofing industry. Over these decades, BFRL teamed with the National Roofing Contractors Association (NRCA) to co-sponsor the biennial Conferences on Roofing Technology. In the 1970s, William Cullen received the NRCA Piper Award and also the ASTM Voss Award for his contributions to elucidating factors affecting the performance of roof membranes. Cullen's efforts were further acknowledged in 1980 when he received the Gold Metal Award of the Department of Commerce for his contributions to performance standards for membrane roofing. In the early to mid-1990s, Rossiter was chair of the ASTM Committee D08 on Roofing and Waterproofing. Previously, he had served a lengthy appointment as chair of Subcommittee D08.18, which has responsibility for standards for elastomeric and thermoplastic polymeric membranes. His contributions were acknowledged when he received the ASTM Award of Merit and the ASTM Voss Award for his standards development efforts and for advancing the understanding of the performance of seams in EPDM membranes. Rossiter was also chair of the joint CIB/RILEM Committee on Roofing that provided recommendations on needs for roofing standards. Based on this Committee's recommendations, five standards were issued by ASTM.

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13.5 LEAD HAZARD ABATEMENT IN RESIDENTIAL BUILDINGS

Walter Rossiter, research chemist, obtains paint sample for lead content analysis. He is investigating the presence of lead in household paints.

From the early 1970s, NIST has conducted research and field studies to support the programs of the U.S. Department of Housing and Urban Development (HUD) to identify lead-based paint in housing and provide appropriate, cost-effective remediation actions. HUD programs were developed in response to federal legislation (the Lead-based Paint Poisoning Prevention Act of 1971 and its amendments of 1973, 1987, 1992) that aimed to reduce the number of children having excessive blood-lead levels. In the United States in 1978, the number of children with excessive blood-lead levels was approximately 14.8 million, while in the early 1990s the number was approximately 1 million.

In the 1970s NIST research by Stanley Rasberry [1], Phillip Cramp, and Harvey Berger [2] led to specification and evaluation of new instruments to determine the content of lead in paint films and to the development of cost-effective abatement strategies. Lead-based paint abatement options were evaluated by David Waksman, Leo Skoda, Elizabeth Clark [3] and others. Robert Chapman and Joseph Kowalski [4] conducted economic studies and developed cost models for lead-based paint abatement. Harvey Berger received the Department of Commerce Bronze Medal Award in 1976 for leadership of the lead-based paint hazard abatement research.

In the late 1980s, NIST conducted research in several areas to assist HUD in developing regulations in response to new legislation. In BFRL, Mary McKnight led research to evaluate the performance of new portable instruments to determine the lead content of paint films [5]. Walter Rossiter developed performance criteria for coatings used to overcoat existing lead-based paint films [6]. BFRL also collaborated with NIST's Chemical Science and Technology laboratory in the development of Standard Reference Materials for lead in paint films and other environmental media [7]. A total of 17 materials were developed.

In early 1991, HUD recognized an urgent need for standards for detecting, controlling, and abating lead hazards associated with housing, and requested that ASTM initiate their development. In response, in late 1991, ASTM formed Subcommittee

Mary McKnight, leader of lead paint hazard mitigation research.

E06.23 on "Lead Hazards Associated with Buildings" with McKnight as its chair. Under her leadership, E06.23's work was swift and broad [8]. By the end of the decade, more than 20 new standards were issued. In recognition of her efforts, McKnight received the National Lead Abatement Council Technical Recognition Award in 1993, the Department of Commerce Bronze Medal Award in 1995, and the Standards Engineering Society (SES)/ASTM Robert J. Painter Award in 1996.

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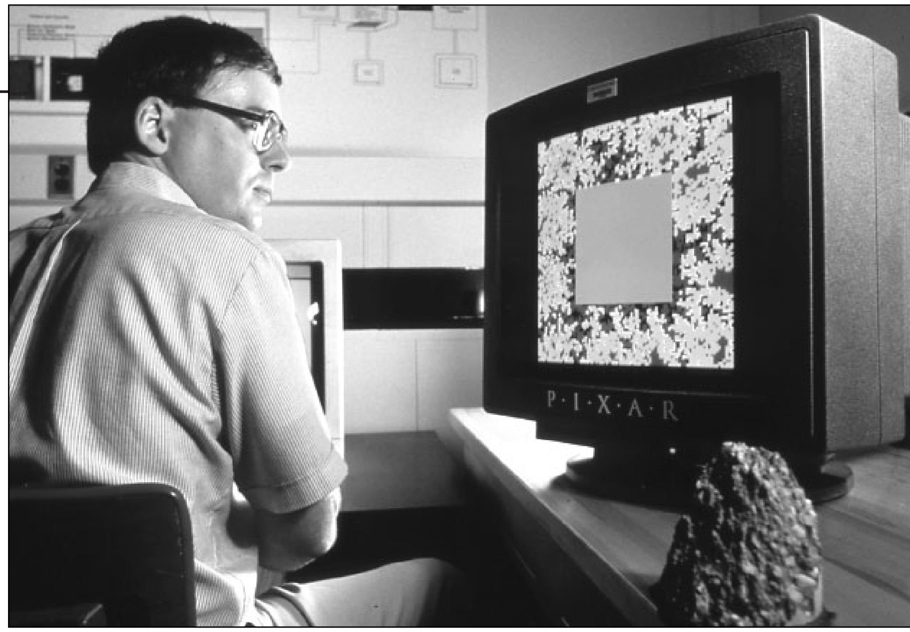
13.6 HIGH-PERFORMANCE CONCRETE

NIST has a long history of research on concrete as a material and on the structural performance of concrete. However, NIST's research on the material aspects of concrete fell to a low level from the mid-50s until a new era began in the 1970s. The new research was in accord with the performance concept [1] and, in broad terms, its goal throughout has been: To develop or improve methods for characterizing concrete materials and for measuring and predicting the performance, including service life, of concrete, and to disseminate the knowledge gained so as to facilitate innovation and advance concrete technology. The general approach has been to identify and prioritize needs for measures of performance and tools for performance prediction; then, to the extent possible with available resources, to develop needed knowledge, measures, and tools that have a sound basis in the materials science of concrete and concrete materials. The results have had a significant influence on concrete technology and, by providing tools for predicting performance, the latest ones appear to be leading a revolution in the technology.

In 1973, at the suggestion of Geoffrey Frohnsdorff, ASTM Committee C01, Cement, established a task group under his leadership to develop performance specifications for blended cements. This led, 19 years later, to the first ASTM performance specification for hydraulic cements, ASTM C1157-92 [2]. Though the specification was initially only for blended cements, by 1997 it had been broadened to apply to all cements for general construction. While BFRL was only one of many contributors to development of the specification, its final approval came about when the ASTM C01 was chaired by Frohnsdorff. The importance of the performance specification is in its potential for facilitating innovation in cement technology. Among the benefits it is expected to bring is facilitation of increased use of waste and by-product materials in cement manufacture, thereby reducing fuel consumption, reducing the quantity of carbon dioxide liberated into the atmosphere, and reducing the need for stockpiling of wastes. The potential was noted in the report from the 1979 NIST/DoE workshop, Possible Contributions of Cement and Concrete Technology to Energy Conservation by the Year 2000 [3]. In the same year, Frohnsdorff, James Clifton and Paul Brown received the P.H. Bates Memorial Award from the ASTM C01 for their review of the history and status of standards relating to alkalis in hydraulic cements [4]; (P.H. Bates, for whom the award was named, was a renowned cement researcher at NIST in the 1920s).

The year 1978 may be looked upon as the one in which the seeds of BFRL's present high-performance concrete program were planted. In that year, with support from the NEL Director's Reserve fund, a project was undertaken to model the reactions with water of a single, spherical, monophase cement particle. While the problem was greatly simplified, and the available computational capability limited, the results published by James Clifton and guest researcher James Pommersheim [5] laid the groundwork for a successful 1981 competence initiative to develop mathematical models for simulating cement hydration and to generate experimental data for their validation.

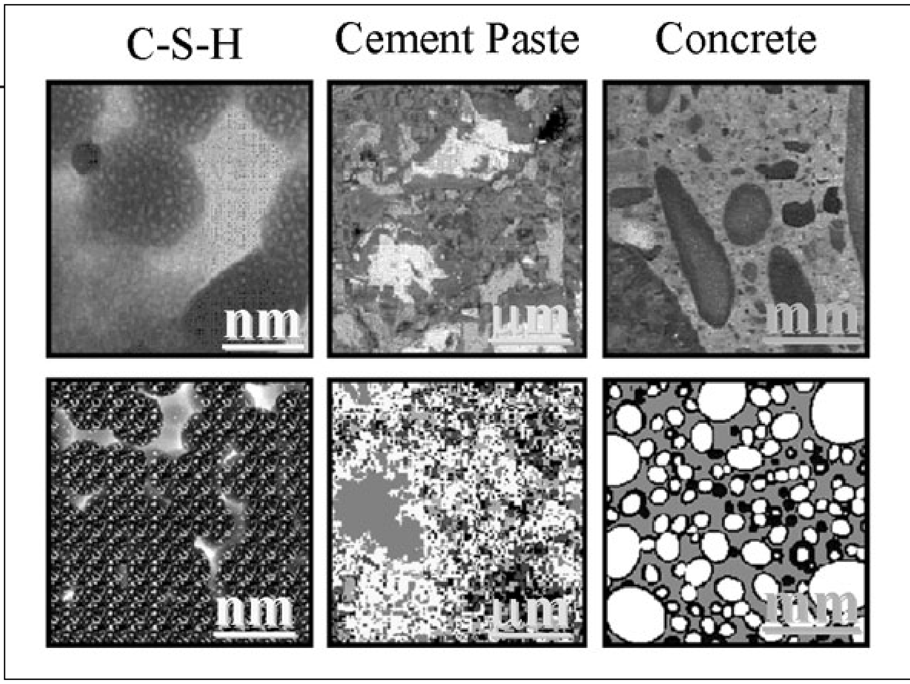
The Cement Hydration competence project, led by Paul Brown with Hamlin Jennings in Clifton's Inorganic Building Materials Group, made excellent progress. By 1986, the project was sufficiently advanced for Jennings and Stephen Johnson to receive the Brunauer Award from the American Ceramic Society's (ACerS) Cements Division for their paper on computer simulation of microstructure development in a model cement paste [6]. Unfortunately, at about this time, as the work was gaining recognition, Brown and Jennings left CBT for academic positions, Brown going to Penn State and Jennings to Northwestern. However, on the recommendation of Jennings, James Clifton recruited Edward Garboczi, and he also brought back Dale Bentz from industry, to continue the work.



Edward Garboczi, physicist, develops computer models that simulate the microstructure of concrete during the setting process. These models are used to predict concrete performance, strength, and durability.

With BFRL becoming recognized as the leader in the computational materials science of cement-based materials, it was invited to join with Northwestern University and three other major universities (Illinois, Michigan, and Purdue) in a 1988 proposal to the National Science Foundation for establishment of a Center for the Science and Technology of Advanced Cement-Based Materials (ACBM). The proposal was successful, in spite of NSF's normal policy of not funding research in Federal agencies, and the ACBM was established in 1989 with the period of NSF support being renewable up to a maximum of 11 years. During the 11 year period, the ACBM, with NIST as an important participant, did much to strengthen the material science base of concrete technology.

NIST's contributions, often in collaboration with university researchers, e.g. [7], including its organization of annual modeling workshops, further enhanced its standing as the leader in the computational materials science of cement and concrete. In the first 12 years, the modeling workshops, all organized by Garboczi, introduced more than 300 persons to the computational and experimental techniques developed by BFRL and collaborating



Material-science-based predictions of the performance of concrete require knowledge of the structure-property relationships at all scales from nanometers to meters. The structure can be determined experimentally (top row), but it is becoming practical to use computer simulations (bottom row) as the basis for performance predictions.

researchers. When the NSF funding ceased in 2000, sufficient industrial support was obtained to keep the ACBM viable with Northwestern University, the University of Illinois, and BFRL being the core members. At about that time, Leslie Struble, a former BFRL researcher who had started to build BFRL's X-ray diffraction capability before moving to the University of Illinois, was appointed Associate Director of the ACBM.

BFRL's world-leading capability in computational materials science of concrete has been demonstrated in a continuing series of papers on simulation of the development of the 3-dimensional microstructure in cement paste, mortar, and concrete, and the heat liberation and changes in transport and mechanical properties accompanying microstructure development [8, 9, 10, 11]. These papers, and many others from the BFRL program, have been widely disseminated through the pioneering, continuously-growing, "electronic monograph" that was first put on the World-Wide Web by Garboczi and Bentz in 1997 [12]. By the end of 2001, the electronic monograph had five authors and had grown to the equivalent of a 2300-page document and, each month, it was being accessed from more than 7000 locations, and from more than 70 countries. The excellence of the work of Garboczi and Bentz was recognized internationally, with each being honored by the award of the RILEM Gold Medal -- Garboczi received the medal in 1992, and Bentz in 1997; (RILEM is the International Union of Research and Testing Laboratories for Structures and Materials). The significance of their honor is apparent from the fact that, although this award was established over 30 years ago, only two other Americans have received it.

BFRL's advances in ability to simulate the behavior of cements demanded advances in the ability to characterize cements and cement-based materials. Techniques have been developed for determining distributions of size, shape and chemical phases among cement particles and for comparable determinations of distributions of phases, pores and microcracks in concrete. BFRL's contributions to establishment of the first ASTM standard method for the use of X-ray diffraction in identification of the phase composition of a portland cement or a portland cement clinker was initiated by Struble and reported in a paper [13] with Howard Kanare of the Construction Technology Laboratory. The work was continued by Paul Stutzman and brought to fruition as ASTM C 1365 under his leadership [14]. Similarly, the first ASTM standard method for use of the petrographic microscope in determining the phase composition of a portland cement clinker, ASTM C 1356, was also established under Stutzman's leadership [15]. These two techniques, complemented by scanning electron microscopy - a technique for application of which [16] he had received the P.H. Bates Memorial Award from the ASTM Cements Committee in 1991 -- were applied by Stutzman [17], in collaboration with Stephan Leigh of ITL, in characterizing the members of the first suite of Standard Reference Materials for the phase composition of portland cement clinkers (SRMs Numbers 2686, 2687, and 2688).

The national importance of BFRL's concrete research on prediction of performance and service life is apparent from some of its applications. For example, the work of Nicholas Carino and guest researcher Rajesh Tank [18] in developing maturity functions for predicting the effects of early-age temperature variations on strength development in concretes of a wide range of compositions was recognized by award of the 1994 Wason Medal for Materials Research from ACI; their important work also provided the technical basis for ASTM and ACI standards. Another example was Kenneth Snyder and Clifton's development of software, 4SIGHT [19], for use by the Nuclear Regulatory Commission in predicting the service life of concrete used to contain low-level nuclear wastes when exposed to any likely combination of degradation factors. In another application, Stutzman used BFRL's ability to describe concrete in mathematical terms in determining, in 1999, the most probable cause of widespread deterioration of concrete highway pavements in Iowa and five other mid-western states [20]. And in yet another, Bentz developed a model for the FHWA to use in predicting the surface temperature and time-of-wetness of concrete pavements and bridge decks [21], an essential step in service life prediction. In other work related to steel-reinforced concrete bridge decks, Snyder, Ferraris, Martys, and Garboczi coupled computer simulations with impedance spectroscopy measurements to show limitations of the widely-used rapid chloride test method for determining the electrical conductivity of concrete [22].

An essential attribute of fresh concrete in almost every application is that its flow properties should allow ease of placement and consolidation. Nevertheless, no standard for measuring the flow properties of concrete in fundamental physical units has yet been achieved. This reflects experimental difficulties caused by:

a) concrete's non-Newtonian behavior,
b) changes in properties resulting from ongoing chemical reactions of the cement,
c) settling of aggregate particles under gravity, and
d) the necessity for direct tests to be carried out on a large scale because of the presence of large aggregate particles.

To begin to address the problems, Chiara Ferraris, with Nicos Martys and French guest researcher, François de Larrard, published a survey of methods for studying the rheological properties of cement pastes, mortars and concretes, including the possibility of predicting the flow properties of concrete from measurements on cement paste [23]. Then, as chair of an ACI subcommittee set up on her recommendation, Ferraris led an international inter-laboratory comparison of the five main types of concrete rheometer in 2000 [24]. At the same time, to aid understanding and prediction of flow properties of cement-based materials, Martys, with Raymond Mountain of CSTL, developed a dissipative particle dynamics model to simulate the flow of concrete [25]; this provided a generic capability to model the flow of concrete in rheometers with different geometries.

Although modern concretes tend to have lower water/cement ratios than older concretes, ACI guidelines for the curing of concrete have not yet been changed to take lower water/cement ratios into account. Following their critical review [26] of ACI's curing guidelines, Carino and guest researcher Kenneth Meeks, cooperated with the FHWA in detailed studies of moisture movements during the curing of concretes of different formulations under different environmental conditions [27]. The experiments were complemented by experiments and computer simulations of moisture movements in concrete by Bentz in collaboration with Hansen of the Technical University of Denmark [28]; subsequently, Bentz and Snyder continued the studies of moisture movements in an investigation of the benefits of using unsealed, porous aggregates as internally-distributed water reservoirs to aid the curing of concrete with a low water-cement ratio [29]. The results are being used by Carino to support recommendations to ACI Committee 308, Concrete Curing, to change ACI's curing guidelines.

With serious questions about the fire resistance of high-strength concrete being raised in the early 90s, Long Phan published a review of the literature in 1996; in it, he presented the evidence that high-strength concrete has a greater tendency than normal-strength concrete to spall rapidly in a fire [30]. Then, to provide a technical base for guidelines for assessing fire-related risks in using high-strength concrete, Phan, with Randy Lawson and Frank Davis, carried out an extensive series of experiments to investigate the effects of heating to high temperatures on the mechanical behavior of concretes of different formulations, both unconstrained and under a compressive load [31]. The experimental work was accompanied by computer simulations of internal pressure caused by evaporation of water as the concrete was heated. Some of the simulations, like some of the tests, included concretes containing small volume fractions of thermoplastic fibers; results of the simulations carried out by Bentz supported reports that inclusions of thermoplastic fibers could reduce the spalling tendency [32]. The results of the BFRL research are providing the technical basis for guidelines on the fire resistance of concrete being drafted in the ACI Committee 216, Fire Resistance and Fire Protection of Structures, chaired by Phan.

On the international standards level, BFRL, through the efforts of James Gross, was instrumental in arranging, in the mid-90s, for the secretariat of ISO Technical Committee TC71 on Concrete, Reinforced Concrete, and Prestressed Concrete to be transferred from Austria, where it had been dormant for many years, to the United States, with ACI as the secretariat. The committee and its subcommittees gained new life when ACI took on the responsibility in 1995; in response to a recommendation from Frohnsdorff, a new subcommittee, SC7, Service Life Design of Concrete Structures, was set up in TC71 in 2001.

In 1990, BFRL and ACI cosponsored a workshop on high-performance concrete, that resulted in publication, by Clifton and Carino, of the report, A National Plan for High-Performance Concrete [33]. The use of the term "high-performance concrete" in the title of the workshop was one of the first uses of a term that is now in common use and which has helped give concrete technology an improved image. (Subsequently, Frohnsdorff led the task group that defined the term for the ACI.) The plan helped set the pattern for BFRL's later concrete research as well as influencing the National Plan for High-Performance Construction Materials and Systems published by CERF (the Civil Engineering Research Foundation) in 1993 [34]. Preparation of the CERF plan was led by a committee chaired by Richard Wright, with Frohnsdorff leading the subcommittee on high-performance concrete, and John Gross the subcommittee on high-performance steel; the plan recommended formation of an industry council to facilitate implementation of the plan. This was the genesis of the CONMAT Council set up by CERF in 1994 to promote research on high-performance construction materials of all major categories. In 1995, a successful NIST Material Science and Engineering Laboratory-led programmatic initiative for materials research brought increased funding to BFRL for a high-performance construction materials program, with high-performance concrete as a major component. The concrete program was later renamed the Partnership for High-Performance Concrete Technology, or the HYPERCON Program for short [35].

The program goal was:
In partnership with industry, to enable reliable application of high-performance concrete in buildings and the civil infrastructure by developing, demonstrating, and providing assistance in implementing a computer-integrated knowledge system incorporating verified multi-attribute models for predicting and optimizing the performance and life-cycle cost of HPC.

The remarkable progress made towards the achievement of this goal is a result of collaboration among all the units of BFRL-the Divisions and the Office of Applied Economics.

In another important activity started in 1995, Shyam Sunder worked with

William Plenge of ACI to develop, with broad industry support, a white paper proposing establishment of a $100M focus area on high-performance concrete in NIST's Advanced Technology Program (ATP). Although the proposal could not be accepted because of an unexpected reduction in the funds available to the ATP, sustained industry enthusiasm for it resulted, in 1997, in ACI's formation of a Strategic Development Council (SDC) to provide a mechanism for formation of consortia to advance concrete technology [36]. In 2000, the SDC, of which BFRL was a charter member, published Vision 2030 [37] to put on record industry leaders' vision of what the concrete industry could, and should, be like by the Year 2030. Drafting of the "vision" required strong cooperation from all segments of the industry that is being continued with the drafting of a research road map to lead to achievement of the vision.

While simulation models have been a major element of BFRL's concrete research, other applications of information technology have also been important. The first widely-used knowledge-based expert system for use as a decision-support tool relating to concrete was HWYCON (for HighWaY CONcrete) [38]. It was developed by Larry Kaetzel and Clifton in consultation with the late Paul Klieger of the Portland Cement Association. HWYCON, which was produced under the National Academy's Strategic Highway Research Program (SHRP), aids identification of causes of distress in concrete highway bridges and pavements, and suggests repair methods and materials. Three thousand copies of the HWYCON software and manual were issued by the Transportation Research Board in 1993, with copies being distributed to Departments of Transportation of all 50 states. HWYCON was judged to be one of the top three products from the $100M, 5 year, SHRP program.

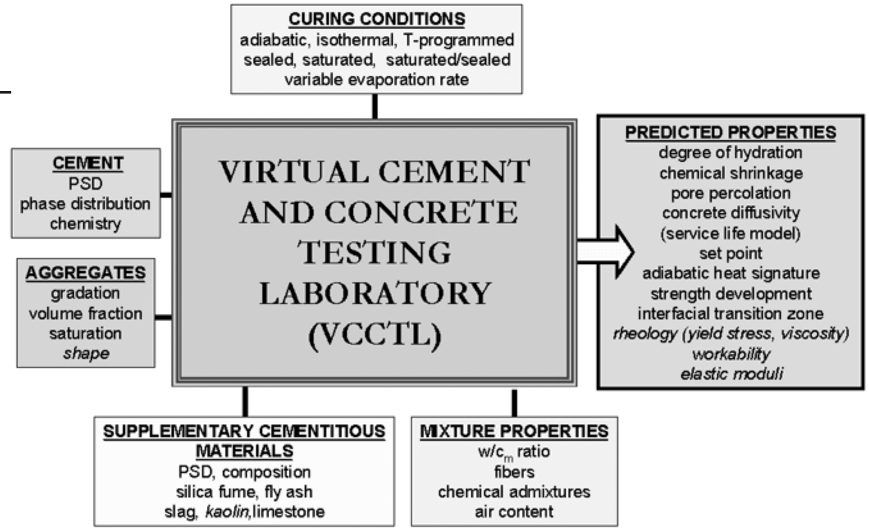
In the 1990s, to help advance the materials science of concrete, BFRL successfully recommended the establishment of four ACI committees. The committees, and their first chairmen, were: ACI 126, Database Formats for Concrete Material Property Data (chair, Frohnsdorff); ACI 235, Knowledge-Based Systems and Mathematical Modeling of Materials (chair, Kaetzel); ACI 236, Materials Science of Concrete (chair, David Lange, University of Illinois); and ACI 365, Service Life Prediction (chair, Clifton); ACI 236, and its subcommittee 236A, Rheology, are now both chaired by Ferraris. These committees produced the first recommended formats for concrete materials property data (39), the first ACI state-of-the-art report on service life prediction of concrete [40], the previously-mentioned report on the international comparison of concrete rheometers [24], and a report on computerized knowledge in concrete technology [41]. Much earlier, in 1985, as chair of ACI Committee 225 on Hydraulic Cement, Frohnsdorff led the writing and editing of the first version of the ACI Guide to Selection and Use of Cements [42]. Building on this, Frohnsdorff is now leading an ACI inter-committee coordinating group overseeing development of a Web-based interoperable version of the Guide. If acceptable to ACI, this could become ACI's first interoperable committee document. The coordinating group includes representatives of ACI Committees 225, 235, and 236.

In 1996, Bentz, Clifton, and Snyder published a prototype computer-integrated knowledge system (CIKS) for predicting the service life of steel-reinforced concrete exposed to chlorides, as in a concrete bridge deck [43]. The CIKS gave results that, according to bridge engineers with the New York Department of Transportation (NYDoT), were of the correct order of magnitude observed in NYDoT bridges. The CIKS was later used in conjunction with the life-cycle costing model, BridgeLCC [44], that Mark Ehlen had developed to aid decisions concerning the use of high-performance concrete, or other innovative materials, in highway bridge decks.

Just as life-cycle cost is normally important when considering the use of high-performance concrete, or any innovative material, so, in the future, life-cycle analyses to estimate life-cycle ("cradle-to-grave") environmental impacts will be important in material selection. The BEES (Building for Economic and Environmental Sustainability) software [45], developed by Barbara Lippiatt to aid such decisions, has been applied by her to life-cycle analyses of concretes formulated with and without supplementary cementing materials (fly ash and ground granulated blast furnace slag). Inclusion of BEES enhanced the HYPERCON Program and justified adding some important words to the last sentence of the goal statement:

...... optimizing the performance, life-cycle cost, ***and life-cycle environmental impact of HPC***.

In 1995, Frohnsdorff, Clifton, Garboczi, and Bentz published a paper entitled, "Virtual Cement and Concrete" [46], in which they speculated on the possibility of predicting the performance of cement and concrete from knowledge of the chemistry and physics of the system. In 1999, under the HYPERCON Program, Bentz initiated a pioneering project, the Virtual Cement and Concrete Testing Laboratory (VCCTL), to bring this about and use the results of BFRL's theoretical and experimental research to reduce the amount of costly long-term testing in concrete laboratories, whether for research purposes or for mixture design and quality assurance. The attractiveness of the VCCTL concept, as documented in the user's guide written by Bentz and Glenn Forney [47], was shown when a VCCTL Consortium was established in 2001 with six industrial participants, including units of three of the world's largest cement companies and the two largest U.S. manufacturers of chemical admixtures for concrete. It is expected that, as the VCCTL concept is further developed, it will be applicable to prediction of the performance of concrete in service in the field.



The VCCTL program will make it possible to predict the properties of concrete listed on the right-hand side from knowledge of the materials and processing conditions listed on the other three sides (from Reference 47).

Throughout the period of this history, most of the research mentioned was carried out in BFRL's Inorganic Building Materials Group. Until 1999 when he died, the Group was ably led by James Clifton. Clifton was a prolific author who transferred his enthusiasm, and gave wise guidance, to his Group in its efforts to advance concrete technology. It was a great loss when he died, but his outstanding Group, now led by a worthy successor, Edward Garboczi, remains as a living tribute to his leadership [48].
In summary, during 1974 to 2000, BFRL's research on the materials aspects of concrete grew from a small NEL Director's Reserve project in 1978, to a competence project in 1981, and to the world-leading program in the computational materials science of concrete by 2000, where it was well-placed to achieve its goal of making the performance of concrete predictable, thereby revolutionizing concrete technology.

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