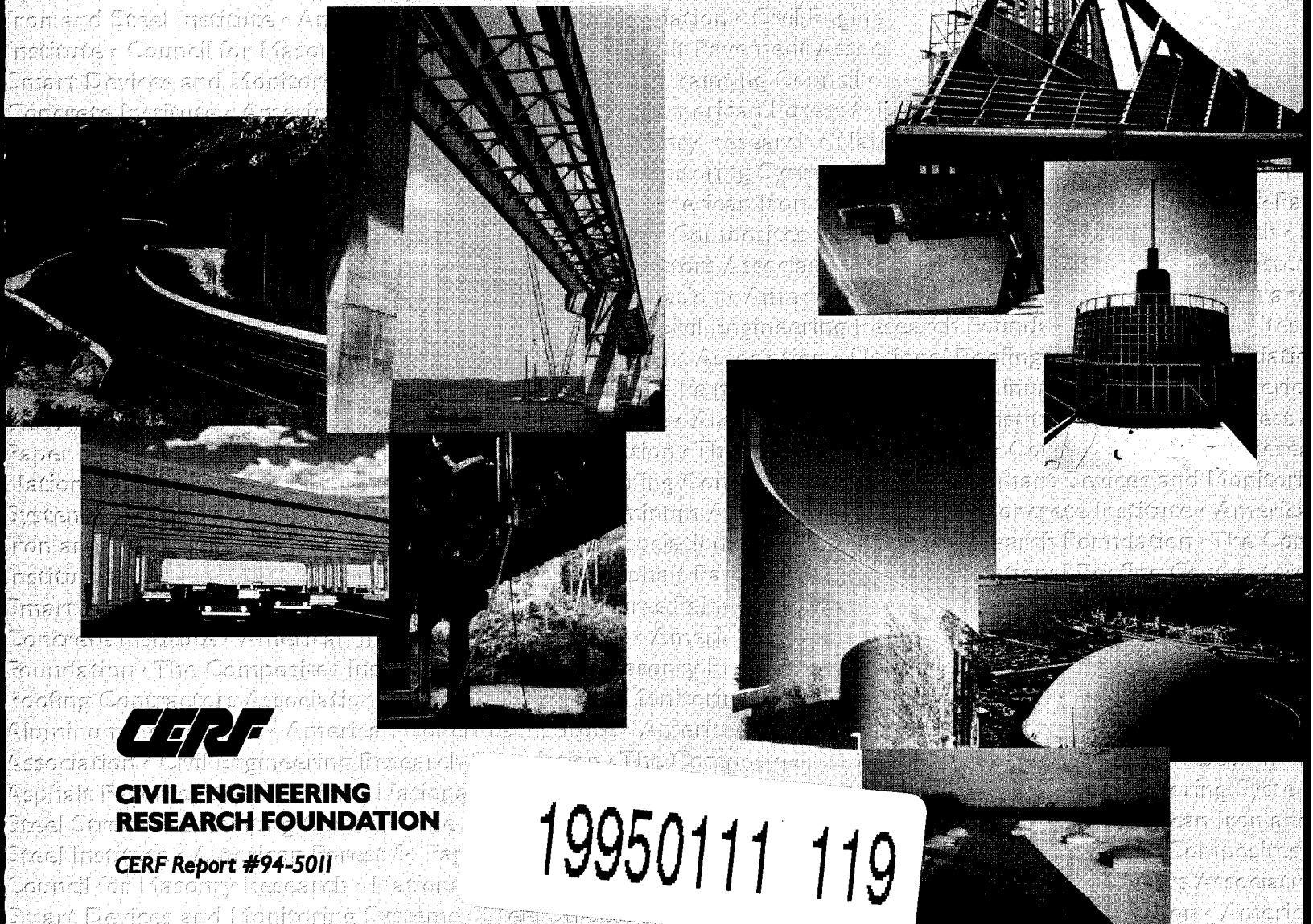


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Materials for Tomorrow's Infrastructure:

**A Ten-Year Plan for Deploying
High-Performance
Construction Materials and Systems**
Technical Report

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CERF

**CIVIL ENGINEERING
RESEARCH FOUNDATION**

CERF Report #94-5011

19950111 119

December 27, 1994

The President
The White House
1600 Pennsylvania Avenue
Washington, D.C.

Dear Mr. President:

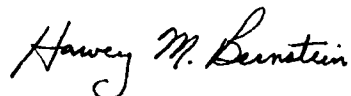
The Civil Engineering Research Foundation (CERF) is currently working with the National Science and Technology Council (NSTC) to reduce barriers and spur innovation in the construction industry. As a result of this effort, CERF is well positioned to facilitate a cooperative industry/government effort to promote the research, development and deployment of high-performance construction materials and systems. Such a program is essential to improving the quality of our nation's civil infrastructure and to increasing the competitiveness of the United States construction industry.

The volume you hold in your hands reflects a strong commitment by industry. The undersigned, representing ten different sectors of the construction materials industry, strongly believe in the necessity of this program. As described in this Technical Report, *Materials for Tomorrow's Infrastructure: A Ten-Year Plan for Deploying High-Performance Construction Materials and Systems*, we have the opportunity to research and deploy a variety of "high-performance" materials that will dramatically change the ways we build, repair, and rehabilitate our aging infrastructure. A commitment to support the high-performance CONstruction MATerials and systems program (CONMAT) is necessary. The success of this program will not only ensure higher quality and longer lasting elements of the nation's highways, bridges, ports, and other critical facilities, but will also enhance our economic well-being, international competitiveness, and technological leadership.

CONMAT is designed as an industry-led effort, in partnership with government and academe. The ten-year program of research and deployment described in this report will succeed because it recognizes that cooperative efforts are necessary in order to leverage scarce resources prudently.

The CONMAT program will profoundly affect the very fabric of our national life—the way we commute to work and the conditions under which we live. **We therefore urge you to support this critical initiative by officially endorsing the CONMAT program and directing federal agencies to consider the research priorities contained herein when developing their respective program budgets.**

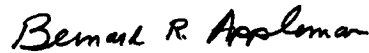
Respectfully,



Harvey M. Bernstein
President
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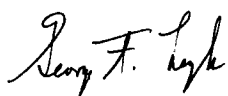
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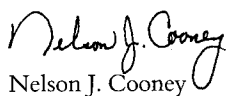
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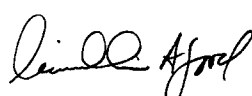
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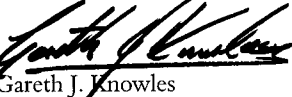
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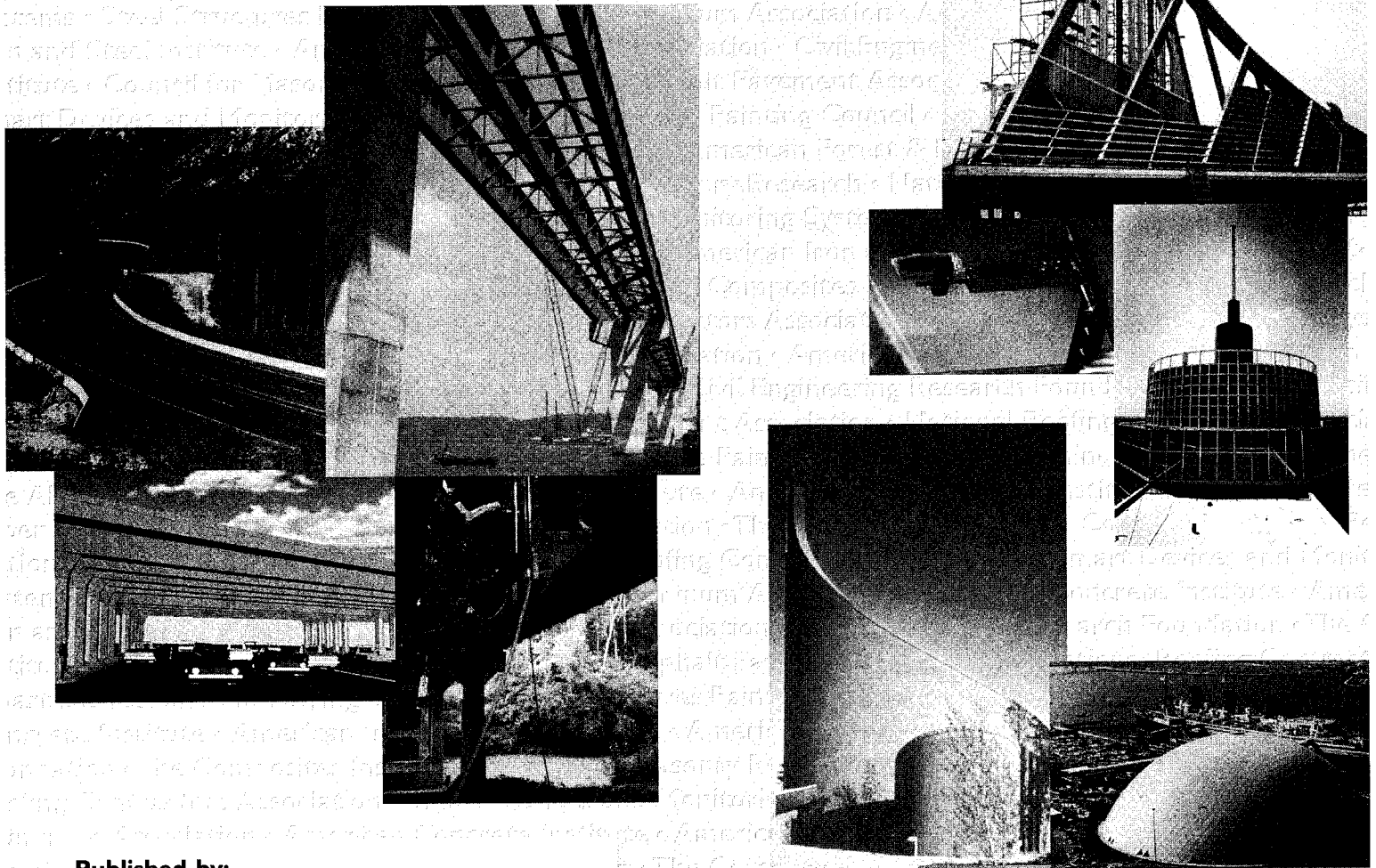


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DTIC QUALITY IMPROVED 3

Materials for Tomorrow's Infrastructure:

**A Ten-Year Plan for Deploying
High-Performance
Construction Materials and Systems**
Technical Report



Published by:



**CIVIL ENGINEERING
RESEARCH FOUNDATION**

*Affiliated with the
American Society of Civil Engineers*

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Abstract

This report, *Materials for Tomorrow's Infrastructure: A Ten-Year Plan for Deploying High-Performance Construction Materials and Systems* (CERF Report #94-5011) presents a detailed program to transform our nation's infrastructure. The intended audience is the Administration and Congress, other national policy makers, and government and industry leaders. Descriptions of major high-performance research and commercialization projects are provided by working groups representing ten different materials: aluminum, coatings, fiber-reinforced polymer composites, concrete, hot mix asphalt, masonry, roofing materials, smart material devices and monitoring systems, steel, and wood. The report builds on the 1991 National Civil Engineering Research Needs Forum organized by the Civil Engineering Research Foundation (CERF) and the 1993 initial program plan as presented in *High-Performance Construction Materials and Systems: An Essential Program for America and its Infrastructure* (CERF Report #93-5011). The high-performance CONstruction MATerials and systems program (CONMAT) will create significant improvements in the nation's infrastructure and U.S. competitiveness in the construction market. The report concludes by reviewing the strong support that the Administration has shown the CONMAT research effort to date and recommends continued support from government, industry, and academia to support this critical initiative.

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In addition to the in-kind and financial support of the ten material groups, this study was also sponsored by CERF, the Federal Highway Administration (FHWA), the National Institute of Standards and Technology (NIST), the United States Army Corps of Engineers (USACE), and the Naval Facilities Engineering Command (NAVFACENGCOM)/ Office of Naval Research (ONR). The report greatly benefitted from the insights and suggestions of many readers who read all or parts of draft versions of the report. CERF would like to acknowledge the very helpful input of Richard N. Wright, Geoffrey Frohnsdorff, S. Shyam Sunder, H.S. Lew and James Clifton, all of NIST; Thomas J. Pasko Jr., FHWA; Tony C. Liu, USACE; Ken P. Chong, National Science Foundation; Farhad Ansari, New Jersey Institute of Technology; E. Ray Brown, National Center for Asphalt Technology; John Gray, Gray & Associates; Alexander D. Wilson, Lukens Steel Company; Thomas L. Anderson, Critical Technologies Institute at Rand; Dean E. Stephan, Charles Pankow Builders, Ltd; John Fisher, ATLSS Engineering Research Center; and Roger Wildt, Bethlehem Steel Corporation.

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Harvey M. Bernstein

Harvey M. Bernstein, President
Civil Engineering Research Foundation

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Steel

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American Iron and Steel Institute

Wood

R. Michael Caldwell
American Forest & Paper Association

Abbreviations

AASHTO	American Association of State Highway and Transportation Officials
ACBM	NSF Center for Advanced Cement-Based Materials
ACI	American Concrete Institute
AF&PA	American Forest and Paper Association
AISC	American Institute for Steel Construction
AISI	American Iron and Steel Institute
ALT	Acceptable Level of Technology
ARPA	Advanced Research Projects Agency
ASCE	American Society of Civil Engineers
ASTM	American Society for Testing and Materials
ATLSS	NSF Center for Advanced Technology for Large Structural Systems
ATP	Advanced Technology Program
BIRL	Basic Industrial Research Laboratory at Northwestern University
BOCA	Building Officials and Code Administrators International
CAB	CERF's Corporate Advisory Board
CCB	Construction Criteria Base
CCIT	Committee on Civilian Industrial Technology
CERF	Civil Engineering Research Foundation
CERL	Army Construction Engineering Research Laboratory
CFC	chlorofluorocarbons
CRREL	Army Cold Regions Research and Engineering Laboratory
CMR	Council for Masonry Research
CONMAT	CONstruction MATerials and Systems Program
ConREF	Concrete Research and Education Foundation
CPAR	Construction Productivity Advancement Research Program
CPI	Chemical Processing Industry
CRADA	Cooperative Research and Development Agreement
CWC	Canadian Wood Council
DOD	Department of Defense
DOE	Department of Energy
DOL	Department of Labor
DOT	Department of Transportation
EIS	Electrochemical Impedance Spectroscopy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FEA	Finite Element Analysis
FEMA	Federal Emergency Management Agency
FHWA	Federal Highway Administration
FRP	Fiber Reinforced Polymers
GDP	Gross Domestic Product
GMA	Gas Metal Arc
HAPS	Hazardous Air Pollutants
HAZ	Heat Affected Zone
HAZMAT	Hazardous Materials
HCFC	hydrochlorofluorocarbons
HDPE	High Density Polyethylene
HIC	Hydrogen Induced Cracking
HITEC	Highway Innovative Technology Evaluation Center
HMA	Hot Mix Asphalt

HP	High Performance
HPC	High-Performance Concrete
HPMS	High-Performance Materials and Systems
HPS	High-Performance Steel
HSC	High Strength Concrete
HSLA	High Strength/Low Alloy
HUD	Housing and Urban Development
HVLP	High Volume/Low Pressure
HWYCON	Highway Concrete Expert System for Highway Concrete Structures
ISO	International Standards Organization
IVHS	Intelligent Vehicle Highway Systems
ksi	kilopounds per square inch
LBL	Lawrence Berkeley Laboratory
LCCA	Life-Cycle Cost Analysis
LRFD	Load and Resistance Factor Design
MEMS	Microelectromechanical Systems
MEP	Manufacturing Extension Partnership
MPa	Mega-Pascals
NAPA	National Asphalt Pavement Association
NC	Numerical Control
NCCER	National Council for Civil Engineering Research
NCHRP	National Cooperative Highway Research Program
NCMA	National Concrete Masonry Association
NCMCC	National Construction Materials Coordinating Council
NDE	Non-Destruction Evaluation
NIBS	National Institute of Building Sciences
NIST	National Institute of Standards and Technology
NRCA	National Roofing Contractors Association
NSF	National Science Foundation
NSTC	National Science and Technology Council
NSWC	Naval Service Warfare Center
OE	Original Equipment
OSHA	Occupational Safety and Health Administration
OSTP	Office of Science and Technology Policy
OTA	Office of Technical Assessment
psi	pounds per square inch
QA/QC	Quality Assurance/Quality Control
R&D	Research and Development
RBD	Reliability-Based Design
rebar	reinforcing bar
SHRP	Strategic Highway Research Program
SMA	Shape Memory Alloys
SPI	Society of the Plastics Industry, Inc.
SSPC	Steel Structures Painting Council
SWRI	Sealant, Waterproofing, and Restoration Institute
T ²	Technology Transfer
TCCMaR	Technical Coordinating Committee for Masonry Research
TMCP	Thermomechanical Controlled Processing
TRIP	Transformation Induced Plasticity
TRP	Technology Reinvestment Project
USACE	United States Army Corps of Engineers
USAF	United States Airforce
USDA	United States Department of Agriculture
USN	United States Navy
VOC	Volatile Organic Compound

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Executive Summary

This executive report summarizes an industry plan for implementing a ten-year, \$2 billion national program of technological research, development and deployment to accelerate the commercialization of High-Performance CONstruction MATerials and Systems (CONMAT). The proposed cooperative industry-government program will be conducted in partnership with academia.

This plan is the culmination of an intense industry-led voluntary effort that began five years ago that has involved detailed planning studies by 10 material groups (aluminum, coatings, fiber-reinforced polymer composites, concrete, hot mix asphalt, masonry, roofing materials, smart material devices and monitoring systems, steel, and wood) with the enthusiastic participation of major industry trade and professional organizations.

The goal of the CONMAT program is to help create the materials and systems for an entirely new generation of constructed facilities. This will enable the nation to meet the rapidly changing demands of society and industry as we enter the 21st century and to help renew our aging public works infrastructure through innovations in repair, rehabilitation, and retrofit technologies. Realization of this goal is critical to the global competitiveness of all sectors of the U.S. economy, particularly the construction and building industry which represents about 13 percent of the nation's gross domestic product, and to improve the every day quality of life for Americans by designing and building facilities that provide a leap forward in functionality, economy, and durability.

The rapid advances now occurring in materials science and engineering, computing and telecommunications, building materials research, and other emerging technological innovations, make it possible to realize this ambitious national goal. National leadership is critical, however, to ensure program success.

In pursuit of the goal, the construction and building industry will seek to achieve the six key performance improvements set forth by the Subcommittee on Construction and Building of the National Science and Technology Council's Committee on Civilian Industrial Technology by contributing to the accelerated commercialization of high-performance construction materials and systems. The six areas of improvement are:

- Reduction in project delivery time
- Reduction in operation, maintenance and energy costs
- Increase in productivity and facility comfort
- Fewer occupant related illnesses and injuries
- Less waste and pollution
- Greater durability and flexibility

Four principles will guide the operation of the CONMAT program. They are that the program: (1) be a truly cooperative industry-government effort in close

The goal of the CONMAT program is to help create the materials and systems for an entirely new generation of constructed facilities.

A National Construction Materials Coordinating Council (NCMCC), consisting of representatives of the construction-materials industry and liaison members from selected government agencies, will be established to facilitate the implementation of the CONMAT program.

CONMAT must continue to be an industry-led program.

working partnership with academia; (2) be based on active collaboration among different material groups working under a single organizational umbrella towards the CONMAT goal; (3) seek to reduce or remove institutional barriers and other obstacles that prevent technical innovations from reaching the market place; and (4) continuously demonstrate the technical feasibility and commercial viability of program results through prototype projects with measurable short- to medium-term impact.

A National Construction Materials Coordinating Council (NCMCC), consisting of representatives of the construction-materials industry and liaison members from selected government agencies, will be established to facilitate the implementation of the CONMAT program. The NCMCC will be responsible for:

- Translating the overall goal and research priorities of the CONMAT plan into specific projects for execution, including the definition of their scope, duration, and cost
- Identifying and recruiting suitable partners from industry, government and academia for collaboration and consortia on research, development and demonstration projects
- Implementing a comprehensive technology deployment program to help industry accelerate the commercialization of innovative technologies
- Providing a forum for the construction and building industry to make CONMAT plans part of their business and corporate strategies
- Initiating and maintaining communications with executive and legislative bodies, such as the National Science and Technology Council and the U.S. Congress, and with the construction and building community through periodic reports, briefings, and newsletters
- Reviewing the implementation plan on a periodic basis, revising it as needed, and making decisions on the possible addition of new material groups to the program

An executive steering committee appointed by the NCMCC will be responsible for the day-to-day operation of the program, including program oversight and fiscal management. The Civil Engineering Research Foundation (CERF), the research affiliate of the American Society of Civil Engineers (ASCE), will provide overall coordination for the CONMAT program.

CONMAT must continue to be an industry-led program. The ten material groups which came together to produce this report are committed to:

- **Cooperative action.** The commercial opportunities are so great that all material groups recognize the virtue of cooperative ventures in areas beyond their current market niche. CONMAT participants understand that the research and technology deployment activities will be periodically reviewed and updated, as the needs of the construction community and the nation's infrastructure are regularly reassessed.
- **Industry leadership.** Construction industry leaders must direct the implementation of the CONMAT program, demonstrating how it directly responds to the needs and vision of the construction community. These leaders will strengthen the CONMAT program by establishing partnerships and collaborative efforts where appropriate.
- **Financial commitment.** CONMAT must truly become a dynamic cooperative effort between the public and private sectors. The program will succeed only if there is active industry participation, including cash and in-kind support, and oversight.

- **Implementation and technology deployment.** Industry is well positioned to take the results of the CONMAT program to the marketplace. CONMAT will succeed only if it can develop and demonstrate practical, commercially-viable applications.

Active participation by the federal government is essential to the success of CONMAT. The Administration and Congress should support the CONMAT program by:

- **Endorsing the concept and objectives of the CONMAT program,** recognizing it as an essential element of this nation's commitment to upgrade the nation's civil infrastructure.
- **Supporting the establishment** of CERF's National Construction Materials Coordinating Council (NCMCC) with authority for program implementation.
- **Directing all Federal agencies to consider the budget and program objectives outlined herein** when developing their respective program budgets. The strength of the CONMAT program will be in its ability to leverage private and public sector funds to most efficiently accomplish its goals.
- **Continuing to provide a construction program focus** through the National Science and Technology Council (NSTC) and the Office of Science and Technology Policy (OSTP).
- **Ensuring Federal support** through cost-sharing/support mechanisms as the Technology Reinvestment Project (TRP), Manufacturing Extension Partnership (MEP), the U.S. Army Corps of Engineers Construction Productivity Advancement Research (CPAR) program, Cooperative Research and Development Agreements (CRADA's), the Advanced Technology Program (ATP) and other programs as appropriate.
- **Continuing to modify user agency** procurement policies to encourage the inclusion of innovative technologies in new and rehabilitation construction projects. As a major customer, Federal support is essential for many of the key CONMAT demonstration projects.
- **Facilitating the CONMAT effort to reduce barriers to commercialization** by supporting new approaches in such areas as new product evaluation, life-cycle costing, contract/bid systems, tort liability and regulations which affect the introduction of innovation into the construction industry.

The long-term success of this ambitious national program will be visible through its impact on the quality of the nation's constructed facilities, the competitiveness of the U.S. construction and building industry, and the quality of life for all Americans as we enter the 21st century.

Active participation by the federal government is essential to the success of CONMAT.

Chapter I

Background

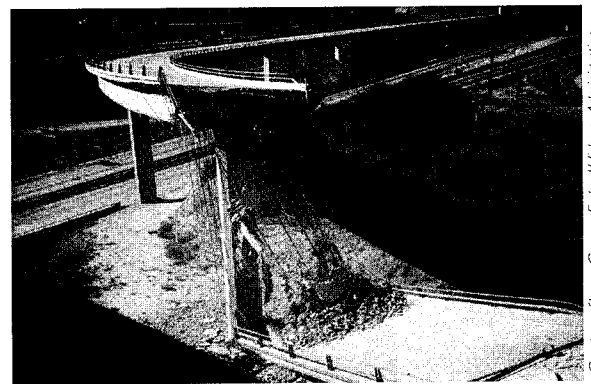
Major natural disasters of the past few years— earthquakes in southern California, flooding in the Midwest, forest fires in the West, and hurricanes in the south and southeast—have focused attention on the fragility of the nation's built environment. Yet these dramatic events are only part of the story: many of the nation's bridges, highways, buildings, pipelines, and other key elements of a modern society are falling below capacity or are in need of immediate repair or replacement. The visible consequences include ruptured water and sewer lines, structurally deficient bridges and deteriorating highway pavements. For example, 230,000 (40 percent!) of the nation's 575,000 bridges are structurally deficient or functionally obsolete. Moreover, 143,000 of these 575,000 bridges are 50 years old or more and unsuitable for current or projected traffic demands.¹

The situation is no better with our nation's highways or wastewater treatment plants and sewer systems. Ten percent (60,000 miles) of the federal-aid roadway pavements require immediate repair or replacement. The American Association of State Highway & Transportation Officials (AASHTO) calculates that 40 percent of federal-aid pavement falls below minimum engineering standards. The Road Information Program notes that 60 percent of the nation's pavements require rehabilitation. Half of all communities in the United States cannot expand because their wastewater treatment plants are currently operating at or close to full capacity.²

The costs of an inadequate infrastructure are enormous: poorly maintained or obsolete sewer systems and waste treatment systems pose significant public health risks; leaking pipes affect our water supply and constrain urban growth and reduce the tax base; while nearly 60 major airports in the United States will experience "serious congestion" by the year 2000. One study estimates that by the year 2005, the traffic delays caused by inadequate roads will cost the nation \$50 billion a year in lost wages and wasted fuel.³ A well-defined strategy for the *intelligent renewal* of our aging infrastructure is essential if we are to maintain our current quality of life.⁴

History has shown that investments in technology for this renewal have direct benefits for the private sector. The construction of the interstate highway system led to the development of new concretes and steels and new design technologies which have direct application to commercial structures. New materials and systems which focus on durability and ease of construction will have obvious and direct benefits for life cycle improvements in, for example, the nation's housing stock. Finally, the development of expertise in the application of high performance materials and systems will help to restore America to its leadership position in world construction markets.

...many of the nation's bridges, highways, buildings, pipelines, and other key elements of a modern society are falling below capacity or are in need of immediate repair or replacement.



Aftermath of the Northridge earthquake: One of two collapsed connector structures at the Golden State Freeway (I-5)—Antelope Valley Freeway (State Route 14) interchange.

Courtesy of James Cooper, Federal Highway Administration

We must build the 21st century civil infrastructure with tomorrow's materials and systems.

Unfortunately, the construction sector suffers from lack of a well-organized and focused constituency to implement this strategy. Fragmentation in the industry and a strong focus on low first cost of construction has resulted in low investments in technology in both the private and public sector and adversarial relationships which impede solutions. The goal of this report is to set in motion some specific commitments that will reverse that trend. In preparing it, representatives from industry, academia, and government have come together to achieve one overriding goal: to create a new generation of high-performance construction materials and systems to meet the demands of a deteriorating infrastructure in the 21st century. Merely defining research goals and priorities is insufficient. The program must go beyond "paper recommendations" and laboratory experiments—**deployment of high-performance construction materials and systems is the ultimate goal.**

This report describes the conclusions of ten different industry groups, reflecting interests in traditional construction materials like concrete and steel and materials that have not been used extensively in construction to date, such as composites, aluminum, and smart materials. The report does not attempt to judge the relative merits of one material against another. Indeed, for many infrastructure applications, a combination of materials is essential to fulfill all performance requirements and the existence of competing materials encourages the development of highly economical solutions. The programs outlined below will result in quantum improvements in our nation's quality of life through meeting the well-documented needs for construction and retrofit of our nation's infrastructure with a *variety* of construction materials.



Courtesy of Mowbray-Rodgers, Inc.

Deteriorated concrete in a bridge parapet well. Corrosion caused by the use of chloride de-icing salts was the probable cause of the damage.

The deterioration of our nation's civil infrastructure is linked directly with overall economic development, and reduces our global competitiveness and our quality of life. Our principal economic rivals recognize this relationship. **We must build the 21st century civil infrastructure with tomorrow's materials and systems.** The High-Performance CONstruction MATerials and Systems Program (CONMAT) will give us the tools to be so far-reaching. The implementation plan outlined herein provides a detailed roadmap for identifying, exploiting, demonstrating, and utilizing high-performance materials for our nation's infrastructure.

CONMAT, an industry-driven program, has brought together ten different material groups: aluminum, coatings, composites, concrete, hot mix asphalt, masonry, roofing materials, smart material devices and monitoring systems, steel, and wood. The program is challenging and plots a course of action with a budget in the range of \$2 billion over ten years. **Such a decade-long investment, viewed as an annual investment of \$200 million, represents a commitment in dollars of slightly less than one-twentieth of one percent of the annual construction put-in-place.⁵** Such an investment will be repaid many times over in a flourishing infrastructure for our children!

Merely developing budgeted research and development priorities is insufficient to ensure the success of the CONMAT program. This report details the structure and operating principles that will guide the CONMAT effort. While laboratory research and development is an integral element of the CONMAT effort, it is only one element. The goal of CONMAT is accelerating the com-

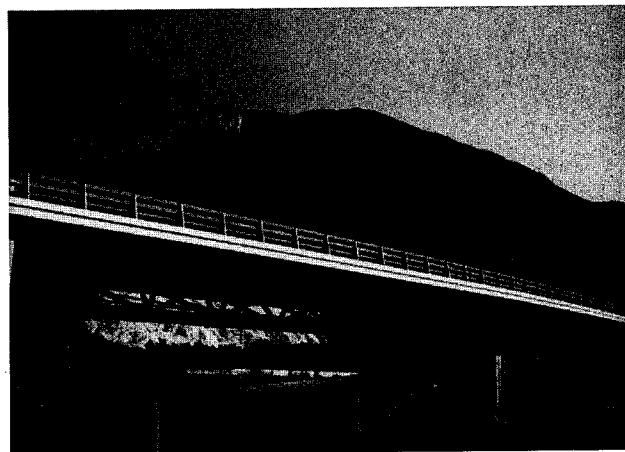
mercialization of the results of the research and development program. Accordingly, the plan is designed to confront and remove the barriers that prevent research findings from reaching the marketplace. The deployment strategy outlined herein will ensure that this report will not just be a paper document, but will help to equip our construction industry to enhance our infrastructure, and with it our economic well being and international competitiveness.

Structure of the Report

In the next chapter, the objectives of a national program to develop and exploit high performance materials and systems are presented. The concept of "high-performance materials and systems" is discussed more fully. The background and early successes of the CONMAT program are described. The ten-year implementation plan is presented, including the organizational mechanisms that will govern such a research and commercialization effort. In particular, the structure and objectives of the National Construction Materials Coordinating Council (NCMCC) are described. Chapter 2 ends with a summary of the material groups' research schedules and budgets.

Chapters 3-12 present the ten-year implementation plans for CONMAT's material groups. Each chapter provides a brief overview of how each particular high-performance material may be expected to perform, likely research areas, and current constraints to deployment. Detailed project descriptions are presented in accompanying tables, including key objectives, methodology, budget outlays, project duration, and potential public sector partners. Chapter 13 closes with a few key recommendations to ensure the success of the CONMAT program.

In addition to this technical report, the reader may find the *Materials for Tomorrow's Infrastructure: A Ten-Year Plan for Deploying High-Performance Construction Materials and Systems—Executive Report* useful. The executive report presents the operating principles and organization structure that will ensure CONMAT's success. A discussion of cross-cutting technology deployment issues is offered as well. Lastly, brief summaries of each material group's objectives are presented.



Roize bridge, Grenoble, France. Elevation of completed bridge having three spans. The bridge was constructed of high-strength concrete with post-tensioning steel. The concrete strength was in excess of 76 MPa (11 ksi), more than double than what is typically used.

Courtesy of J. Muller International

Endnotes

1. Federal Highway Administration. April 1993. "National Bridge Inventory" (Chapter 3) in *Highway Bridge Replacement and Rehabilitation Program, Eleventh Report of the Secretary of Transportation to the United States Congress*. Washington, DC.
2. These reports cited in Portland Cement Association. 1992. *Investing in our Future*. Skokie, IL: Portland Cement Association.
3. Information on the nation's deteriorating infrastructure, including the documentation cited in American Society of Civil Engineers (ASCE). *Infrastructure—A Good Investment* is presented in The Civil Engineering Research Foundation. 1993. *High-Performance Construction Materials and Systems: An Essential Program for America and its Infrastructure*.
4. National Science Foundation. 1993. *Civil Infrastructure Systems Research: Strategic Issues*. NSF 93-5. Arlington, VA.
5. Bureau of the Census. 1993. *Annual Value of Construction Put in Place: Preliminary Estimates for 1992*. Washington, DC: Bureau of the Census. n.p.

Chapter 2

High-Performance Construction Materials and Systems: Transforming the Nation's Infrastructure

...infrastructure, productivity, economic growth and competitiveness are inexorably linked.

The United States' emergence as a 20th century world leader was based, in part, on a state-of-art infrastructure. But, our infrastructure investment relative to GDP (Gross Domestic Product) has declined by almost 50 percent over the past three decades. Today, we no longer enjoy an infrastructure advantage.

These critical developments coincide with a growing awareness that infrastructure, productivity, economic growth and competitiveness are inexorably linked. Infrastructure determines, in fundamental ways, what a society can achieve. Compared to other advanced industrialized countries, the United States has not made proportionate investments in infrastructure and is suffering for it, both in terms of productivity growth and international competitiveness.

Infrastructure problems reduce the economy's health. To promote economic growth in the 21st century, an innovative infrastructure research program exploiting high-performance materials and systems is needed. Public- and private-sector investment must be directed toward construction of better designed, more efficient, durable, and trouble-free infrastructure. This can be done by effectively leveraging research funds to provide the quality infrastructure components necessary for enhancing private sector productivity.

What Do We Mean by "High-Performance Construction Materials and Systems?"

A program of infrastructure renewal could use traditional, present-day materials and processes. Such an effort would address some immediate needs, but it would not deliver the benefits in improved performance that should be demanded for the 21st century. Average life cycles of constructed facilities would not be improved and would probably diminish, given the increased demands of a larger, more mobile population. Also, it would be difficult to effect significant improvements in durability, constructability, and maintainability. **The nation's constructed facilities, whether in public or private hands, need the benefits inherent in high-performance construction materials and systems.**

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The nation's construction industry is highly fragmented and consists mostly of small and medium sized firms. Individual firms cannot, on their own, conduct the research and development necessary to create innovative materials and processes.

Significant advances have been made in the field of materials science and structural analysis in the past two decades. The challenge for high-performance construction materials and systems is applying this knowledge to create an infrastructure that will be characterized by:

- Superior strength, toughness, and ductility
- Enhanced durability/service life
- Increased resistance to abrasion, corrosion, chemicals and fatigue
- Initial and life-cycle cost efficiencies
- Improved response in natural disasters and fire
- Ease of manufacture and application or installation
- Aesthetics and environmental compatibility
- Ability for self-diagnosis, self healing, and structural control

Tomorrow's high-performance construction materials and systems will bring substantial savings because they:

- Reduce material requirements and provide opportunities for new construction applications
- Show greater resilience and adaptability to environmental factors, ability to accommodate and sustain higher design loads or load frequency
- Are easier and faster to fabricate and of consistently high quality
- Incorporate sensing technologies that enable self-diagnosis

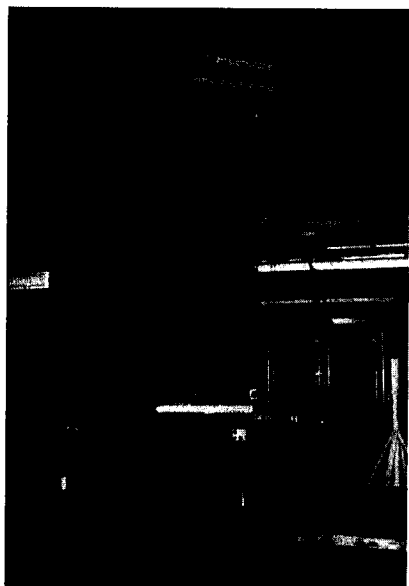
Development of the CONMAT Program

The nation's construction industry is highly fragmented and consists mostly of small and medium sized firms. Individual firms cannot, on their own, conduct the research and development necessary to create innovative materials and processes. As a result, technical leadership has shifted largely to other nations. Foreign competitors have made marked advancements in state-of-the-art and in forging a close government/private sector partnership.

At the same time, the public works infrastructure in the U.S. is governed and managed by various states and federal agencies, and system management is diffuse and complicated. Development of a successful and coordinated R&D program requires addressing the critical problems that are common to the public works infrastructure.

For these reasons, in 1991, the Civil Engineering Research Foundation (CERF), the research affiliate of ASCE, convened private and public sector experts in construction research and practice as well as major owners of infrastructure to define a national research agenda for civil engineering. A key priority of this national forum was to develop "super construction materials," with the initial focus on concrete and steel in improving performance, installation, durability, and strength.

In response to the Forum recommendation, a planning committee made up of experts from industry, academia and government developed a specific strategy and program to exploit high-performance construction materials and systems, initially concentrating on concrete and steel. The program, the High-Perfor-



Courtesy of Center for Advanced Technology for Large Structural Systems (ATLSS)

Robotics increase precision of steel erection.

mance CONstruction MATerials and Systems Program (CONMAT), soon attracted the interest of other construction material groups such as aluminum and composites. The CONMAT program, as envisioned by CERF, consists of a series of industry-led R&D activities costing at least \$2 billion over ten years. A strong private, public sector partnership is critical to the success of the program.

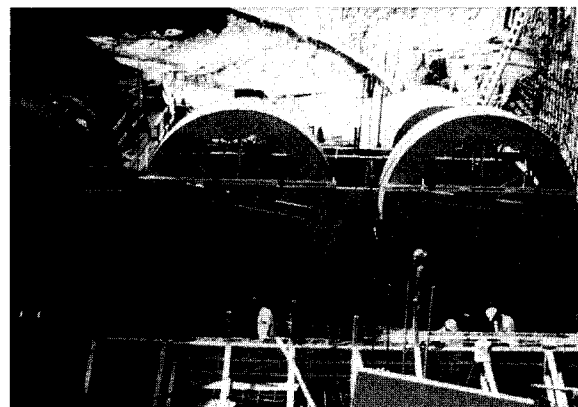
CONMAT now encompasses ten important construction material groups. The list, which includes high-performance traditional as well as emerging materials, comprises aluminum, coatings, composites, concrete, hot mix asphalt, masonry, roofing, smart material devices and monitoring systems, steel, and wood. For traditional materials, the program focuses on new high-performance derivatives and applications. The program is dynamic, with some industry-led groups being far advanced in developing an R&D strategy, while others have only recently made the commitment to develop a consensus approach to respond to the construction industry's needs. It is anticipated that other material groups not currently involved with CONMAT (e.g., geotextiles, rock/aggregate, gypsum, and others) may soon become part of the process.

*Although its history is brief,
the CONMAT program can
already point to several
successes.*

Industry and Government in Partnership: Practical Successes to Date

Although its history is brief, the CONMAT program can already point to several successes. Industry has shown its commitment by devoting resources to the formation of ten working groups, typically including representatives from their own industry and experts from academia and government. A series of industry meetings and workshops have been held across the country to formulate, often for the first time, a focused national research, development, and deployment agenda that reflects the needs of the marketplace. This effort, estimated at over \$1 million in in-kind labor costs alone, has had several important benefits. Most importantly, with the workshop and publication of *High-Performance Construction Materials and Systems: An Essential Program for America and its Infrastructure* in April of 1993, supporters of the program demonstrated the strong national consensus for a high-performance construction materials and systems program. Recent administration and congressional policies support this effort and include:

- Establishing the subcommittee on Construction and Building within the Committee on Civilian Industrial Technology (CCIT) of the National Science and Technology Council (NSTC)
- Fostering a close working relationship with the Office of Science and Technology Policy (OSTP) and CONMAT representatives
- Establishing CERF as the primary liaison for research and innovation in the construction industry
- Increasing funding for the National Institute of Standards and Technology's Advanced Technology Program (ATP), resulting in significant monies for innovative but high-risk enabling technologies with strong commercial potential in program focus areas of interest to the construction industry



Fiber optic sensors permit remote monitoring of constructed facilities. In this instance, the sensors are placed beneath a turbogenerator's framework prior to concrete pours.

The implementation plan rests on four operating principles.

- Promoting the Technology Reinvestment Project (TRP) that has resulted in support of high-performance construction materials related projects such as the San Diego composite vehicular bridge project
- Providing support for key FHWA priorities, including infrastructure maintenance and environmental monitoring
- Promoting other agencies' programs in high-performance construction materials and systems research

There is much yet to be done. The major task is to ensure that the critical high-performance research is implemented and quickly leads to commercialization of new products and processes.

A Cooperative Ten-Year Implementation Plan: Goals and Operating Principles

The CONMAT program is envisioned as a ten-year program of research and development, research dissemination and commercialization of new products and processes. The implementation plan rests on four operating principles.

1. The CONMAT program must be industry-led. While active cooperation and partnership with academic and the public sector are critical to the success of CONMAT, the program will fall short of its goals if it is not driven by those industries who can support and benefit from program implementation. Industry is expected to take the lead identifying research needs and implementing research results.
2. The CONMAT strategy requires the active collaboration and cooperation of the material groups in research projects of overlapping interest and in the realization of mutual technological deployment objectives, such as the creation of an integrated CONMAT data base system and the training/retraining of engineers and technicians in the construction community.
3. The implementation plan focuses on overcoming knowledge gaps and institutional barriers that currently limit the construction industry's use of these high-performance materials and systems. A variety of strategies are recommended, such as promoting changes in product evaluation and contract bid systems and establishing evaluation and demonstration projects.
4. Finally, the CONMAT program must demonstrate results! Some projects are specifically designed as near-term or intermediate-term, and their successful completion is a pre-requisite for subsequent projects. All material groups have prioritized their research agendas. The most critical projects are clearly designated.

For the collective responsibilities described above, the CONMAT plan requires an ongoing body to coordinate both day-to-day and long-term activities. The creation of a CONMAT National Construction Materials Coordinating Council (NCMCC) is proposed to serve as an industry-led group that will work closely with federal agencies, academic institutions, and federal laboratories. The NCMCC mandate will be to facilitate the implementation of the CONMAT program.

The NCMCC will provide a forum for the construction community to make CONMAT plans part of their business and corporate strategy. The NCMCC will help to determine the specific plans for realizing research and technology deployment objectives. For example, the Council may identify and recruit suitable industry partners for collaboration on a research project, bring together

private and public sector representatives for evaluation and demonstration efforts, and target and follow through with individual firm and/or trade associations in creating consortia that will commercialize and promote new products or processes. The NCMCC will publicize and promote research efforts, as well as promote education efforts and initiate technology deployment activities.

Summary of Material Groups' Research Schedules and Budgets

In preparing this report, material groups have closely reviewed the objectives of CONMAT and the specific aims of their particular research and commercialization plan. **Table 1 presents the ten-year budgets for each group, along with some of the key objectives established to advance our knowledge and use of each material.** The budgets reflect the current development of each material group's plan. While some groups such as concrete and steel have been established for nearly three years, other groups such as wood and hot mix asphalt have only recently been formed. In particular, hot mix asphalt is currently refining its research objectives; at this time is it premature to present specific budget projections for this material group.

Table 1 also presents an eleventh line item for those technology deployment activities that cut across two or more material groups and are coordinated through the NCMCC. Based on an understanding of the types of technology deployment activities that must be completed relative to the range of material-specific research efforts for the entire program, it is estimated that the deployment activities will represent approximately 10 percent of the material group budget outlays. This follows the detailed technology transfer/technology deployment estimates in the 1993 volume, *High-Performance Construction Materials and Systems: An Essential Program for America and its Infrastructure*, where the CONMAT steel and concrete agendas were initially presented.

Table 1: Proposed Ten-Year Budgets and Key Objectives by Material Groups

Material Groups	Key Objectives	Ten-Year Budget
Aluminum	Optimization of aluminum alloys and structural systems to demonstrate competitive life-cycle costs for bridges and structures for severe environments	\$48,250,000
Coating	Enhancement of environmental characteristics and improvement in the overall life-cycle costs of coated structures	\$150,450,000
Composites	Creation of a new generation of bridge, marine and utility structures with the benefits of reduced life-cycle costs and construction time	\$882,750,000
Concrete	In-place quality improvements and optimized design for durability and strength enhancement	\$171,950,000
Hot Mix Asphalt	In-place quality and environmental acceptability	NA*
Masonry	Construction quality enhancement and natural hazard reduction	\$68,450,000
Roofing	Extended service life and energy conservation	\$103,500,000
Smart Materials	Technology development in communications and sensors focusing on life-cycle cost reduction	\$206,000,000
Steel	Enhancements in materials predictability, and life-cycle performance	\$190,560,000
Wood	New product forms with enhanced durability, strength, and affordability	\$69,950,000
Technology Deployment	Integrated knowledge base, technical education, life-cycle costing procedures, evaluation, and prototype demonstrations	\$189,186,000
TOTAL		\$2,081,046,000

* Specific funding levels have not been established at this time.

Material groups propose budgets of slightly over two billion dollars over a ten-year period.

Table 2 presents the annual budgets, by material group, for each of the next ten years. As with Table 1, a separate line item has been assigned to the NCMCC's technology deployment activities.

Table 2: Proposed Year-by-Year Budgets in Millions of Dollars, by Material Groups

Material Groups	Dollar Amount, in Millions, by Year of Program										
	1	2	3	4	5	6	7	8	9	10	Total*
Aluminum	6.35	6.35	5.70	4.95	4.90	4.50	4.50	4.00	3.50	3.50	48.25
Coatings	7.00	13.70	16.30	22.71	21.88	21.88	17.30	13.93	12.13	3.60	150.45
Composites	35.00	63.00	111.00	211.00	222.00	122.75	56.00	31.00	21.00	10.00	882.75
Concrete	7.55	12.60	15.20	20.05	18.35	23.40	22.44	20.73	15.73	15.90	171.95
Hot Mix Asphalt	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA**
Masonry	4.00	5.25	7.80	7.85	8.50	9.25	8.40	6.40	5.90	5.10	68.45
Roofing	9.50	8.00	11.94	13.44	14.44	11.44	10.44	9.94	7.94	6.44	103.50
Smart Materials	14.70	26.40	29.70	28.90	29.20	26.00	23.70	14.30	8.30	4.80	206.00
Steel	18.66	20.76	22.71	26.16	27.21	20.61	18.45	18.45	12.00	5.55	190.56
Wood	8.15	8.85	10.48	9.28	9.28	7.13	4.43	4.88	3.88	3.63	69.95
Technology Deployment	9.46	9.46	9.46	18.92	18.92	18.92	18.92	28.38	28.38	28.38	189.19
Total*	122.10	181.60	253.74	378.74	391.14	271.54	182.04	135.84	106.34	65.44	2081.05

* Totals may differ slightly from sum of yearly outlays, due to rounding.

** Specific funding levels have not been established at this time.

Chapter 3

High-Performance Aluminum Alloys

Traditionally, the construction industry has largely limited its application of aluminum to exterior building curtain wall and light structural members. However, when compared to other conventional structural materials, aluminum provides a unique combination of light weight, ductility, high strength, and excellent resistance to corrosion. It is appropriate to re-examine the opportunities to enhance the infrastructure in situations where this combination of properties brings about significant economic and technical improvements.

Of the 9-million ton annual domestic production of aluminum and aluminum alloys, approximately 14 percent goes into construction and approximately 19 percent goes into transportation. Thus aluminum is already often a key material for infrastructure applications. The aluminum alloy class of materials is widely respected for its combination of strength and toughness in critical aerospace and process industry structural applications.

Unlike other metals, aluminum, when exposed to air, forms an unusually durable protective oxide film that protects its surface from corrosion. Alloying aluminum further extends its serviceability for applications requiring high strength and toughness as well as durability in severe weather and/or environmental conditions. These characteristics can be effectively used in vital infrastructure applications. As one example, industry experts calculate that extending the life of 10 percent of the approximately 575,000 bridges in the U.S. with aluminum alloy bridge decks (for an average 279 sq. m. [3,000 sq. ft.] per bridge) would produce replacement and maintenance cost savings of in excess of \$100 billion.

What are High-Performance Aluminum Alloys?

Aluminum is an engineered material: its properties can be tailored to the requirements of the specific construction. Today's aluminum alloys range in applications from automotive "bodies in white" to highly durable machine parts. High-performance aluminum alloys bring many advantages to the construction industry, including one or more of the following:

- Light weight
- High strength
- Superior corrosion resistance
- Ready fabrication
- Recyclability

Traditionally, the construction industry has largely limited its application of aluminum to exterior building curtain wall and light structural members.



Internal structure of aluminum clear-span roof for waste water treatment clarifier.

Courtesy of The Aluminum Association

- Workability and process capability
- Toughness and strength at subzero temperatures

Properties and Benefits of High-Performance Aluminum Alloys

Aluminum's low density, one-third that of many traditional load-bearing materials, allows for quick retrofit to extend existing bridge life, upgrades in load-carrying capacity, and reduced energy consumption. Its weight also reduces transportation and handling energy and costs. In addition, aluminum's great resistance to corrosion minimizes maintenance expense, and assures long life at high performance.

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Structural aluminum alloys are readily welded, easily machined and formed, and may be finished by a great variety of methods, allowing for great flexibility in fabrication options. The extrusion process is especially valuable in enabling designers to tailor shapes to optimum configurations, placing the metal in position to carry the most load or increase stiffness. The easy recyclability of aluminum increases scrap values and offers flexibility in re-use options at end of service life. Finally, aluminum alloys are as strong or stronger than mild steels and much stronger than concrete, permitting direct substitution with equal or improved structural performance.

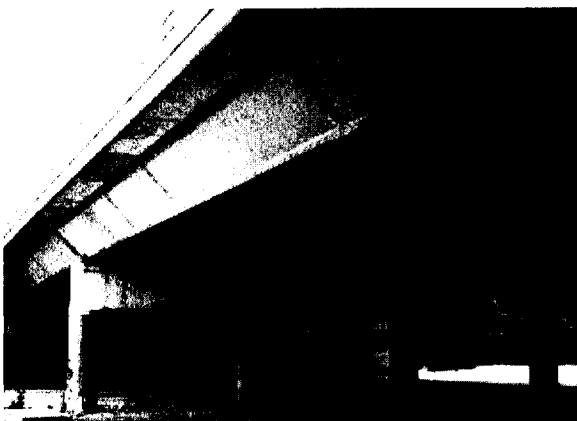
While some optimization of aluminum alloys and production processes would further enhance their applicability to infrastructure applications, the application of these alloys at their present performance level to upgrade and extend the life of U.S. bridges would have great economic impact.

Current Constraints to High-Performance Aluminum Alloy Use

The principal reason why aluminum alloys are not more widely used for major highway structures, including retrofit bridge decks, is their relatively high cost compared to steel and concrete construction. Aluminum construction first cost is typically 1.5 to 2 times that of steel and/or concrete, and so significant savings must be made elsewhere to justify its use. The retrofit of bridge decks to extend the life of existing steel and concrete bridges is one major opportunity for such savings; this application would be enhanced by developments to further reduce the cost of the aluminum construction.

Technical barriers to reducing the cost of using aluminum alloys for more infrastructure applications include (a) the need for more efficient welding and joining procedures, (b) limited fatigue data covering heavy-duty highway loadings, and (c) the limited application of mathematical modeling of aluminum bridge design and behavior to enable understanding of seismic effects. The low mass of aluminum bridge decks may actually be a very positive contributor to enhanced seismic performance, but the analyses of such problems are not available.

Although some aluminum bridges have been in service for more than 30 years, more definitive data is required to illustrate the performance of a wider range of designs and service loadings.



Aluminum girder bridge structure, Sunrise Highway Overpass, New York

Courtesy of The Aluminum Association

Like most improvements in the construction industry, focused university and post-college education and training will be the keys to the successful and continued use of aluminum alloys. Aluminum alloys are too closely identified with the packaging markets; thus, the use of alloys in the construction market is often overlooked. The application of aluminum alloys to major structures is often hindered by engineers' and designers' lack of awareness of aluminum alloys' properties and performance. Designers have also tended to overlook their broad use in pressure vessel and aircraft applications.

As important as it is to address the economic and technical barriers to increased use of aluminum in infrastructure, the educational and training barriers are just as great, and are addressed in a major way in the program outline below.

Centers of Excellence for High-Performance Aluminum Alloy Research and Technology Transfer

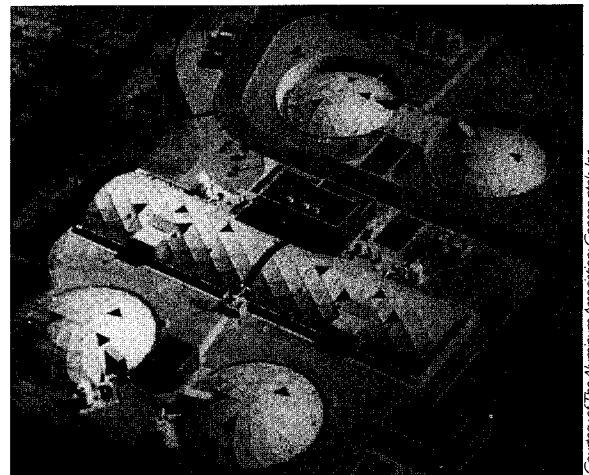
To address the education and training issues noted above and develop the expertise for the mathematical modeling and analytical needs identified, **industry and government should partner** to establish an aluminum center of excellence for infrastructure design. The establishment of a center is critical, since research and commercialization objectives require consistent and knowledgeable focus over a period of years, especially in the fields where the individual companies no longer have great depth of expertise. The existence of such a center would also ensure that the progress made in recent years on optimizing the capabilities of high-performance aluminum alloys are effectively implemented in infrastructure applications.

Coordinated Development Programs on Aluminum

Implementing a series of well-focused programs of the types outlined below, along with the creation of the Center of Excellence for Infrastructure Design noted above, will also help optimize designs and performance capabilities. Consistent funding over the next ten years will be a vital element of the success achieved. The activities would fall into the following individual program areas:

- Innovative Aluminum Alloy Bridge Technology
- Aluminum Earthquake-Resistant Structures
- Enhanced Aluminum Welding and Joining Technology
- Advanced Aluminum Alloy Net-Shape Production Technology
 - Extrusion Technology
 - Forging Technology
 - Casting Technology

As important as it is to address the economic and technical barriers to increased use of aluminum in infrastructure, the educational and training barriers are just as great.



Aluminum roof structures for municipal waste water treatment plant facilities.

Courtesy of The Aluminum Association, Conservatek, Inc.

Current Projects Demonstrating High-Performance Aluminum Alloys' Effectiveness

Progress in the development of design and fabrication technology for high-performance aluminum alloys has already been made on the laboratory scale. Developing these projects on a commercial scale promises improvements and cost savings for the construction industry. For example, automated welding technology developed by Professor Valdemar Malin of the Building Industrial Research Laboratory (BIRL) at Northwestern University offers the potential, if commercializable, to **halve the cost of welding aluminum bridge decks** and increase the consistency of high weld quality, thus reducing the amount of repair welding needed.

Another research project modifying the design of aluminum bridge decks by Swedish inventor Lars Svensson **reduces the cost of aluminum retrofit decks to near a trade-off** with concrete and steel decks insofar as first cost is concerned. The Royal Swedish Institute of Technology continues to test and evaluate these new designs in prototype installations.

Experimental/semi-commercial Al-Si-Mg alloys 6070 and 6071 have demonstrated up to 20 percent higher strengths than those of 6061 and 6063, the standards for aluminum alloy welded structures. Thus far, the strengths of welds in these alloys have not been increased proportionately. A combination of enhanced joining technology and these advanced aluminum-magnesium-silicon alloys could further enhance the advantages for aluminum retrofit bridges.



Courtesy of The Aluminum Association, Inc.

Interior of aluminum geodesic dome roof structure for gymnasiums, auditoriums and convention centers.

ALUMINUM

Prioritized Research Projects

Research Topic	Research Project	Objective	Approach	Schedule	Budget	Public Agency	Benefits
Aluminum Center of Excellence for Infrastructure	Establish Center of Excellence	Provide a technical center for (a) the development and dissemination of technology on the application and design of aluminum structures for infrastructure, and (b) the education of material science and civil or mechanical engineering university students on the application of aluminum alloys to structures where the combination of light weight, high strength, rapid erection and low-maintenance requirements are most effectively used to advantage.	A center for teaching and research in structural design of aluminum alloys will be established at a major university in the United States, Cornell. The proposed center will provide: education, research programs, mathematical models information, new design procedures and specification development on key design features for infrastructure. Development of user-friendly finite element program for static, dynamic, and fatigue design of aluminum structures.	2.5 years development plus continuous support	\$7.55M	NSF NIST DOE FHWA EPA	Continuity of expertise in design and development know-how on aluminum. Training and education of new and post-graduate engineers and designers.
Aluminum Center of Excellence for Infrastructure	Establish lecture series "Cost Effective Use of Light-Weight Aluminum Alloy Structures"	Assure high quality teaching program on aluminum structures	An experienced structural engineer with an extensive background in the design and erection of aluminum structures, and who has developed a working lecture series on aluminum alloys, will be asked to expand the materials into a ten-lecture course suitable for university use. Input to the course will also be provided by two other individuals, one very experienced in the design of bridges and pressure vessels of aluminum, the other a university educator and engineering consultant adept at tailoring the material to the university environment.	4 years	\$0.2M	NSF NIST DOE FHWA EPA	Continued education of new designers and engineers on aluminum structural design technology.

Research Topic	Research Project	Objective	Approach	Schedule	Budget	Public Agency	Benefits
Innovative Aluminum Alloy Bridge Technology	Inspection and Documentation of Existing Aluminum Bridges	Certify that aluminum has been and can continue to be used successfully as a bridge material, and to develop a comprehensive understanding of successful practices that should continue to be utilized and of mistakes or omissions that should be avoided in future aluminum bridges.	Aluminum bridges have been in continuous use in the United States for over 60 years, and also in some European countries. A comprehensive and impartial analysis of their designs, load history, and performance is needed. A specification covering the content of the study will be developed; the purpose of the specification will be to insure that a thorough and complete review will be made with the intent of learning how to improve future designs as well as employ what has been proven to work. After the specification is written, an impartial entity will be identified and employed to conduct the study. The entity will be one with a reputation for integrity and having considerable experience in bridge design and analysis, such as a university with an extensive program in structural design or a government agency/laboratory.	1 year	\$0.25M	NIST FHWA NSF SHR	Assure maximizing potential use of knowledge from previous highly successful use of aluminum in bridge applications.
Innovative Aluminum Alloy Bridge Technology	Demonstration Aluminum Bridge Deck Replacement	Design and build aluminum orthotropic bridge decks to replace concrete or steel decks on bridges in Virginia and/or New York; document erection process, and collect performance data over service life for demonstration of concept viability. Add additional application sites at rate of 1-3/year	With the cooperation of state department(s) of transportation in Virginia and/or New York, identify an application or applications where the light weight of an aluminum bridge deck makes possible both increased load-carrying capacity on an existing foundation and also a shorter erection time, and hence period of restricted closure. Employ the most efficient and cost-effective bridge deck design available at the present time, the Svensson extruded panel deck, for the application(s). The combination of integrally stiffened extrusions and bolted assembly provide sufficient weight savings to increase capacity by 15% at a cost only slightly greater than that of concrete or steel. Virginia/New York DOT will fund the basic bridge replacement. Approximately \$200,000 of aluminum industry funds will support the material procurement, special fabricating costs, and documentation of the entire job. Matching federal funds will be sought.	10 years	\$5.0M	VA DOT NY DOT	Assure most cost-effective design utilization and verify its safety and effectiveness, as well as document cost-savings potential. Expected savings about \$3-5B through bridge life extension.

Research Topic	Research Project	Objective	Approach	Schedule	Budget	Public Agency	Benefits
Innovative Aluminum Alloy Bridge Technology	Evaluation of Iowa State Aluminum Beam Bridge	Preserve and performance test highly stressed portions of an aluminum beam bridge built in Iowa State in 1957 that is being removed because a bridge is no longer needed at that location.	Iowa State University will recover portions of the aluminum girders and arrange for static and dynamic property evaluations at ISU and at Lehigh University. Iowa DOT will provide some financial support and additional industry support will be sought.	1 year	\$0.25M	DOT/FHWA	Gain high-reliability measure of durability of aluminum in bridge structures, specifically potential for 50-100 years of service life.
Innovative Aluminum Alloy Bridge Technology	Advanced Concept for Aluminum Highway Bridge Deck	Develop and demonstrate an advanced concept for a bridge deck fabricated entirely from high-strength aluminum extruded shapes, taking full advantage of light weight and shorter erection periods while reducing the costs of all-aluminum	Utilizing the concepts of Lars Svensson bridge designs (the leader in advanced bridge deck design in Europe) and the potential new fabrication technologies, such as that from Northwestern University (long a major civil-engineering design leader in Department of Transportation projects), develop and demonstrate an optimized design of aluminum bridge and/or bridge deck, and subsequently participate in the prototype erection and evaluation of a commercial installation. The program will include bridge deck designs of both unwelded and welded construction. Included in the program will be an extensive business analysis reflecting cost limits and targets, projections on application opportunities, and total potential savings on U.S. infrastructure enhancement costs.	4.5 years	\$4.25M	FHWA	Gain documentation of potential for \$3-5 billions savings in fabrication and erection costs by use of innovative replacement bridge decks design. To greatly extend life of thousands of existing bridges.
Innovative Aluminum Alloy Bridge Technology	Aluminum Alloys for Long Span Highway Bridges	Evaluate the advantages of aluminum alloys for long span bridges by (a) developing two or more alternative designs for a long span aluminum alloy bridge (about 260 ft), (b) evaluating the relative economics and performance of alternative designs of aluminum bridge with those of steel bridges, and (c), if justified, building a demonstration bridge of the best design.	At least two long span bridge design approaches will be used to explore the advantages of aluminum in combination with steel girders or as a replacement: one using custom designed aluminum girders and another using aluminum-enclosed steel girders. In addition, various configurations such as arched or cabled systems as well as deep beams will be explored. The various design alternatives will be evaluated based upon fabrication, erection and maintenance economics and upon performance, including fatigue life. An optimum design will be selected and, if justified, a demonstration bridge will be built and evaluated. Included in this analysis also will be an extensive business analysis reflecting cost limits and targets, projections on application opportunities, and total potential savings on U.S. infrastructure enhancement costs.	5 years	\$5.0M	FHWA	Verification of extension of multi-billion dollar savings through use of aluminum in bridge deck structures to long-span bridge applications as well.

Research Topic	Research Project	Objective	Approach	Schedule	Budget	Public Agency	Benefits
Aluminum Earthquake-Resistant Structures	Structural Analysis of Behavior of Aluminum Building Structures During Earthquake Loading	Develop finite-element analyses (FEA) structural design analyses of the behavior of aluminum structures subject to earthquake imposed loading. Compare that with the behavior of steel and concrete structures.	a) Identify key earthquake sensitive structures for candidate analysis, including multi-level bridge structures, high-level building structures. b) Develop candidate designs intended to provide extraordinary earthquake resistance, and define FEA analysis programs and techniques. c) Carry out analyses under earthquake imposed loading; define deformation impact. d) Employ results to ascertain value of aluminum characteristics to earthquake resistance, and develop optimized designs based upon those key characteristics.	2 years	\$0.5M	NSF NIST DOT DOE FHWA EPA	Determination magnitude of savings potential in earthquake damage replacement cost through use of low-mass structural material, estimated at up to \$18 per incident.
Aluminum Earthquake-Resistant Structures	Demonstration Construction and Testing of Earthquake Resistant Aluminum Structures	Based upon results of Phase I structural design analyses of the behavior of aluminum structures subject to earthquake imposed loading, design, build and test prototype earthquake resistant bridge and building structures. Add new sites in 4-5 years	Identify two earthquake sensitive structures for candidate analysis, including a multi-level bridge structure and a multi-level building structure. Develop candidate designs intended to provide extraordinary earthquake resistance. Build bridge and building structures. Employ simulated seismic loading to conduct tests of both bridge and building structures, and modify or refine design concepts based upon the results.	4 years for initial application and for each additional application	\$9.75M	NSF NIST DOT DOE FHWA EPA	Verification of magnitude of billions of dollars in savings potential in earthquake damage replacement cost through use of low-mass structural material.
Enhanced Aluminum Welding Technology	Aluminum Alloy Fusion Welding Data Base	To develop a fusion welding data base that can be accessed by various means to obtain pertinent welding information, and establish an appropriate facility to administer this data base.	Select an appropriate university (possibly in conjunction with the proposed "Aluminum Center of Excellence for Infrastructure"). Potential universities might be Ohio State, the University of Iowa or Lehigh University. Assemble a world wide compendium of fusion welding information, edit and publish this information. Develop multiple access strategies.	10 years	\$5.5M	NIST ATP DOE DOT NSF	Existence of world class searchable database, saving millions of dollars in search cost and decision quality.
Enhanced Aluminum Welding Technology	Acoustic Emission Weld Evaluation Technology for Field Use on Aluminum Weldments	To develop a practical device which can be used in the field for evaluating weld process quality on the basis of acoustic emissions produced during welding.	A great deal of laboratory research has been conducted on acoustic emission evaluation for welding control feedback. This technology must be converted to practical use by developing a marketable device that can be used in the field.	5.2 years	\$1.0M	NIST ATP	Savings of 50% or more in inspection cost for welded aluminum structures.

Research Topic	Research Project	Objective	Approach	Schedule	Budget	Public Agency	Benefits
Enhanced Aluminum Welding Technology	Laser welding of Aluminum Plates	To determine the feasibility and properties of weldments made on thick structural aluminum alloy members with lasers. This technology offers the opportunity to make weldments with reduced heat affected zones and better properties.	a) Conduct a literature search to determine previous work with aluminum using laser techniques. b) Establish alloys to be evaluated. c) Determine maximum thicknesses that can be welded (butt joints) using commercially available lasers. d) Compare weldments made using lasers with similar joints produced with conventional GMA welding processes.	2 years	\$0.5M	NIST ATP DOE NSF	Maximization of savings potential by use of most advanced aluminum joining technology.
Enhanced Aluminum Welding Technology	Prototype Mobile Robotic Welding Cell for Aluminum Structures	Design and build a prototype mobile robotic welding cell that would be carried on a flat bed truck to a bridge or other site for welding fabrication of aluminum structures.	Select appropriate university, government and private industry consortium to design and fabricate a prototypical working model. Develop production techniques for the manufacture of this model for commercial use. The robot would be mounted on a track, which could be part of a large frame, to allow movement in multi-axis directions. The robot could be used for all joining fabrication procedures, i.e., plasma (or laser) cutting, grit blast cleaning and welding.	5.3 years	\$1.0M	NIST ATP DOE DOT	Reduction of 50-75% in cost of multi-track welds in aluminum bridge decks and similar structures.
Advanced Aluminum Alloy Net Shape Production Technology - Extrusions	Innovative Extrusion Technology for Infrastructure Applications	Develop specialized hollow, multi-void extrusion technology to permit the application of premium quality extrusion know-how to high volume, relatively low-cost extruded products for transportation and infrastructure applications.	Premium extrusion technology has been employed in the production of near-net-shape, high strength extruded parts for aerospace applications for a number of years. These techniques, while leading to high quality, have been produced for small lot sizes and cost-intensive applications. Infrastructure applications could effectively use the premium performance, but the process technology must lend itself to high-volume, low-cost products. It is proposed that the die shape, dimension, heat treatment and composition control parameters applied for aerospace applications be transitioned and applied to these high-volume structural markets.	8 years	\$2.5M	NSF NIST DOT DOE FHWA EPA	Increased economy of fabrication and superior performance of structures.

Research Topic	Research Project	Objective	Approach	Schedule	Budget	Public Agency	Benefits
Advanced Aluminum Alloy Net Shape Production Technology - Forgings	Innovations Forgings for Infrastructure Applications	Develop specialized die and semi-solid forging technology to permit the application of premium quality forging know-how to high volume, relatively low-cost forged products for automotive and infrastructure applications.	Premium forging technology has been employed in the production of near-net-shape, high strength forged parts for aerospace applications for a number of years. These techniques, while leading to high quality, have been produced for small lot sizes and cost-insensitive applications. Infrastructure applications could effectively use the premium performance, but the process technology must lend itself to high-volume, low-cost products. It is proposed that the die, dimension, heat treatment and composition control parameters applied for aerospace applications be transitioned and applied to these high-volume markets.	8 years	\$2.5M	NSF NIST DOT DOE FHWA EPA	Redirection of superior performance of forged components from aerospace to the commercial sector. Lighter weight. Higher strength.
Advanced Aluminum Alloy Net Shape Production Technology - Castings	Innovative Casting Technology for Infrastructure Applications	Develop specialized premium quality squeeze and semi-solid casting technology to high volume, relatively low-cost sand or permanent mold cast products for automotive and infrastructure applications.	Premium casting technology has been employed in the production of near-net-shape, high strength cast parts for aerospace applications for a number of years. These techniques, while leading to high quality, have typically been produced for small lot sizes and cost-insensitive applications. Infrastructure applications could effectively use the premium performance, but the process technology must lend itself to high-volume, low-cost products. It is proposed that the pressure, mold, dimension, heat treatment and composition control parameters applied for aerospace applications be transitioned and applied to these high-volume markets.	8 years	\$2.5M	NSF NIST DOT DOE FHWA EPA	Higher strength and toughness of cast components. More efficient, lower cost structures.
Total Program Outlay					\$48.25M		

Prioritized Timeline and Budget Allocation

Year	Project	Duration (in years)	Cost
I	Establish Center of Excellence	10	\$1,400,000
	Establish lecture series	4	50,000
	Documentation of existing aluminum bridges	1	250,000
	Bridge deck replacement demonstration	10	500,000
	Aluminum beam bridge evaluation	1	250,000
	Advanced Highway bridge deck concept	5	250,000
	Earthquake loading structural analysis	2	250,000
	Earthquake resistant demonstration	10	750,000
	Welding database	10	1,000,000
	Acoustic emission weld evaluation	5	200,000
	Laser welding	2	250,000
	Prototype mobile robotic welding	5	200,000
	Innovative extrusion technology	8	333,333
	Innovative forgings	8	333,333
	Innovative casting technology	8	333,334
Year I Total \$6,350,000 Cumulative Total \$6,350,000			
2	Establish Center of Excellence	10	\$1,400,000
	Establish lecture series	4	50,000
	Bridge deck replacement demonstration	10	500,000
	Advanced Highway bridge deck concept	5	1,000,000
	Earthquake loading structural analysis	2	250,000
	Earthquake resistant demonstration	10	1,000,000
	Welding database	10	500,000
	Acoustic emission weld evaluation	5	200,000
	Laser welding	2	250,000
	Prototype mobile robotic welding	5	200,000
	Innovative extrusion technology	8	333,333
	Innovative forgings	8	333,334
	Innovative casting technology	8	333,333
Year 2 Total \$6,350,000 Cumulative Total \$12,700,000			
3	Establish Center of Excellence	10	\$1,250,000
	Establish lecture series	4	50,000
	Bridge deck replacement demonstration	10	500,000
	Advanced Highway bridge deck concept	5	1,000,000
	Earthquake resistant demonstration	10	1,000,000
	Welding database	10	500,000
	Acoustic emission weld evaluation	5	200,000
	Prototype mobile robotic welding	5	200,000
	Innovative extrusion technology	8	333,334
	Innovative forgings	8	333,333
	Innovative casting technology	8	333,333
Year 3 Total \$5,700,000 Cumulative Total \$18,400,000			

Year	Project	Duration (in years)	Cost
4	Establish Center of Excellence	10	\$500,000
	Establish lecture series	4	50,000
	Bridge deck replacement demonstration	10	500,000
	Advanced Highway bridge deck concept	5	1,000,000
	Earthquake resistant demonstration	10	1,000,000
	Welding database	10	500,000
	Acoustic emission weld evaluation	5	200,000
	Prototype mobile robotic welding	5	200,000
	Innovative extrusion technology	8	333,333
	Innovative forgings	8	333,333
	Innovative casting technology	8	333,334
Year 4 Total \$4,950,000 Cumulative Total \$22,350,000			
5	Establish Center of Excellence	10	\$500,000
	Bridge deck replacement demonstration	10	500,000
	Advanced Highway bridge deck concept	5	1,000,000
	Earthquake resistant demonstration	10	1,000,000
	Welding database	10	500,000
	Acoustic emission weld evaluation	5	200,000
	Prototype mobile robotic welding	5	200,000
	Innovative extrusion technology	8	333,333
	Innovative forgings	8	333,334
	Innovative casting technology	8	333,333
Year 5 Total \$4,900,000 Cumulative Total \$28,250,000			
6	Establish Center of Excellence	10	\$500,000
	Bridge deck replacement demonstration	10	500,000
	Long span highway bridges	5	1,000,000
	Earthquake resistant demonstration	10	1,000,000
	Welding database	10	500,000
	Innovative extrusion technology	8	333,334
	Innovative forgings	8	333,333
	Innovative casting technology	8	333,333
Year 6 Total \$4,500,000 Cumulative Total \$32,750,000			
7	Establish Center of Excellence	10	\$500,000
	Bridge deck replacement demonstration	10	500,000
	Long span highway bridges	5	1,000,000
	Earthquake resistant demonstration	10	1,000,000
	Welding database	10	500,000
	Innovative extrusion technology	8	333,333
	Innovative forgings	8	333,333
	Innovative casting technology	8	333,334
Year 7 Total \$4,500,000 Cumulative Total \$37,250,000			

Year	Project	Duration (in years)	Cost
8	Establish Center of Excellence	10	\$500,000
	Bridge deck replacement demonstration	10	500,000
	Long span highway bridges	5	1,000,000
	Earthquake resistant demonstration	10	1,000,000
	Welding database	10	\$500,000
	Innovative extrusion technology	8	166,666
	Innovative forgings	8	166,666
	Innovative casting technology	8	166,666
			Year 8 Total \$4,000,000
			Cumulative Total \$41,250,000
9	Establish Center of Excellence	10	\$500,000
	Bridge deck replacement demonstration	10	500,000
	Long span highway bridges	5	1,000,000
	Earthquake resistant demonstration	10	1,000,000
	Welding database	10	500,000
			Year 9 Total \$3,500,000
			Cumulative Total \$44,750,000
10	Establish Center of Excellence	10	\$500,000
	Bridge deck replacement demonstration	10	500,000
	Long span highway bridges	5	1,000,000
	Earthquake resistant demonstration	10	1,000,000
	Welding database	10	500,000
			Year 10 Total \$3,500,000
			Cumulative Total \$48,250,000

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Chapter 4

High-Performance Coating Materials

Many construction materials, particularly steel and concrete, are susceptible to the corrosive effects of moisture, salts and chemicals. Organic coatings provide versatile, cost-effective means for protection of structures against adverse environmental conditions. The alternatives to coatings are shortened service lives and expensive design options.

Without the protection that is currently provided by coatings, our public works infrastructure system would have had a very significant decrease in its service life. For example, a pipeline coated with a high-performance coating such as inorganic zinc can last without corrosion for forty years or more, such is the case with the Morgan-Whyhalla pipeline in Australia. By way of contrast, a poor choice of coating can lead to early corrosion after ten years, as seen with the Alaska pipeline.

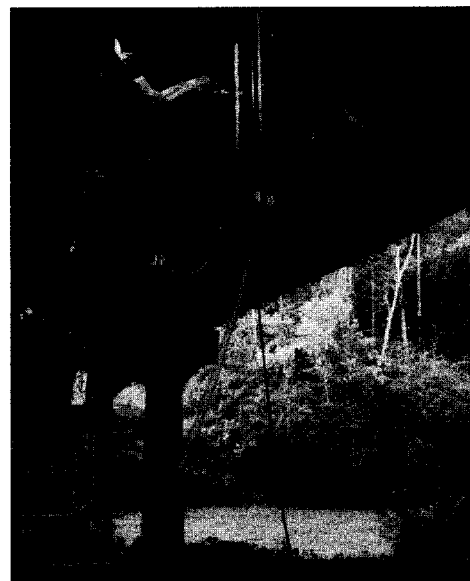
What Are High-Performance Coatings?

Engineers often use coatings in order to protect structures against corrosion and excessive wear and tear. Most coatings are thin layers of materials that are directly applied to the surfaces of structures. A coating can also serve other purposes, such as maintaining and enhancing appearance, energy conservation, or color coding for safety. Coating materials, collectively with the surface preparation methods e.g., sand blasting, and application techniques such as liquid and plasma spray procedures, make up the essence of the coating industry. High-performance coatings provide one or more of the following:

- Prolonged service life up to double that of normal coatings
- Near total prevention of corrosion
- Resistance to abrasion
- Resistance to high temperatures
- Resistance to aggressive chemicals, acids
- Resistance to high humidity
- Resistance to immersion in natural waters
- Resistance to fading/cracking caused by sunlight

Although coatings have served the construction industry well, the current state-of-the-art may not meet anticipated demands without a significant research effort. Ensuring environmental compatibility, adhesion to new and high-performance structural materials, cost-effectiveness, and energy efficient surface preparation techniques are key goals. High-performance coatings will fulfill the requirements set by the above-

Although coatings have served the construction industry well, the current state-of-the-art may not meet anticipated demands without a significant research effort.



Robotic blast cleaning on North Carolina bridge.

Courtesy of North Carolina State University

...performance relates to specific coating system attributes like temperature resistance or immunity to specific chemicals...



Example of containment ventilation system on leg of water tower.

Courtesy of Steel Structures Painting Council

mentioned prerequisites. These new materials will be life-cycle cost efficient, longer lasting, compatible with a variety of new and existing construction materials, and environmentally acceptable.

Applications of High-Performance Coatings

Coatings find use in many applications in the infrastructure. Contrasting applications like interior linings on flue gas scrubbers and exterior coatings for bridges both demand high performance. Other high-performance applications include galvanized highway guard rail and coating of concrete dikes for secondary containment of chemical process areas. Bridges, water towers, and other public structures all receive protection and life extension from high-performance coatings. High-performance coating formulations must meet extremely wide functional and protective requirements, such as resistance to different chemical and environmental conditions and suitability for different types of substrates. A major advantage of a coating is that it conforms to the shape and form of the structure requiring protection. These formulations also adapt to the varied application methods like liquid spray, powder bonding, plasma spray, dipping or immersion. Specific formulations will allow coating applications and cure under variable settings and weather conditions.

Properties and Benefits of High-Performance Coatings

Coating systems, as defined earlier, pertain to the coating materials and the surface preparation and application processes for achieving protection against premature wear and tear. Furthermore, coating systems are application specific, and they are selected according to key environmental conditions explicit to the application. Therefore, the properties of high-performance coatings vary according to the application, i.e., the function and type of structure, and the structure's service environment. In summary, performance relates to specific coating system attributes like temperature resistance or immunity to specific chemicals (e.g., sulfides and chlorines). It also includes tolerance for marginally prepared surfaces, and application under adverse environmental conditions. High performance for specific applications demands a combination of high-performance materials and processes. These include:

- Advanced surface preparation methodologies, such as laser and microwave surface cleaning techniques
- Application of multi-layered materials composed of zinc-rich primers in very corrosive environments, with polyurethane topcoats for protection against water penetration
- Advanced coating application techniques such as electrostatic or airless sprays, and robotics for specialized applications

A key characteristic of the proposed research and technology deployment program is the development of such new materials, methods, and technologies..

Development of High-Performance Coating Materials

State-of-the-art protective coatings in the infrastructure do not fit one kind or type. Some specialized coatings find use in extreme conditions. Examples include the insulating heat shield for the space shuttle, or chemically resistant linings for flue gas desulfurization units (power plant scrubbers). Such exotic coatings exhibit very high performance yet are produced in extremely small volumes. They are very expensive and not affordable for most infrastructure needs. For conventional use, the state of the art is liquid-applied two or three

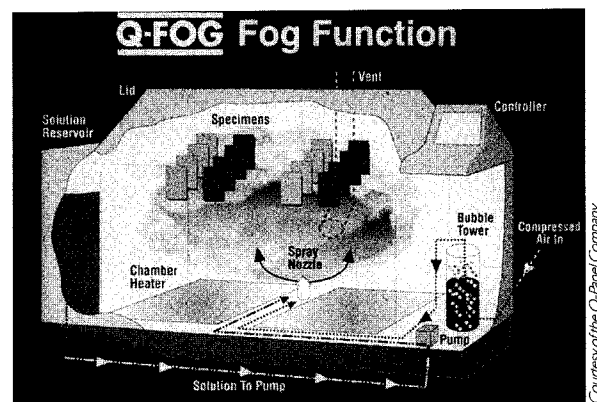
layer systems. The state-of-the-art primer coat is typically a zinc-filled silicate or a chemically cured epoxy. The topcoat is a polyurethane. Use of thermal spray metallic aluminum or zinc coatings is also increasing, particularly in military applications. Such "flame-sprayed" metallic films show very high resistance to marine corrosion.

For evaluation and prediction of performance, the ASTM B-117 salt spray test is the *de facto* standard among so-called cabinet tests. These laboratory exposures create an aggressive artificial exposure environment. Unfortunately ASTM B-117 uses a constant high temperature environment where coated panels receive a high concentration salt spray which is highly unrealistic. Cyclic corrosion accelerated tests represent the state of the art; their popularity is increasing. Cyclic tests typically use far lower concentration salt solutions to induce corrosion. In addition, these cyclic tests put coatings through wetting and drying cycles, and often incorporate exposure to humidity and ultraviolet light. Preliminary results show improved agreement between performance in the artificial test and the much longer real time exposure.

There are, however, still no accepted standards for these cyclic methods. Many users also question the reliability, relevance and accuracy of these methods. This is largely due to a lack of comparative data. Another area showing promise is nondestructive evaluation (NDE) of coating and substrate condition. Lack of availability of portable, reliable hardware for field use, or user-friendly software to process and interpret the results hinders acceptance of these newer methods. A lack of demonstration of the benefits and validity of these techniques further limits their appeal. Finally, there is considerable interest in Electrochemical Impedance Spectroscopy (EIS)—a method that probes fundamental characteristics of the coating film such as permeability. Efforts to develop portable devices receive continued scrutiny by coating test laboratories.

Air atomizing and airless spray and modifications are dominant for application equipment. Some specialized techniques include high volume, low pressure and electrostatic spray. Use of robotics is very limited, even for shop applications on structural steel. With new volatile organic compound (VOC)-compliant coatings there is also the risk of excessive film build.

Due to concerns about VOC's, most materials for protection of civil structures are now—or soon will be—VOC compliant. This has two direct impacts on coating formulation. First, coating formulations will contain less solvent. The trend is to use either high solids solvent-borne, or waterborne, water-soluble coatings. The choice will also dictate application techniques. Predicted future trends include increased use of plural component application equipment, or high volume/low pressure (HVLP) application equipment. Second, concerns about heavy metal pigments in protective or decorative coatings have fueled the movement to either find effective non-toxic substitutes for anti-corrosive pigments, or move to the use of effective barrier pigmentation in place of heavy metal, anti-corrosive pigments.



Cyclic Corrosion Tester

**Another area showing
promise is nondestructive
evaluation (NDE) of
coating and substrate
condition.**

...many highway departments of transportation have a strong need for an environmentally sound means for lead paint removal.

Centers for Research and Technology Transfer

National Institute of Standards and Technology

Army Construction Engineering Research Laboratory

Naval Service Warfare Center

Oak Ridge National Laboratories

North Dakota State University

North Carolina State University

University of Missouri-Rolla

Kent State University

Lehigh University

Carnegie Mellon University

Massachusetts Institute of Technology

Battelle Memorial Institute

Sealant, Waterproofing and Restoration Institute

Carnegie Mellon Research Institute

Pennsylvania State Applied Research Laboratory

Current Constraints to High-Performance Coating Use

The major limitations of currently used protective coating systems are mainly technical constraints. These include applying ultra-high performance materials, removing hazardous materials, improving coating durability, and evaluating performance and coating condition. Techniques for applying ultrahigh-performance materials—namely, powder epoxy coatings or thermal spray metallic powders are limited to shop-type operations. They require adaptations to field use, where there is the greatest need for application of coatings. Other required improvements include the portability and ease of use of this type of application equipment. Improved tolerance of these new coatings to field application, and their cure under variable weather conditions merits attention. Because of the prevalence of lead pigments (which are highly hazardous to workers) on many existing structures, the cost of maintenance and rehabilitation has become significant. Improved techniques are needed to remove and dispose of the lead and other hazardous materials, which will limit both worker exposure and contamination of the environment, greatly reducing maintenance costs.

In certain severe exposure environments, conventional coating systems often have limited durability. This type of service (e.g., high temperatures, salt exposure, and interiors of process vessels) demands new coating materials. In addition, the challenge is to develop materials that meet future restrictions on VOC's hazardous air pollutants (HAPS), and heavy metals. The methodology for evaluating and predicting coating performance is currently inadequate. Our understanding of the mechanisms of coating failure and degradation is progressing, but still needs improvement. Critical needs exist for improved and validated short-term testing of high-performance coatings, and for means to assess the performance of coatings in situ. However, most of these constraints can be lessened by more funded research and application.

Current Projects Demonstrating Use of High-Performance Coatings

High-performance coatings are under examination at a number of centers. The Steel Structures Painting Council (SSPC) is currently engaged in analysis of the value of flame-sprayed thermoplastic copolymers for structural steel coating repairs. This is work on behalf of the National Cooperative Highway Research Program (NCHRP). The National Aeronautics and Space Agency (NASA) is involved in two key projects. The first one (from the Cape Kennedy facility) is examining next generation waterborne inorganic zinc rich primers. The second project now in the hands of the technology transfer division is seeking development of a totally new concept in polymer coatings—conductive polymer primers. These show great promise in providing excellent protection of immersed or static structures from corrosion.

High-performance coatings and high-performance coating processes are finding use in many civil infrastructure projects. For example, highway departments of transportation have a strong need for an environmentally sound means for lead paint removal. Each lead paint removal project is a test-bed for state-of-the-art concepts in dustless surface preparation or containment. Each and every scrubber installation for a utility power plant requires high-performance coatings or linings. Many current pipeline installations now use powder deposited epoxy coatings, placed over chemically clean surfaces.

COATINGS

Prioritized Research Projects

Research Topic	Research Project	Objective	Approach	Schedule	Budget	Public Agency	Benefits
New Coating Processes	Identify Areas of Inadequacy	Provide a comprehensive review of coating materials & technologies allowing coordination of research program.	Develop a database using a mixture of literature data and data from an industry survey. Prioritize needs and potential solutions. Provide continuing refinement of research program.	3 years	\$ 0.5M	FHWA USACE USN NIST	Provides assurance that the research program dollars are well directed. Allows latest developments entry into the program.
New Coating Processes	Identify & Evaluate New Application Processes	Select best coating application techniques.	Evaluate promising solutions identified above under short term field and shop conditions.	3 years	\$ 0.8M	USN USACE	Refines the list of candidate technologies to best few.
New Coating Processes	Demonstrate New Coating Systems in Field	Select best combinations of coating processes and materials.	Evaluate best combinations of application technology and new materials in real time field exposures on actual structures at a number of exterior sites.	6 years	\$ 3.0M	FHWA USN NIST	Real time exposures reveal the truth about material performance.
New Coating Processes	New Coating Materials	Develop and evaluate new coating materials.	The focus will be on entirely new types of protective coatings meeting key goals for high performance coating materials. Examples include conductive polymer coatings to reduce corrosion, high abrasion resistance materials and photo-oxidative resistant polymers or inorganic coatings.	8 years	\$ 20.0M	USN NASA FHWA	A core activity of this program is to bring new coating technologies to market. Improved corrosion resistance and ease of use are direct benefits.
Surface Preparation & Cleanliness	Improve Existing Surface Preparation Methods	Reduce the impact of a key cost driver, surface preparation, on infrastructure maintenance.	Determine inadequacies of current surface preparation techniques. Integrate improvements from outside industries and evaluate improvements to existing techniques.	3 years	\$ 2.0M	USACE FHWA	Reduce the cost to maintain the infrastructure.
Surface Preparation & Cleanliness	Develop & Evaluate Innovative Methods for Surface Preparation	Provide new technology for surface preparation of infrastructure surfaces.	Identify new or promising surface preparation methods. Develop from benchtop ideas to demonstration projects.	5 years	\$ 5.0M	USACE FHWA	Improve coating life by eliminating contaminants that reduce coating life.
Surface Preparation & Cleanliness	Provide Objective Measures of Visible & Chemical Surface Cleanliness	Develop user friendly, operator independent methods to determine surface cleanliness.	Review existing standards for visual and chemical cleanliness of surfaces. Increase portability of NDE equipment to field.	4 years	\$ 2.0M	FHWA	Improved surface evaluation and inspection methods provide error free assurance of surface cleanliness.

Research Topic	Research Project	Objective	Approach	Schedule	Budget	Public Agency	Benefits
Application Technology	Technology Evaluation - Application Methods to Meet VOC emission requirements	Evaluate application methods ability to a) apply VOC compliant coatings, and b) increase transfer efficiency.	A parametric experimental design is proposed which examines critical film forming coating characteristics with combinations of : a) Equipment Type; b) Coating Material; c) Ambient Conditions during application and cure, and; d) uses field applications.	3 years	\$ 1.0M	USN EPA	Coating material costs are driven by inefficiencies of current application methods. Improve these while adapting techniques to new materials and costs go down.
Application Technology	New Methods Development	Bring improved methods of application from factory settings to field use.	Identify highest efficiency, lowest cost methods used in fixed facilities, adapt suitable methods to field use.	3 years	\$ 1.5M	EPA USN USACE FHWA	Reduced emissions of VOC, improvement in film quality and coating life.
Improved Durability & Performance	Accelerated Test & Service Life Predictions	To get true predictions of long term performance from short term test methods.	A reliability analysis approach is suggested. This will allow the influence of real environmental factors to be mimicked in short term laboratory tests.	10 years	\$ 8.0M	NIST USN FHWA USACE	A method to predict coating life and avoid premature failure.
Improved Performance & Durability	Improved Laboratory & Field Characterization Methods	Develop methods for characterizing coating films suitable for both laboratory and field use.	Examine the capabilities of new NDE methods for characterizing corrosion and coating fitness for service. Make new NDE methods user friendly, low cost and field suitable.	7 years	\$ 12.0M	NIST USN FHWA USACE	Provides portable, operator independent methods to assess how good is a coating material.
Improved Performance & Durability	Improved Condition Assessment Methods	Develop Standardized method & Equipment to evaluate coating condition in field.	The emphasis is to phase into field use quantitative condition assessment methods developed from above project. Use this information to develop criteria for predicting surface preparation requirements and assessing the likelihood of early failure.	5 years	\$ 3.0M	NIST FHWA USACE	Determine and improve cost effectiveness of new systems.
Improved Performance & Durability	Investigation of Relationship Between Fundamental Coating Properties & Degradation Modes	Develop relations between failure mechanisms and coating system properties to help improve system design.	A reliability analysis approach is suggested. Models relating mechanistic failure and quantitatively assessed coating condition will be developed.	10 years	\$ 8.0M	NIST USN FHWA USACE	Permit early detection and avoidance of coating failures.
Improved Performance & Durability	Atmospheric Environment - Improved Characterization	Develop improved computer aided atmospheric characterization methods.	Primary approach is to adapt existing techniques for environmental characterization to today's computer technology.	10 years	\$ 15.0M	NIST FHWA USACE	Permit more economical use of high performance coatings.

Research Topic	Research Project	Objective	Approach	Schedule	Budget	Public Agency	Benefits
Lead Paint Abatement & Removal	Improved Removal Methods for Lead Pigmented Coatings	Develop methods to remove lead pigmented coatings which improve worker safety while reducing environmental emissions and waste volumes.	Examine current techniques and problems. Focus on the use of non-traditional methods, robotics, non-blast media and recyclable media. Investigate sensor technology for determining adequacy of lead pigment removal.	5 years	\$ 3.0M	FHWA Awwarf USACE USN DOE	Reduction of lead hazards to workers and the environment.
Lead Paint Abatement & Removal	Integrated Waste Handling Processes	Provide means to enhance reuse of lead pigmented coating waste.	Identify candidate markers for lead pigmented coating waste, battery manufacture, leaded glass. Marry with removal methods which produce acceptable waste feed streams.	5 years	\$ 2.5M	EPA FHWA Awwarf USACE	Minimizes production of waste and reduces hazard to the public.
Lead Paint Abatement & Removal	Assessing Effectiveness of Overcoating Materials	Develop procedures to evaluate effectiveness of Overcoating materials.	Identify methods and criteria for characterizing new coating material, which provide techniques to show an existing structure is a good candidate for Overcoating.	4 years	\$ 2.0M	EPA FHWA USACE USN	Establish procedures and criteria for reducing long-term maintenance costs.
Lead Paint Abatement & Removal	Methods to Assess Current Condition of Lead Pigmented Coatings	Develop techniques sensors and field stress tests to determine coatability of existing lead pigmented coatings.	With a statistical sampling develop a procedure to determine coated structure characteristics by visual and instrumental means. This project can work as a sub-set of an Improved Performance research item.	8 years	\$ 4.0M	NIST USACE FHWA USN	Eliminates radical failures currently plaguing owners when repairing old lead pigmented coatings.
Coatings for Concrete	Concrete Coatability	Develop criteria and procedures for determining coatability of new and aged concrete.	Use a factorial approach to assess the influence of concrete cure, moisture content, mix design, surface preparation, coating material type and application method on short and long term coating system performance.	6 years	\$ 4.0M	ACI NIST FHWA USACE USN	Drastically reduces construction cost currently concrete is released to other crafts after a 28 day delay adding to costs.
Coatings for Concrete	Evaluation of Secondary Containment Coating Systems	Develop design criteria for coated secondary containment structures; Develop criteria to accept an existing structure for secondary containment use and coatings; Provide performance tests for selection and application of secondary containment coatings.	A three phase program is suggested to address each of the three primary objectives. The first objective demands a design approach where new structures will easily and economically receive coatings, married to compatible joint sealants in a structure designed with coating in mind. Focus will remain on early coating of the secondary containment structure. The second phase approach is to examine current standards for assessing concrete soundness and coatability. Find & evaluate new methods for concrete condition assessment and develop the needed criteria for structure acceptance. The third phase approach is to look at existing and new tests which provide assurance of long term performance of the secondary containment coating system.	5 Years Phase I - 1.5 Years \$ 0.75M Phase II - 2.5 Years \$ 1.5M Phase III - 3 Years \$ 1.5M	\$ 3.75M	EPA DOE USACE USN	This project will deliver three benefits: Reduced likelihood of damaging the environment by spills from secondary containment failure. Clear performance criteria to permit successful use of coatings on older adapted containment areas. Containment coatings which last for longer periods of time, resulting in significant cost savings.

Research Topic	Research Project	Objective	Approach	Schedule	Budget	Public Agency	Benefits
Coatings for Concrete	Standards for Prepared Concrete Surfaces	Develop visual and instrumental standards for concrete surface preparation.	Examine existing written and visual concrete surface preparation standards. Assess inadequacies of current standards. Create visual and instrumental methods to depict concrete surface cleanliness.	6 Years	\$ 1.2M	NIST USACE USN	Improves coating lifetime and reduces early costly failures.
Data & Cost Analysis	Standard Data Forms & Procedures	Develop standard data forms and reporting procedures for databases and expert systems.	Identify types of information to characterize coating lifetime, performance. Provide data forms for cost model data entry. Acquire and enter data on coating performance.	5 Years	\$ 2.5M	NIST	Provides basic data for evaluating and confirming material and technology.
Data & Cost Analysis	Expert System for Coating Lifetime Prediction	Develop model & expert system to predict coating lifetime.	Use data from standard data forms project along with decision criteria developed under condition assessment projects - (Lead Paint Abatement & Improved Durability topics) - and create an expert system to aid engineers in assessing coating material selection and maintenance issues.	5 Years	\$ 2.5M	NIST EPA FHWA	Provide long sought means to identify best performing coating system.
Data & Cost Analysis	Engineering Management System	Develop protocols and data for engineered management of coated structures.	A knowledge based approach is urged. The expert system above will form the core tool for this project. Refine the expert system model and assumptions to encompass the lifetime of the structure. Focus is on key structures e.g. bridges, tanks, buildings and allows distinction between new and existing structures.	3 Years	\$ 1.5M	NIST	Provide tool for more cost effective design and selection of corrosion protection.
Technology Transfer	Guide Material Standardization	Develop standard guides and procedures for successful use of high performance coating systems.	Define need for new standards including surface preparation, application, materials, inspection. Meet these needs by developing the standards in cooperation with consensus standard setting bodies.	4 years	\$ 1.5M	NIST	Standards convey credibility to new technology and encourages its use.
Technology Transfer	Electronic Clearinghouse & Hotline	Establish electronic clearinghouse and computer aided hotline for high performance coating research dissemination.	Three approaches are suggested: a) Creation and maintenance of an Internet-based suite of client server tools to allow inquiries of the knowledge based expert system. b) Creation and manning of a hotline with a Fax-Back service on high performance coating research and use. c) Creation and manning of a hotline with human technical assistance.	5 years	\$ 1.2M	NIST USN FHWA	Eases acceptance of new products and processes, by making information available.

Research Topic	Research Project	Objective	Approach	Schedule	Budget	Public Agency	Benefits
Technology Transfer	Training & Educational Programs	Provide seminars, pre-packaged teaching aids and on site training in the use of high performance coatings and processes.	The approach will initially favor those areas of interest deemed most urgent: Improved worker safety & health in lead pigmented coating removal, meeting environmental regulations, and; Use and application of new high performance coating systems and processes. The scope includes continuous updating of material.	5 years	\$ 2.5M	EPA OSHA DOE DOT	Provide skilled, knowledgeable force of designers, engineers and trade mechanics.
Technology Transfer	Video Tapes, Publications & Other Media	Provide informational pieces on the high performance coatings research program and its results.	The approach is to focus on the production of a mixture of video tapes, computer video presentations, (Multimedia) and written research highlights from the research.	5 years	\$ 1.5M	EPA DOE DOT	Provide easy to use materials to allow rapid introduction of new technology.
Technology Transfer	Demonstration Projects	Provide test cases of the research program work products in real applications.	It is critical that the research product see commercial application. To facilitate this the researchers will work hand-in-hand with interested industrial partners and government agencies to help bring products and technologies to the marketplace.	6 years	\$ 35.0M	DOT DOE FHWA USACE USN	Shows engineers that the research product is real, useful and cost saving.
Total Program Outlay					\$150.45 M		

Coatings Prioritized Timeline and Budget Allocation

Year	Project	Duration (in years)	Cost
1	Atmospheric environment - Improved Characterization	10	\$1,500,000
	Improved Laboratory & Field Characterization Methods	7	1,714,000
	Accelerated Test & Service Life Predictions	10	800,000
	Investigation of Relationship Between Fundamental Coating Properties & Degradation Modes	10	800,000
	Improve Existing Surface Preparation Methods	3	667,000
	Assessing Effectiveness of Overcoating Materials	4	500,000
	Standard Data Forms & Procedures	5	500,000
	Identify & Evaluate New Application Processes	3	356,000
	Identify Areas of Inadequacy	3	167,000
	Year 1 Total \$7,004,000 Cumulative Total \$7,004,000		
2	Atmospheric environment - Improved Characterization	10	\$1,500,000
	Improved Laboratory & Field Characterization Methods	7	1,714,000
	Accelerated Test & Service Life Predictions	10	800,000
	Investigation of Relationship Between Fundamental Coating Properties & Degradation Modes	10	800,000
	Improve Existing Surface Preparation Methods	3	667,000
	Assessing Effectiveness of Overcoating Materials	4	500,000
	Standard Data Forms & Procedures	5	500,000
	Identify & Evaluate New Application Processes	3	356,000
	Identify Areas of Inadequacy	3	167,000
	New Coating Materials	8	2,500,000
	Develop & Evaluate Innovative Methods for Surface Preparation	5	1,000,000
	Concrete Coatability	6	667,000
	Improved Removal Methods for Lead Pigmented Coatings	5	600,000
	Integrated Waste Handling Processes	5	500,000
	Expert System for Coating Lifetime Prediction	5	500,000
	Improved Condition Assessment Methods	5	600,000
	Technology Evaluation - Application Methods to Meet VOC emission requirements	3	333,000
	Year 2 Total \$13,704,000 Cumulative Total \$20,708,000		

Year	Project	Duration (in years)	Cost
3	New Coating Materials	8	\$2,500,000
	Atmospheric environment - Improved Characterization	10	1,500,000
	Improved Laboratory & Field Characterization Methods	7	1,716,000
	Develop & Evaluate Innovative Methods for Surface Preparation	5	1,000,000
	Accelerated Test & Service Life Predictions	10	800,000
	Investigation of Relationship Between Fundamental Coating Properties & Degradation Modes	10	800,000
	Evaluation of Secondary Containment Coating Systems	5	750,000
	Concrete Coatability	6	667,000
	Improved Removal Methods for Lead Pigmented Coatings	5	600,000
	Improve Existing Surface Preparation Methods	3	666,000
	Assessing Effectiveness of Overcoating Materials	4	500,000
	Standard Forms & Procedures	5	500,000
	Integrated Waste Handling Processes	5	500,000
	Expert System for Coating Lifetime Prediction	5	500,000
	Provide Objective Measures of Visible & Chemical Surface Cleanliness	4	500,000
	Methods to Assess Current Condition of Lead Pigmented Coatings	8	500,000
	Demonstrate New Coating Systems in Field	6	500,000
	Improved Condition Assessment Methods	5	600,000
	Guide Material Standardization	4	375,000
	Technology Evaluation - Application Methods to Meet VOC emission requirements	3	334,000
	Electronic Clearinghouse & Hotline	5	240,000
	Identify Areas of Inadequacy	3	166,000
	Identify & Evaluate New Application Processes	3	88,000
Year 3 Total			\$16,302,000
Cumulative Total			\$37,010,000

Year	Project	Duration (in years)	Cost
4	Demonstration Projects	6	\$5,834,000
	New Coating Materials	8	2,500,000
	Atmospheric environment - Improved Characterization	10	1,500,000
	Improved Laboratory & Field Characterization Methods	7	1,714,000
	Develop & Evaluate Innovative Methods for Surface Preparation	5	1,000,000
	Accelerated Test & Service Life Predictions	10	800,000
	Investigation of Relationship Between Fundamental Coating Properties & Degradation Modes	10	800,000
	Evaluation of Secondary Containment Coating Systems	5	750,000
	Concrete Coatability	6	666,000
	Improved Removal Methods for Lead Pigmented Coatings	5	600,000
	Assessing Effectiveness of Overcoating Materials	4	500,000
	Standard Forms & Procedures	5	500,000
	Integrated Waste Handling Processes	5	500,000
	Expert System for Coating Lifetime Prediction	5	500,000
	Provide Objective Measures of Visible & Chemical Surface Cleanliness	4	500,000
	Methods to Assess Current Condition of Lead Pigmented Coatings	8	500,000
	Demonstrate New Coating Systems in Field	6	500,000
	Training & Educational Programs	5	500,000
	New Methods Development	3	500,000
	Improved Condition Assessment Methods	5	600,000
	Guide Material Standardization	4	375,000
	Technology Evaluation - Application Methods to Meet VOC emission requirements	3	333,000
	Video Tapes, Publications & Other Media	5	300,000
	Electronic Clearinghouse & Hotline	5	240,000
	Standards for Prepared Concrete Surfaces	6	200,000
Year 4 Total			\$22,712,000
Cumulative Total			\$59,722,000

Year	Project	Duration (in years)	Cost
5	Demonstration Projects	6	\$5,833,000
	New Coating Materials	8	2,500,000
	Atmospheric environment - Improved Characterization	10	1,500,000
	Improved Laboratory & Field Characterization Methods	7	1,714,000
	Develop & Evaluate Innovative Methods for Surface Preparation	5	1,000,000
	Accelerated Test & Service Life Predictions	10	800,000
	Investigation of Relationship Between Fundamental Coating Properties & Degradation Modes	10	800,000
	Evaluation of Secondary Containment Coating Systems	5	750,000
	Concrete Coatability	6	667,000
	Improved Removal Methods for Lead Pigmented Coatings	5	600,000
	Standard Forms & Procedures	5	500,000
	Integrated Waste Handling Processes	5	500,000
	Expert System for Coating Lifetime Prediction	5	500,000
	Provide Objective Measures of Visible & Chemical Surface Cleanliness	4	500,000
	Methods to Assess Current Condition of Lead Pigmented Coatings	8	500,000
	Demonstrate New Coating Systems in Field	6	500,000
	Training & Educational Programs	5	500,000
	New Methods Development	3	500,000
	Improved Condition Assessment Methods	5	600,000
	Guide Material Standardization	4	375,000
	Video Tapes, Publications & Other Media	5	300,000
	Electronic Clearinghouse & Hotline	5	240,000
	Standards for Prepared Concrete Surfaces	6	200,000
Year 5 Total			\$21,879,000
Cumulative Total			\$81,601,000

Year	Project	Duration (in years)	Cost
6	Demonstration Projects	6	\$5,834,000
	New Coating Materials	8	2,500,000
	Atmospheric environment - Improved Characterization	10	1,500,000
	Improved Laboratory & Field Characterization Methods	7	1,714,000
	Develop & Evaluate Innovative Methods for Surface Preparation	5	1,000,000
	Accelerated Test & Service Life Predictions	10	800,000
	Investigation of Relationship Between Fundamental Coating Properties & Degradation Modes	10	800,000
	Evaluation of Secondary Containment Coating Systems	5	750,000
	Concrete Coatability	6	666,000
	Improved Removal Methods for Lead Pigmented Coatings	5	600,000
	Integrated Waste Handling Processes	5	500,000
	Expert System for Coating Lifetime Prediction	5	500,000
	Provide Objective Measures of Visible & Chemical Surface Cleanliness	4	500,000
	Methods to Assess Current Condition of Lead Pigmented Coatings	8	500,000
	Demonstrate New Coating Systems in Field	6	500,000
	Training & Educational Programs	5	500,000
	Engineering Management System	3	500,000
	New Methods Development	3	500,000
	Improved Condition Assessment Methods	5	600,000
	Guide Material Standardization	4	375,000
	Video Tapes, Publications & Other Media	5	300,000
	Electronic Clearinghouse & Hotline	5	240,000
	Standards for Prepared Concrete Surfaces	6	200,000
			Year 6 Total \$21,879,000
			Cumulative Total \$103,480,000

Year	Project	Duration (in years)	Cost
7	Demonstration Projects	6	\$5,833,000
	New Coating Materials	8	2,500,000
	Atmospheric environment - Improved Characterization	10	1,500,000
	Improved Laboratory & Field Characterization Methods	7	1,714,000
	Accelerated Test & Service Life Predictions	10	800,000
	Investigation of Relationship Between Fundamental Coating Properties & Degradation Modes	10	800,000
	Evaluation of Secondary Containment Coating Systems	5	750,000
	Concrete Coatability	6	667,000
	Methods to Assess Current Condition of Lead Pigmented Coatings	8	500,000
	Demonstrate New Coating Systems in Field	6	500,000
	Training & Educational Programs	5	500,000
	Engineering Management System	3	500,000
	Video Tapes, Publications & Other Media	5	300,000
	Electronic Clearinghouse & Hotline	5	240,000
	Standards for Prepared Concrete Surfaces	6	200,000
			Year 7 Total \$17,304,000
			Cumulative Total \$120,784,000
8	Demonstration Projects	6	\$5,833,000
	New Coating Materials	8	2,500,000
	Atmospheric environment - Improved Characterization	10	1,500,000
	Accelerated Test & Service Life Predictions	10	800,000
	Investigation of Relationship Between Fundamental Coating Properties & Degradation Modes	10	800,000
	Methods to Assess Current Condition of Lead Pigmented Coatings	8	500,000
	Demonstrate New Coating Systems in Field	6	500,000
	Training & Educational Programs	5	500,000
	Engineering Management System	3	500,000
	Video Tapes, Publications & Other Media	5	300,000
	Standards for Prepared Concrete Surfaces	6	200,000
			Year 8 Total \$13,933,000
			Cumulative Total \$134,717,000

Year	Project	Duration (in years)	Cost
9	Demonstration Projects	6	\$5,833,000
	New Coating Materials	8	2,500,000
	Atmospheric environment - Improved Characterization	10	1,500,000
	Accelerated Test & Service Life Predictions	10	800,000
	Investigation of Relationship Between Fundamental Coating Properties & Degradation Modes	10	800,000
	Methods to Assess Current Condition of Lead Pigmented Coatings	8	500,000
	Standards for Prepared Concrete Surfaces	6	200,000
	Year 9 Total \$12,133,000 Cumulative Total \$146,850,000		
10	Atmospheric environment - Improved Characterization	10	\$1,500,000
	Accelerated Test & Service Life Predictions	10	800,000
	Investigation of Relationship Between Fundamental Coating Properties & Degradation Modes	10	800,000
	Methods to Assess Current Condition of Lead Pigmented Coatings	8	500,000
	Year 10 Total \$3,600,000 Cumulative Total \$150,450,000		

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Chapter 5

Fiber-Reinforced Polymer Composites

Fiber-reinforced polymer (FRP) composite materials and structures are one of the key advanced technologies offering potential performance, life cycle and installed cost advantages for civil infrastructure renewal. This technology is currently practiced extensively in eight major market areas: transportation, corrosion-resistant equipment, consumer and recreation products, electrical and electronic equipment, construction applications, appliance and equipment parts, and marine and aerospace/defense products. In addition, over the last 25 years, hundreds of thousands of underground metal storage tanks have been replaced with fiber-reinforced composite structures, which now claim over 90 percent market share.

What are FRP Composites?

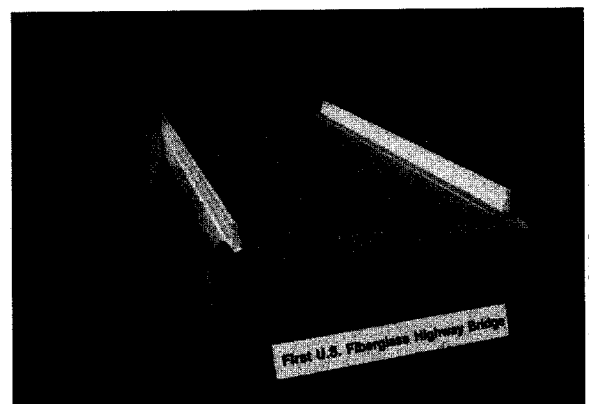
Composite materials are created through the combination of two or more materials. In the case of fiber-reinforced and some other composites, one serves as the reinforcement for the other which serves as the matrix. The reinforcement provides the primary strength, and the matrix holds the reinforcement in its proper orientation to give optimum properties. The first known use of man-made composite materials involved making bricks of straw and clay. An example of composite use in the construction industry is the use of steel reinforcing bars (rebars) in a concrete matrix.

Over the past 50 years, scientists and engineers have developed man-made fibers (glass, boron, carbon, and aramid) and polymer resins (thermoplastic/thermoset of a variety of chemical compositions) which go into making a new high-performance class of materials - fiber-reinforced polymer matrix composites—that can be designed to give unique combinations of light weight, high strength, high stiffness, strong resistance to corrosion, resistance to fatigue, and parts consolidation.

Applications of FRP Composites

These materials, through tailored design, have a consistent track record of providing better product performance than conventional materials for applications ranging from space flight vehicles and missiles, military and commercial aircraft, automotive components, and boats to consumer and industrial applications. For example, FRP composites can be used in bridge decks, offshore oil platforms, water treatment plant components, and in marine infrastructure systems. To date, FRP composites have been used in the construction industry for largely non-structural applications (panels, glazing, bathtubs). One notable exception is underground storage tanks. As noted above, over the last 25 years, hundreds of

...a new high-performance class of materials—fiber-reinforced polymer matrix composites—can be designed to give unique combinations of light weight, high strength, high stiffness, strong resistance to corrosion, resistance to fatigue, and parts consolidation.



This three-piece modular bridge is factory produced, road transportable, and is installed in 8 hours.

Courtesy of Polymer Bridge Systems, Inc.

This market shift did not come easily; it took a substantial amount of communication between the composites industry and construction industry followed by a significant amount of product development, structural engineering, and manufacturing process development to optimize the product and cost effectiveness.



Composite marine fender piling that uses 100 percent recycled polymer.

Courtesy of Seaward International, Inc.

thousands of underground metal storage tanks have been replaced with FRP composite tanks. This market shift did not come easily; it took a substantial amount of communication between the composites industry and construction industry followed by a significant amount of product development, structural engineering, and manufacturing process development to optimize the product and cost effectiveness.

Properties and Benefits of FRP Composites

FRP composites should be attractive to designers, builders, and users of civil engineering structures for a number of reasons. FRP composites offer the following possible attributes:

- High strength
- Light weight
- High strength-to-weight ratio
- Corrosion resistance
- High dielectric strength (electrical resistance)
- Design flexibility
- Parts consolidation
- Low tooling and finishing costs
- Color and finish molded-in
- Low-to-no maintenance
- Installed cost savings

These properties translate to many advantages both in initial construction and life cycle maintenance and repair. Another important benefit is the ability to produce large, complex structural parts that will result in increased reliability, improved productivity, and reduced job-site labor.

Development of FRP Composites

The process of applying composite technology to civil infrastructure problems is occurring worldwide. In fact, Japan, China and Europe are making a significantly greater investment in this technology than the United States. At present the Japanese have installed and are evaluating an estimated 150 composite demonstration projects including bridges, buildings, and a variety of seismic retrofits.

In the United States, industry, academe, and government partnerships have initiated a variety of demonstration projects focusing on bridges, bridge component parts for retrofit and repair, concrete reinforcement (rebars, tendons, grids, and cable stays), marine infrastructure (pilings, bumpers and fenders) and seismic building upgrades. While these efforts are making significant progress in demonstrating the value of, and creating interest in these technologies by the users (largely government customers like the U.S. Department of Transportation, Army Corps of Engineers, and others), a more comprehensive, industry, academe, and government coordinated program is essential to ensure widespread commercialization.

Current Constraints to FRP Composite Use

Constraints on implementation of the proposed plan for FRP composites in civil engineering fall into two general categories: (1) Technical and (2) Institutional. Because the nature of the two types of constraints is so different, each is treated separately below.

Technical Constraints

The composites industry has a high level of confidence that composites can be developed for civil engineering end-use applications. As with other material groups, the goals of the proposed FRP composites program are to create innovative new technologies to produce structural composite products that are technically superior and commercially viable. The realities of the construction/civil engineering market require that to meet these goals, structural composite products must be cost competitive or lower in cost on a first-cost (installed or built-cost) basis, provide significant life-cycle cost advantages and be constructed, at least for the first several product generations, in accordance with traditional industry practices.

To achieve these goals, it will be necessary to develop new fabricating/manufacturing processes which reduce cost, provide factory-built quality with large structural part geometry and be road transportable and readily fabricated or erected in the field. By and large, these manufacturing processes do not exist today. Inability to develop the required composites fabricating technology could severely hinder the industry in reaching these goals.

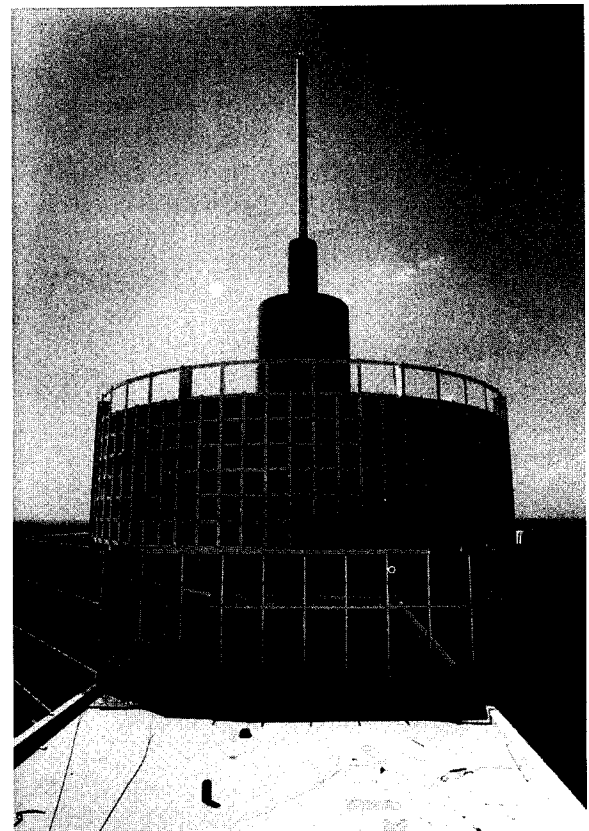
Also, because most FRP composite materials (resins, reinforcements and related constituent materials) were developed for other end-use applications, they are not optimized for civil engineering/construction applications. Additional work is required in the areas of reduced VOC's, improved fire/smoke resistance and ability to sustain high levels of structural loading over time. Failure to achieve an acceptable level of technology in the first phases of the composites development program could severely limit application of composite technology to civil engineering applications.

Institutional Constraints

Probably more troublesome in potential than the technical constraints noted above is the prospect that the U.S. civil engineering community will be unwilling or unable to make widespread use of structural composite technology in building bridges, roads, piers, utility structures, buildings, etc. The conservative nature of the industry coupled with fear of liability and lack of 50-years of in-place structural performance data may prohibit even the most visionary and creative of practitioners from taking the first steps with structural composites.

The composites industry faces constraints that differ from the steel and concrete industry. Currently, there is little or no interface with the civil engineering/construction industry. This places a high priority on the communications between the two industries to learn the endusers' needs and the suppliers' capabilities, and on an effective technical transfer mechanism to disseminate information broadly and quickly. While the application of fiber-reinforced

...it will be necessary to develop new fabricating/manufacturing processes which reduce cost, provide factory-built quality with large structural part geometry, be road transportable and readily fabricated or erected in the field.



"Wedding Cake" communicating tower for St. Luke's Medical Center is low maintenance and radio-frequency transparent.

Courtesy of Creative Pultrusions, Inc.

composite technologies to civil infrastructure problems ultimately may offer high rewards to the entire product value chain: the material suppliers, part fabricators, construction industry and the final users, there are major knowledge and communications gaps today between the composites and construction industries that prevent the use of these materials in solving our civil infrastructure problems.

An FRP Composites-Government Partnership

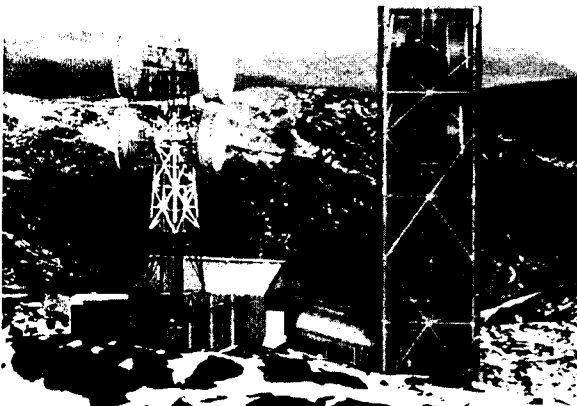
The goal of the proposed composites implementation plan is to capitalize on existing U.S. technical superiority in high-tech composite materials and combine them with the talents of our civil engineering/construction industry. Strong partnerships between industry, academe and government are required to succeed. Government at the federal, state and local levels has two major roles in this effort. The first is as an enabler to help close the technology gap between the two industries by supporting the partnership programs such as ARPA's Technology Reinvestment Project, NIST's Advanced Technology Program and NSF's basic infrastructure effort. The second role is for government to serve as the influential first customer, sharing with industry the risk of bringing new technology to the marketplace. The proposed program to develop and apply FRP composites to rebuild and upgrade the nation's civil infrastructure has four key areas:

- Use the best existing technology to demonstrate FRP composite product performance, accelerate end-use customer interest and create the framework for developing products specifically for the construction industry
- Develop cost effective, quality manufacturing processes and construction systems for FRP composites
- Develop codes and standards required for widespread use of the technology
- Educate the supplier and user communities on both manufacturing and construction system technologies

Each of the four key thrusts in the plan is organized for Near Term (2-4 years), Intermediate Term (5-7 years) and Long Term (8-10 years) deliverables. The ability to deliver near-term benefits is necessary to develop and sustain support and interest from both industry and government. However the process to establish a new industry segment is an iterative effort. Success in initial product demonstrations will start a chain of reactions in the development of cost effective, quality manufacturing and construction systems and all the other processes necessary for eventual success. A nationally coordinated program effort will provide the framework for all elements necessary for commercialization.

The program is directed at bridge structures, a range of marine infrastructure products, concrete repair and upgrade, and building retrofit and repair. This does not exclude other areas, but represents the highest level of current interest by a range of materials suppliers, fabricators and potential endusers. Greater detail on the proposed program from near, intermediate and long term efforts is given in the project descriptions below.

The program is directed at bridge structures, a range of marine infrastructure products, concrete repair and upgrade, and building retrofit and repair.



Arctic construction communications tower erected in one-third the time as compared with conventional construction materials and systems.

Courtesy of Creative Alloys, Inc.

Successful commercialization of FRP composite structures in civil infrastructure applications requires an industry-government partnership, with government often acting both as the influential first customer and as a technology enabler. Comparable to the strategies of other material programs, three specific actions are essential to the efforts in FRP composite commercialization:

1. Continue the government partnership programs (like TRP, ATP, the Army's CPAR, others) that allow industry, academe and government to collaborate in a competitive, but lower risk environment to develop composite products, manufacturing processes, and construction systems. Continue to fund academe composite/construction interdisciplinary programs through the National Science Foundation. **The government is acting as a technology enabler in this role.**
2. Modify user agency procurement policies to encourage the inclusion of innovative technologies in new and rehabilitation construction projects. (One example would be for the U.S Department of Transportation to encourage through funding incentives to State Departments of Transportation to support composite demonstration projects and integrate composite products into low risk construction areas). **The government is acting as the influential first customer in this role.**
3. Support industry-led, government, industry, academe coordination (as recommended in this report) of fiber-reinforced composite infrastructure programs in a way that enhances enduser understanding and reduces risk to all parties in the value chain.

FRP Composite Infrastructure Product Focus Areas

Category	Item (Accepted Practice)
Direct substitutions (application specific)	Pedestrian & small traffic bridges Marine pilings, fenders, bulkheads Reinforcing rods & suspension cables Industrial stacks & liners
Structural rehabilitation (application specific)	Seismic retrofit of bridge columns and selected building components Water treatment plant components Bridge deck retrofit
Innovative standardized structural elements	Bridge decks & other systems components Marine infrastructure systems Off shore oil platform components Modular water & waste treatment systems Dams Lock components
Structural rehabilitation	Structural cladding In-situ repair of original equipment (O.E.) structures
Modular, standardized structural components	Large bridges
Modular standardized rehabilitation systems	Columns Decks Joints Buildings

COMPOSITES

Prioritized Research Projects

Research Topic	Research Project	Objective	Approach	Schedule	Budget	Public Agency	Benefits
Structural Behavior of Composites	Long-Term Structural Behavior of FRP Composites	Determine the structural performance of FRP composites under sustained loads.	Characterize the long-term structural behavior of FRP composites in typical civil engineering application loadings, loaded conditions, (i.e. compressive, tensile, development flex, etc.) as would be required for common structural elements (columns, beams, plates, etc.). A variety of composite combinations (reinforcements, resins, fillers/additives, process variants, etc.) must be investigated to yield a suitable technical "envelope" of structural performance. Over 400,000 hours of structural testing is contemplated to verify the composite performance envelope.	9 years	\$35.0M	NIST NSF USACE FHWA USAF	Establish long-term structural data base for design and code development.
Accelerated Test Methods	Correlation of Real-Time Structural Performance with Accelerated Test Methods	Establish a high degree of correlation between accelerated test methods and long term FRP composite structural behavior.	Develop new accelerated test methods for five-year prediction of properties retention (tensile, compression, flexural, etc.) which have high correlation with long real-time in-situ structural performance. Composite materials must be tested in dry, wet, loaded and unloaded conditions to establish correlation of long-term performance with shorter-term accelerated test method results.	5 years	\$25.5M	NIST NSF	Assure structural safety in constructed facilities.
Design Data Base	Design Data Base Generation	Create a design data base using long-term structural behavior and suitable for common civil engineering structures.	Using long-term structural behavior and validation of properties retention, create a new FRP composites civil engineering design data base. Data base must be user-friendly, and in a format which is compatible with traditional civil engineering practices. Develop new technology for measuring real-time performance of structures in-service.	3 years	\$30.0M	NIST NSF USACE FHWA	Facilitate T2, demonstrations and commercial acceptance of FRP products.

Research Topic	Research Project	Objective	Approach	Schedule	Budget	Public Agency	Benefits
Quality Control/ Quality Assurance	QA/QC Protocols	Develop suitable quality control practices to assure that composite structural are manufactured in accordance with standards & specifications which are acceptable to the U.S. civil engineering and regulatory/code community.	Establish new QA/QC procedures and tests to prove that structural composites meet rigorous civil engineering codes and standards. QA/QC development is a critical issue as the U.S. civil engineering community is unfamiliar with these materials and will demand a higher level of testing and disclosure before applying composite materials technology to the problems of civil structures. Groups including ASCE, CERF, ACI, AASHTO, ASTM, etc. must be involved in this process from the first stages.	4 years	\$11.5M	NIST NSF	Supports and confirms the new design data base production and customer acceptance of composite structural products.
Manufacturing Process Development	New Composite Fabricating Processes	Develop new and optimized composite fabricating processes for large structural shapes, sophisticated fiber architecture placement, high reinforcement content, low VOC's, possible field-compatible and low production costs.	Investigate alternative composite manufacturing/fabrication processes which can achieve the technical goals spelled out in the projects objectives statement. Key to this process development task is creating a new type of process or a family of processes which are well-suited for either factory or field (job-site) conditions. Since one of the most important benefits of new structural composites is the potential for creating large consolidated structural parts to improve performance, increase productivity and reduce costs, the ability to fabricate as much of the structure (bridge, pier, concrete reinforcement, etc.) at the job site could have a dramatic positive effect on overall first constructed costs. Such composite fabrication processes do not presently exist, and must be developed in this phase & task.	5 years	\$45.0M	NIST NSF USACE FHWA	Permits first-cost competitive products to be fabricated either in the factory or in the field.
Attachments And Structural Terminations	Connectivity and Optimized Load-Bearing	Design and develop a new family of structural connections, joints and end fittings capable of achieving and transmitting the full structural capability of structural composites.	Now methods are required for attaching, gripping and termination of structural composites, (beams, tendons, etc.) in the regimes of near-optimum fiber strength. Examples include anchors and tensioning devices for pre-stressed and post-tensioned concrete structures as well as connections between composites or traditional materials in columns, beams and decking (plates).	4 years	\$25.0M	NIST NSF DOE USACE USAF	Optimized connections will permit more cost-effective types of structures as will reduce life-cycle costs of constructed facilities through lower maintenance.

Research Topic	Research Project	Objective	Approach	Schedule	Budget	Public Agency	Benefits
"Smart" Sensor Composites	Embedded Particle Tag Technology	Establish a new level of structural performance assurance through the embedding of minute particle "tags" which can be interrogated to provide essential manufacturing, QA/QC and structural history data.	Generate "smart" sensor technology for in-situ monitoring of manufacturing QA/QC, structural behavior, structural history and warning of incipient damage or pending structural failure. The technology comprises embedding micron-sized particle tags which can be interrogated via external non-destructive means to determine the structure's vital information. This is a major technology to increase U.S. civil engineering community confidence and for shortening time -to-market for structural composites.	6 years	\$15.75M	NIST NSF USACE FHWA USN DOE USAF	Increases safety assurances, builds a real-time structural data base in association with the Design Data Base task.
Polymer Matrix Development	Optimized Polymer Resin Matrix Systems	Demonstrate a new generation of optimized polymer resin matrices developed specifically to meet the requirements of civil infrastructure products and services.	Investigate, develop and demonstrate new structural composite polymer matrix resins. These resins should have zero to low volatile organic compound (VOC) emissions, be capable of high retention of all key structural properties in highly stressed states, improved chemical resistance (particularly to alkali) and fire/smoke resistance equal to or greater than reinforced concrete.	6 years	\$20.0M	NIST NSF	Improved structural performance, greater durability of structures, increased safety, low first and life-cycle costs.
Reinforcement Development	Optimized Fiber Reinforcement Systems	Demonstrate new forms of fiber reinforcement to optimize structural performance in civil infrastructure product applications.	Investigate, develop and demonstrate new reinforcements and new forms of reinforcement to retain properties under high strain loadings, exhibit ductility or pseudo-ductility vs. brittle failure modes, provide greater resistance to moisture and chemical environments (alkali). New fiber architectures must be compatible with manufacturing process development in Manufacturing Process Development task (above).	6 years	\$25.0M	NIST NSF	Improved structural performance, greater durability of structures, increased safety, low first and life-cycle costs.

Research Topic	Research Project	Objective	Approach	Schedule	Budget	Public Agency	Benefits
Prototyping and Structural Demonstration	* Full-Scale Structural Demonstrations of Composites in Civil Infrastructure	Demonstrate the technical superiority and commercial viability of several classes of civil infrastructure applications.	Conduct national and regional composite demonstration projects. Each project will provide valuable experience with long-term durability, field installation, first cost and life-cycle cost data. Each project will be developed and constructed under the guidance of an Advisory Board comprising government, practitioner and regulatory community representatives. Each structure will be designed in accordance with existing codes and specifications, instrumented with sensors and data-gathering devices, and cost-tracked at each stage. Examples of facilities to be built include: • 10-to-12 short span (<60 ft.) vehicular highway bridges • 4-to-10 bridge decks 6-top-10 waterfront piers • Electrical transmission towers • Composite utility poles • Composite fender piles, sheet piles (bulkheading) and bearing piles • Composite-reinforced concrete highway • Composite-reinforced asphalt highway • Residential construction • Building slab floors • Curtain wall & panels and related structures • Restore railroad ties • Composite systems to repair and upgrade deteriorated concrete structures including bridges, piers, highways. • Lumber substitutes	10 years	\$650.0M	NIST NSF USACE USN USAF Coast Guard DOD HUD DOT DOE	Develop credible proof that structural composites provide first-cost effective solutions to the problems of U.S. infrastructure renewal. Provide the U.S. with commanding international commercial leadership. Provide jobs while revitalizing the U.S. infrastructure. Save both first cost and long-term costs by using durable, low maintenance composites.
Total Program Outlay					\$882.75M		

* Activities associated with this deal primarily with issues that would traditionally be considered Technology Transfer (T2) and commercialization. However, since structural composites are viewed by the U.S. civil engineering community largely as unproven materials, a higher-than-normal level of demonstration, long-term monitoring as well as national/regional showcasing will be required to accelerate market acceptance. The Composites Working Group feels that this is an incremental need which is unique to composites material technology.

Composites Prioritized Timeline and Budget Allocation

Year	Project	Duration (in years)	Cost
1	Structural Behavior of Composites	9	\$5,000,000
	Accelerated Test Methods	5	3,000,000
	Smart Sensor Composites	6	2,000,000
	Prototyping and Structural Demonstration	10	25,000,000
Year 1 Total \$35,000,000			Cumulative Total \$35,000,000
2	Structural Behavior of Composites	9	\$7,000,000
	Accelerated Test Methods	5	5,000,000
	Manufacturing Process Development	5	9,000,000
	Smart Sensor Composites	6	3,000,000
	Polymer Matrix Development	6	3,000,000
	Reinforcement Development	6	6,000,000
	Prototyping and Structural Demonstration	10	30,000,000
Year 2 Total \$63,000,000			Cumulative Total \$98,000,000
3	Structural Behavior of Composites	9	\$7,000,000
	Accelerated Test Methods	5	10,000,000
	Design Data Base	3	11,000,000
	Quality Control/Quality Assurance	4	2,000,000
	Manufacturing Process Development	5	12,000,000
	Attachments & Structural Terminations	4	5,000,000
	Smart Sensor Composites	6	3,000,000
	Polymer Matrix Development	6	5,000,000
	Reinforcement Development	6	6,000,000
	Prototyping and Structural Demonstration	10	50,000,000
Year 3 Total \$111,000,000			Cumulative Total \$209,000,000
4	Structural Behavior of Composites	9	\$6,000,000
	Accelerated Test Methods	5	4,000,000
	Design Data Base	3	10,000,000
	Quality Control/Quality Assurance	4	3,000,000
	Manufacturing Process Development	5	10,000,000
	Attachments & Structural Terminations	4	5,000,000
	Smart Sensor Composites	6	4,000,000
	Polymer Matrix Development	6	5,000,000
	Reinforcement Development	6	4,000,000
	Prototyping and Structural Demonstration	10	160,000,000
Year 4 Total \$211,000,000			Cumulative Total \$420,000,000

Year	Project	Duration (in years)	Cost
5	Structural Behavior of Composites	9	\$5,000,000
	Accelerated Test Methods	5	3,500,000
	Design Data Base	3	9,000,000
	Quality Control/Quality Assurance	4	3,000,000
	Manufacturing Process Development	5	8,000,000
	Attachments & Structural Terminations	4	10,000,000
	Smart Sensor Composites	6	2,500,000
	Polymer Matrix Development	6	3,000,000
	Reinforcement Development	6	3,000,000
	Prototyping and Structural Demonstration	10	175,000,000
Year 5 Total \$222,000,000			
Cumulative Total \$642,000,000			
6	Structural Behavior of Composites	9	\$2,000,000
	Quality Control/Quality Assurance	4	3,500,000
	Manufacturing Process Development	5	6,000,000
	Attachments & Structural Terminations	4	5,000,000
	Smart Sensor Composites	6	1,250,000
	Polymer Matrix Development	6	2,000,000
	Reinforcement Development	6	3,000,000
	Prototyping and Structural Demonstration	10	100,000,000
Year 6 Total \$122,750,000			
Cumulative Total \$764,750,000			
7	Structural Behavior of Composites	9	\$1,000,000
	Polymer Matrix Development	6	2,000,000
	Reinforcement Development	6	3,000,000
	Prototyping and Structural Demonstration	10	50,000,000
Year 7 Total \$56,000,000			
Cumulative Total \$820,750,000			
8	Structural Behavior of Composites	9	\$1,000,000
	Prototyping and Structural Demonstration	10	30,000,000
Year 8 Total \$31,000,000			
Cumulative Total \$851,750,000			
9	Structural Behavior of Composites	9	\$1,000,000
	Prototyping and Structural Demonstration	10	20,000,000
Year 9 Total \$21,000,000			
Cumulative Total \$872,750,000			
10	Prototyping and Structural Demonstration	10	\$10,000,000
Year 10 Total \$10,000,000			
Cumulative Total \$882,750,000			

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Chapter 6

High-Performance Concrete

The United States produces more than 500 million tons of concrete yearly. Although many structures are constructed completely or in part using concrete, concrete has not always performed well as a construction material. Concrete's most persistent problem is durability. Durability problems affect structures' service life and repair costs. But high-performance concrete promises extended life in severe environments, shrinkage control, and ultra-high strength. **In fact, denser and less permeable high-performance concrete has the capability to produce light-weight structures with service lives measured in centuries rather than years.**

What is High-Performance Concrete?

High-performance concrete (HPC) is not just high-strength concrete: it meets special performance requirements. HPC can be defined as concrete with improved constructability, improved durability, and improved mechanical properties. Unlike conventional concrete, HPC meets one or more of these requirements:

- Places and compacts easier
- Achieves high strengths at early ages
- Exhibits superior long-term mechanical properties such as strength, resistance to abrasion or impact loading, and low permeability
- Exhibits volume stability and thus deforms less or cracks less
- Lasts longer when subjected to chemical attack, freezing and thawing, or high temperatures
- Demonstrates enhanced durability

These desired properties cannot be achieved with traditional construction materials and normal mixing, placing, and curing methods. Thus new materials, equipment, and construction methods are needed, along with training programs to help ensure desired results. The end result will be the ability to optimize concrete for specific applications. These improved properties will enable engineers to predict performance more accurately.

Applications of High-Performance Concrete

High-rise buildings, long-span bridges, architectural cladding, structural repairs, fast-track construction, structures in seismic regions, marine construction—these represent only a few of the many promising applications for HPC. Much of HPC use has been initiated in the private sector. However, the results of HPC R&D are especially adaptable to use in public infrastructure applications. One of the mechanical properties of HPC—rapid strength gain—allows for

Denser and less permeable high-performance concrete has the capability to produce light-weight structures with service lives measured in centuries rather than years.



Placement of a HPC silica-fume concrete bridge deck overlay by Ohio Department of Transportation. This use of silica-fume concrete takes advantage of the low permeability of the concrete to slow the rate of chloride ingress.

Courtesy of Master Builders, Inc.

Improved durability has perhaps the highest potential of all for achieving remarkable cost-saving benefits in the infrastructure.

quicker structural repairs and fast-track construction. For example, the high costs and traffic delays associated with the repair down time of transportation structures such as bridges, tunnels, and pavement overlays can be virtually eliminated by using HPCs that gain a strength of 48 MPa (7 ksi) within an hour after placement. Clearly, HPC can reduce maintenance costs and minimize inconveniences, such as travel delays, to infrastructure users. **Yet the real breakthroughs are quantum improvements in material properties which primarily apply to new construction and applications.**

However, HPC currently represents no more than perhaps 5 to 10 percent of the total concrete (more than 500 million tons) placed annually in the U.S. Higher initial cost restricts its use for new construction, as does limited experience with the unique properties of this material. HPC is more frequently used for repairs because often only HPC can satisfy demands for specific properties. But the volume of concrete used for repair is substantially less than that of conventional concrete used for new construction. New potential applications for HPC in new construction include: durability-sensitive uses such as marine structures, sewer plants, roads and bridges, and hazardous materials encapsulations; strength-sensitive uses in structural frames and fabrication-sensitive uses such as concrete pipe and architectural elements.

Properties and Benefits of High-Performance Concrete

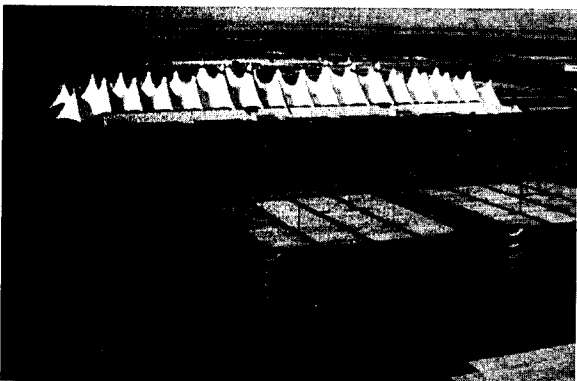
Conventional concrete compressive strengths usually range up to 34 MPa (5 ksi). In contrast, HPC may have compressive strengths exceeding 135 MPa (20 ksi) which will result in stronger and more efficient structures. This will translate into tremendous cost savings associated with materials, labor, weight, and design of high-rise buildings and other structures.

In addition, HPC can be produced so that it is stiffer than conventional concrete; therefore, HPC will deform significantly less under load. Unlike conventional concrete, HPC is less susceptible to damage in severe environments. When subjected to aggressive chemicals such as de-icing salts, HPC with its low permeability will last much longer than conventional concretes. In other words, rebars in snow-covered HPC bridge decks will no longer corrode. High-performance fiber-reinforced concretes have greatly increased tensile strengths compared to conventional concretes. The presence of corrosion resistant fibers in HPC pavements results in better crack resistance.

How do these improvements in concrete's mechanical properties and durability affect performance? High-strength concretes permit use of smaller structural members. This conserves non-renewable materials, increases usable space in buildings, and permits more aesthetically pleasing designs while reducing construction costs. Higher-stiffness HPC reduces short- and

long-term deflection problems, or may permit longer spans and thinner sections, which provide advantages similar to those for high-strength concrete.

Improved durability has perhaps the highest potential of all for achieving remarkable cost-saving benefits in the infrastructure. Some bridges, pavements, sewage and water treatment plants, and similar constructed facilities are quickly deteriorating. These facilities were not poorly built, but they were exposed to service conditions far more severe than anticipated. Low-permeability HPC has



Courtesy of Master Builders Inc.

Parking structure at the Denver International Airport. This parking structure is predominately precast concrete containing a corrosion-inhibiting admixture to help increase the service life.

the capability of permitting service lives measured in centuries rather than years. Similar performance improvements can be passed on to private-sector facilities subjected to severe environments, thus reducing manufacturing costs and allowing dollars diverted to maintenance to be used more constructively.

Improved ductility presents another opportunity for exploiting other properties of HPC. Life safety requirements under seismic loads, blast loadings, or other transient loading conditions require ductile behavior. A more ductile concrete cracks less or results in narrower cracks; however, the current means of achieving this ductility are sometimes cost prohibitive. But HPC with its improved ductility would reduce exposure to destructive elements such as de-icing salts that cause some of the most serious and costly deterioration problems.

Development of High-Performance Concrete Materials

Many high-performance concretes are currently being developed. In the field, high-strength concrete is the most common of the HPCs. The highest strength concretes commercially available today are in the 70 MPa to 100 MPa (10 ksi to 15 ksi) range, with some slightly higher used in building interiors. In the laboratory, strengths as high as 680 MPa (100 ksi), comparable to high-strength structural steels, have been reached. Laboratory technology for producing these strengths must be translated into a practical production methodology. Advances in materials technology have also produced field applications of very low permeability concrete that improves corrosion resistance of reinforcing steel and resistance to chemical attack.

In the laboratory, high-ductility, fiber-reinforced concrete has been produced, improved reinforcing bar deformation patterns are being developed, ultra-high-strength concrete has been tested, and precast connection systems with improved seismic resistance are being tested.

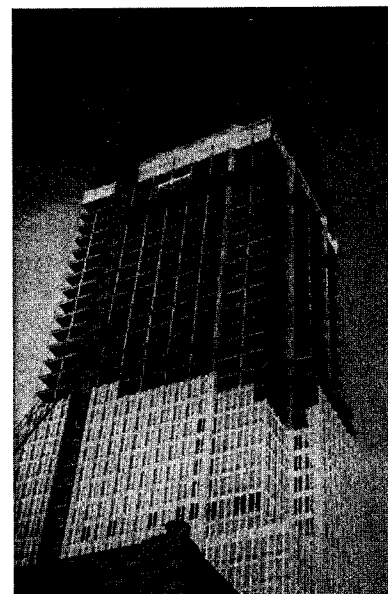
To ensure commercial viability of all HPC initiatives, prototype evaluations and full-scale demonstration projects are essential. Also essential are the databases and knowledge-based systems that are needed for service life predictions that extend beyond the lifetimes of several generations of researchers. Education in HPC use is essential, since concrete is a field-fabricated product which is very sensitive to craftsman knowledge, skill, and procedures. Finally, codes and standards must be responsive to the need for rapid incorporation of the innovative technology.

Current Constraints to High-Performance Concrete Use

Initially, HPC was most often used in buildings. Now durability receives more attention and the use of HPC has been extended to bridges, waste disposal sites, flood control facilities, manufacturing plants, and other commercial ventures. But widespread use of HPC is limited by technical, planning, education, and budgetary constraints.

One barrier to overcome is the lack of a broad knowledge base on material performance. For example, test methods for HPC are inadequate. Without these test methods in place, engineers cannot determine how HPC will perform in certain applications. In addition, engineers have doubts about applying empirically based design methods to concretes with mechanical properties outside the range of values on which empirical methods were based. This lack of information also includes gaps in empirical data regarding optimum curing regimes for HPC, inadequate knowledge about interaction of HPC with

One barrier to overcome is the lack of a broad knowledge base on material performance.



Society Tower in Cleveland. Note the two concrete columns at each corner of the building.

Courtesy of Master Builders, Inc.

Centers for Research and Technology Transfer

HPC Research

Center for Advanced Cement-
Based Materials

National Ready Mixed Concrete
Association

Portland Cement Association

Construction Technology
Laboratories

Wiss, Janney, Elstner Associates

University of Texas-Austin

Purdue University

Technology Transfer

American Concrete Institute

American Society of Civil
Engineers

Center for Advanced Cement-
Based Materials

Composites Institute

National Ready Mixed Concrete
Association

National Institute of Standards
and Technology

Portland Cement Association

University of California-Berkeley

University of Illinois

University of Michigan

reinforcement, and insufficient empirical data on HPC, especially on material effects on performance.

What is needed to overcome this lack of knowledge about HPC performance? The industry needs to promote further development of simulation programs that will give engineers confidence in predictions of HPC service life. Most importantly, the industry needs to initiate many more demonstration projects to show the financial and technical advantages of HPC over conventional concrete.

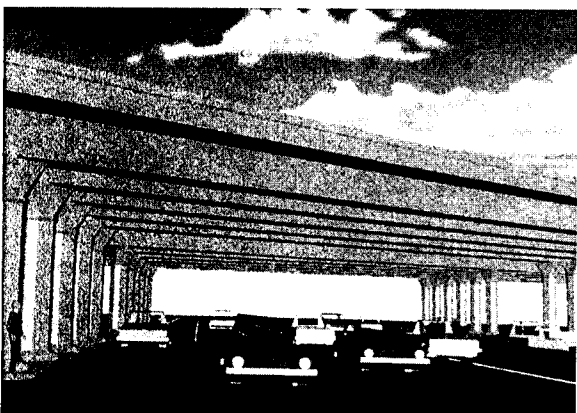
In addition to technical barriers and a low number of engineers and craftspeople trained to work with HPC, development efforts are often hindered by inadequate public policy. Currently, the U.S. lacks an evaluation and approval system for HPC. Without a full-scale-project experience base, interested public and private sector players will be reluctant to commit funds or time to unproven technology. And without contract/bid incentives, few contractors will show interest in advancing HPC uses. One of the major constraints to HPC use is the current emphasis on higher HPC first cost, instead of life-cycle cost benefits. Key organizations (AASHTO, ACI, FHWA, NSF) must make a coordinated effort to remove these barriers.

Current Projects Demonstrating High- Performance Concrete's Effectiveness

The Northridge earthquake of January 1994 illustrates the need and utility for one of the current HPC research projects. It involves precast concrete connection systems designed for structures built in areas of high seismicity. Energy-absorbing ductile joints prevent sudden collapse of structural framing in seismic situations. This project should also accelerate commercialization by showing that the system is a viable alternative to current approaches.

Several research projects currently underway offer excellent opportunities to demonstrate modified materials and new systems. One development is a reinforcing bar with an improved deformation pattern that increases bond strength, thus reducing splice lengths and decreasing the amount of steel needed. While the research is nearing completion, acceptance by the design community may be slowed by lack of field verification of results. Demonstration projects being planned or implemented by FHWA include a bridge in Houston built with high-strength concrete and HPC pavements built at several demonstration sites in the U.S. More demonstration projects such as these are needed to show that HPC technology can be applied practically to provide safe, long-lasting, and economical structures.

In the 21st century, concrete will be specified entirely on the basis of required performance, whether the requirements are for high strength, ease of placement, volume stability, durability, or other properties. Prescriptive specifications will disappear. As a result, future structures will have life expectancies far greater than today's structures that are typically built with design lives of 20, 40, or 50 years. Design lives numbering in the hundreds of years should not be uncommon!



Courtesy of University of Texas at Austin

This is an artistic representation of the Louetta Road Overpass bridge currently under construction in Houston, Texas. This is the first bridge built in the United States fully utilizing the benefits of high performance concrete.

CONCRETE MATERIALS

Prioritized Research Projects

Research Topic	Research Project	Objective	Approach	Schedule	Budget	Public Agency	Benefits
Optimized Proportioning Methodology	Effects of Mixture Proportions on Properties	Classify effects of mixture proportions on fresh and hardened HPC with and without mixtures.	Laboratory; mixture-proportions	3 years	\$1.8M	USACE FHWA	Optimum Mixture
Optimized Proportioning Methodology	Procedure for Optimization of Mixture Design	Develop procedure for optimizing HPC mixture for given application.	Computer; mix-proportions model	3 years	\$1.2M	NSF	Optimum Mixture
Optimized Proportioning Methodology	Decision-Support System to Aid Mixture Design	Develop knowledge-based decision-support system to aid preliminary materials selection and proportions in designing concrete.	Computer; knowledge base	3 years	\$2.8M	NIST	Concrete Design
Material Effects on Performance	Predicting Performance	Develop models for prediction of HPC from mixture proportions and constituents characteristics.	Computer; model mix-proportions	4 years	\$5.7M	NIST	Predictability of HPC
Mixing for High Performance	Evaluation of Existing Mixing Practices	Evaluate efficiency and practicality of existing mixing procedures in mixing HPC.	Laboratory; mixing procedures	3 years	\$2.0M	FHWA NIST NSF	Determine Optimum mixing procedure
Mixing for High Performance	Improved Mixing Practices	Develop improved mixing practices based on Evaluation of Existing Mixing Practices results and in collaboration with equipment manufacturers.	Laboratory; improve mix-practice	3 years	\$1.9M	FHWA NIST NSF	Establish practical workability mixtures
Quality Assurance at the Work Site	Determination of Workability and Placability	Develop workability and placability test methods of HPC.	Laboratory; workability mixtures	3 years	\$3.5M	NIST NSF	HPC strength predictability
Quality Assurance at the Work Site	Strength Potential	Develop prediction methods of HPC strength potential.	Computer/Laboratory; strength prediction	3 years	\$2.6M	NIST	Establish freeze-thaw durability
Quality Assurance at the Work Site	In-Place Evaluation of the Air Void System	Develop and propose for standardization, prediction methods of HPC freeze-thaw durability and other relevant transport properties.	Laboratory; freeze-thaw tests	3 years	\$3.5M	NIST	Establish HPC curing procedure

Research Topic	Research Project	Objective	Approach	Schedule	Budget	Public Agency	Benefits
Curing for Optimum Performance	Fundamental Parameters Affecting Curing of HPC	Develop and implement efficient experimental plan to determine fundamental parameters affecting the curing of HPC.	Laboratory; curing tests	3 years	\$2.9M	USACE NIST NSF	Optimize curing regimes for HPC
Curing for Optimum Performance	Demonstration of Optimized Curing	Demonstrate evaluation of optimized curing regimes and monitoring development of in-place HPC properties.	Laboratory; curing studies	3 years	\$0.9M	USACE FHWA	Establish optimum curing regime
Curing for Optimum Performance	Decision-Support System for Optimized Curing	Develop knowledge-based decision-support to provide guidance on system the curing of HPC.	Computer; knowledge based curing guidance	1.5 years	\$0.6M	NIST	Standard for curing
Curing for Optimum Performance	Recommended Curing Practices	Draft recommended practices for HPC curing and submit for standardization.	Computer; draft standard	1 year	\$0.45M	NSF	Standard material test procedure (short term)
Evaluation of Mechanical Properties	Short-Term Mechanical Properties	Develop short-term mechanical property data and test methods needed for HPC structures design and construction.	Laboratory; establish test methods	4 years	\$2.4M	USACE FHWA	Standard material test procedure (long term)
Evaluation of Mechanical Properties	Long-Term Mechanical Properties	Develop long-term mechanical property data needed in HPC structures design.	Laboratory; establish test procedures	3 years	\$1.9M	USACE FHWA	Minimize cracking
Evaluation of Mechanical Properties	Early-Age Thermal History	Determine early-age temperature and thermal gradient effects on cracking and other aspects of HPC performance which may require changes in design procedures and codes and standards.	Laboratory; establish early age thermal effects	3 years	\$2.6M	NIST	Establish fiber concrete composites
Evaluation of Mechanical Properties	In-Place Determination of Mechanical Properties	Develop reliable and consistent methods for determining the in-place mechanical properties of HPC.	Statistical analysis and laboratory test methods	3 years	\$2.6M	NIST	Standard mechanical property analysis
Fiber-Reinforced HPC Composites	Formation of Fiber-Reinforced HPC Composites	Develop processing procedures for producing high-fiber-volume fiber-reinforced HPC composites.	Laboratory; fiber concrete tests	2 years	\$1.1M	NIST	Establish service life for fiber concrete composites
Fiber-Reinforced HPC Composites	Composition-Performance Relationships for Fiber-Reinforced HPC	Develop composition-performance relationships for fiber-reinforced HPC composites.	Laboratory; fiber concrete tests	3 years	\$1.05M	NIST	Establish guidelines for fiber specific approval of fiber composites

Research Topic	Research Project	Objective	Approach	Schedule	Budget	Public Agency	Benefits
Fiber-Reinforced HPC Composites	Environmental Effects on the Life of Fiber-Reinforced HPC Composites	Determine service environment effects on service life of fiber-reinforced HPC composites.	Laboratory; service life tests	3 years	\$1.05M	NIST	Design HPC for user needs
Fiber-Reinforced HPC Composites	Design Guidelines for Fiber-Reinforced HPC Composites	Develop design guidelines for fiber-reinforced HPC composites for specific applications.	Laboratory; fiber concrete application tests	2 years	\$0.9M	NIST	Design HPC to include field data
Knowledge Base of Properties of HPC	The Knowledge Base Structure	Identify user needs for interactive knowledge base of HPC properties, establish the structure, and develop working system.	Computer; knowledge base	1.5 years	\$1.9M	NIST	Provides a track record of performance
Knowledge Base of Properties of HPC	Development of Knowledge Base	Extend HPC property knowledge-based system to include well-documented data from the field.	Computer; knowledge base	3 yrs	\$2.0M	NIST	Provides a long range performance record
Knowledge Base of Properties of HPC	Demonstration of the Knowledge-Based System	Operate knowledge-based system for trial period as a demonstration project and document successes and failures.	Computer; document performance of HPC	1.5 years	\$0.75M	NIST	Establish reliability of durability tests
Knowledge Base of Properties of HPC	Long-Term Operation and Maintenance of the System	Develop and establish long term program to operate knowledge-based system.	Computer; establish long-term program	1 year	\$0.4M	NIST	Establish reliability of durability tests
Evaluation of Durability	Selection of Candidate Methods	Determine whether existing durability tests provide reliable basis for predicting field performance of conventional concrete.	Laboratory; durability tests	1.5 years	\$0.75M	USACE FHWA	Establish reliability of durability tests
Evaluation of Durability	Adaptability of Existing Methods	Evaluate HPC field durability with those tests found reliable in giving information on regular concrete durability. Are same tests reliable for HPC?	Laboratory; durability tests	3 years	\$3.5M	USACE FHWA	Improve transport properties
Evaluation of Durability	Simulation of In-Service Conditions	Develop new tests to replace those, in studies Adaptability of Existing Methods, found not applicable to HPC, those which did not simulate in-service conditions, and those in which degradation mechanisms not the same as those occurring in the field.	Laboratory; develop new durability tests	3 years	\$3.5M	USACE FHWA	Improve transport properties

Research Topic	Research Project	Objective	Approach	Schedule	Budget	Public Agency	Benefits
Evaluation of Durability	Improved Durability Tests	Develop accelerated durability tests in areas where standard accelerated tests are needed but do not exist.	Laboratory; durability tests	3 years	\$3.5M	NIST	Develop new standards
Transport Properties of HPC	New Methods for Evaluating Transport Properties	Develop new methods for measuring important HPC transport properties.	Laboratory; placing properties	1.5 years	\$0.9M	NIST	Improve service life predictability
Transport Properties of HPC	In-Place Evaluation of Transport Properties	Develop new or improved methods for measuring transport properties of in-place HPC.	Laboratory; placing properties	2 years	\$0.9M	NIST	Establish service life models
Predicting Service Life of HPC	Existing Methods for Service Life Prediction	Determine applicability to HPC of existing methods and models for predicting service lives of concrete exposed to a variety of environments, including air, seawater, and soils.	Laboratory; service life tests	2 years	\$0.5M	NIST	Establish performance criteria
Predicting Service Life of HPC	Improved Methods for Predicting Service Life	Develop new or improved models for use in predicting service life of HPC.	Computer; develop service life models	2.5 years	\$0.8M	NIST	Establish service life predictability
Predicting Service Life of HPC	Validation of Predictive Models	Validate models for predicting service life of HPC.	Laboratory; validate service life models	3 years	\$1.75M	USACE FHWA	Establish service life for various environ-mental exposures
Predicting Service Life of HPC	HPC Performance Criteria	Develop performance criteria for HPC selection, based on service life considerations.	Laboratory; performance testing	1 year	\$0.25M	NIST NSF	Establish service life
Predicting Service Life of HPC	Guidelines for Service Life Prediction	Develop guidelines for making service life predictions of HPC and demonstrate use of guidelines in materials engineering of HPC.	Laboratory; develop service life prediction	1 year	\$0.25M	NIST NSF	Develop material design code
Service Life Design Code	Classification of Environments for Service Life Prediction	Develop scheme for classifying environments to which HPC is likely to be exposed in terms suitable for use in service life prediction.	Laboratory; classify environment exposure	1.5 years	\$0.95M	NIST NSF	Establish guidelines to assess condition of HPC
Service Life Design Code	Degradation Mechanisms	Provide mechanistic knowledge about degradation processes needed for design of durable HPC.	Laboratory; study degradation process	2 years	\$0.5M	NIST NSF	Establish guidelines for repair of HPC
Service Life Design Code	Knowledge Bases for Use in Materials Selection	Ensure that available knowledge bases are suitable for use in development of materials design codes.	Computer; enhance knowledge base	2 years	\$0.5M	NIST	Establish design of properties of HPC material
Service Life Design Code	Service Life Design Code	Develop draft of national service life design code for HPC.	Computer; draft service life design code	2 years	\$1.0M	NSF	Establish HPC resistance to fatigue

Research Topic	Research Project	Objective	Approach	Schedule	Budget	Public Agency	Benefits
Condition Assessment and Repair	Condition Assessment	Provide guidance on selection and use of methods for assessing condition of HPC in a structure.	Computer; develop expert system	3 years	\$0.9M	USACE FHWA	Establish HPC resistance to corrosion
Condition Assessment and Repair	Repair of HPC	Provide guidance in selection of materials and procedures for repair damaged or deteriorated HPC.	Computer; develop expert system	3 years	\$0.9M	USACE FHWA	Establish compatibility of HPC with nonmetallic reinforcement
Reinforcing Materials for HPC Members	Detailing Practices for High-Strength Concrete and High-Strength Steel Reinforcement	a) Establish rational models to represent steel and concrete interaction applicable over full range of material and structural properties foreseen for application over the next 25 years. b) Evaluate applicability of current design provisions for anchorage, development length, splices, hooks and other reinforcing details with respect to full range of high-strength concrete mixtures and develop improved detailing practices, as warranted. c) Evaluate current design provisions for anchorage, development length, splices, hooks and other reinforcing details with respect to application of reinforcing steels with yield strengths in excess of 60MPa (87 ksi) and develop improved detailing practices, as appropriate.	Laboratory; evaluate by testing the current design provisions for material properties of HPC	6 years	\$4.0M	NSF	Establish design/code procedures for HPC
Reinforcing Materials for HPC Members	Fatigue of Reinforcing Steel	a) Develop standard test for U.S. to evaluate fatigue life of reinforcing bars. b) Evaluate current deformation patterns and production practices to determine their effects on fatigue life. c) Develop modifications to reinforcing bar design and manufacturing procedures to improve fatigue of life of U.S. manufactured reinforcement.	Laboratory; fatigue testing	3 years	\$1.6M	NSF	Establish design/code requirements
Reinforcing Materials for HPC Members	Corrosion Resistance	a) Develop accelerated corrosion test procedures that effectively simulate corrosive environment of reinforcing steel in concrete. b) Determine potential of new reinforcing steels, coating systems, and protection systems to extend life of HPC in various environments.	Laboratory; corrosion testing	7 years	\$8.0M	USACE FHWA NSF	Establish design/code requirements

Research Topic	Research Project	Objective	Approach	Schedule	Budget	Public Agency	Benefits
Reinforcing Materials for HPC Members	Nonmetallic Reinforcement	a) Evaluate and develop anchorage techniques for nonmetallic reinforcement for use in high-strength, prestressed HPC members. b) Evaluate long-term environmental performance of nonmetallic reinforcement systems for prestressed concrete members.	Laboratory; tests with non-metallic reinforcement	5 years	\$2.7M	USACE FHWA NSF	Establish design/code requirements
Structural Design of HSC Members	Design and Construction Considerations	a) Review existing codes and standards, identify design parameters and construction requirements that may require modification for use with HSC. b) Conduct a critical analysis and evaluation of design parameters and construction requirements identified in (a) and recommend appropriate modifications based on analytical and experimental studies, and reliability analysis.	Computer; review exist design parameters and their application to HPC	2 years	\$1.1M	NIST NSF	Establish code/standards requirements
Structural Design of HSC Members	Axial Load and Bending	a) Examine design equations for axial and flexural capacity in current codes, such as ACI 318, for their applicability to HSC. b) Document relationship between test member strength of concrete. c) Examine current minimum reinforcement requirements.	Laboratory; test HPC flexural and axial strengths	3 years	\$2.6M	NIST NSF	Establish SOA in the use of HPC in buildings
Structural Design of HSC Members	Shear and Torsion	a) Investigate shear behavior of reinforced and prestressed concrete beams made with HSC, examine applicability of current design criteria for shear and torsion and, if necessary, develop improved provisions. b) Investigate punching shear behavior of HSC slabs. c) Develop rational design models for shear and torsion.	Laboratory; test HPC for shear/torsion properties	3 years	\$5.0M	NIST NSF	Establish SOA in the use of HPC in highways
Structural Design of HSC Members	Seismic Response	a) Examine requirements for confinement steel and compression steel in axial and flexural members for HSC to satisfy ductility for seismic design. b) Explore potential benefits in design using fiber-reinforced HSC to obtain improved ductility.	Laboratory; test for HPC ductility in axial/flexural members	4 years	\$5.2M	NIST NSF	Establish SOA in the use of HPC in special structures
Structural Design of HSC Members	Changes to Codes and Standards	Introduce knowledge gained in Structural Design of HSC Members into codes and standards.	Laboratory; interpret tests	8 years	\$0.65M	NSF	Define experimental program
In-Service Performance of HPC Structures	Buildings	Establish state of the art in the use of HPC in buildings.	Laboratory; interpret tests	5 years	\$2.25M	NIST NSF	Establish fire resistibility

Research Topic	Research Project	Objective	Approach	Schedule	Budget	Public Agency	Benefits
In-Service Performance of HPC Structures	Highway Structures	Establish state of the art in the use of HPC in highway structures (pavements and bridges).	Laboratory; interpret tests	5 years	\$10.5M	FHWA	Establish fire design requirement. for HPC
In-Service Performance of HPC Structures	Special Structures	Establish state-of-the-art in use of HPC in special structures.	Computer; interpret tests	5 yrs	\$2.25M	USACE	Improved products using HPC
Fire Resistance of HPC	Review of Literature and Design of Experiments	Review literature and define needed experimental program.	Computer; review literature	3 years	\$1.0M	NSF	New improved products
Fire Resistance of HPC	Fire Exposure Experiments	Perform fire exposure experiments on several HPC mixtures.	Laboratory; fire test	5 years	\$4.15M	NIST	New improved construction systems
Fire Resistance of HPC	Fire Design Guidelines for HPC	Draft guideline for the structural design of fire safe HPC structures.	Computer study	3 years	\$1.1M	NIST	Establish new HPC conveying techniques
Improved Products	Evaluation of Concepts for Improvement of Existing Products	Identify opportunities for improvement of existing concrete products using HPC and develop and demonstrate viable concepts.	Laboratory study	4 years	\$5.0M	ACBM NIST	Establish new automation procedures for CIP HPC
Improved Products	Evaluation of Concepts for New Products	Identify opportunities for new products that can be made with HPC that will be superior to products made with other materials.	Laboratory testing	5 years	\$5.0M	ACBM NIST	Establish new automation procedures for P/C HPC
New Systems	New Construction Systems	Design, develop and demonstrate new construction systems that take advantage of special combinations of properties attainable with HPC.	Laboratory testing	6 years	\$10.0M	USACE FHWA	Establish new construction systems
Materials Handling	Conveying Techniques	Evaluate suitability of various transporting and conveying techniques for use with HPC and develop guidelines for selection and use of appropriate techniques.	Laboratory testing of conveying techniques	3 years	\$3.0M	USACE	Establish new HPC conveying techniques
Automated and Robotic Construction	Construction with Cast-in-Place HPC	Identify and prioritize needs and opportunities for automation of cast-in-place construction with HPC and develop effective systems to take advantage of opportunities to improve quality and competitiveness of construction.	Laboratory; study possible automation for CIP construction	5 years	\$12.0M	USACE FHWA	Establish new HPC automation procedure for CIP HPC
Automated and Robotic Construction	Construction with Precast HPC Products	Identify and prioritize needs and opportunities for automation of construction with Precast HPC and develop effective systems to take advantage of opportunities to improve quality and competitiveness of construction.	Laboratory; study possible automation for P/C construction	6 years	\$15.0M	USACE FHWA	Establish new automation procedure for P/C HPC

Research Topic	Research Project	Objective	Approach	Schedule	Budget	Public Agency	Benefits
Total Program Outlay					\$ 171.95 M		

Concrete Prioritized Timeline and Budget Allocation

Year	Project	Duration (in years)	Cost
1	Predicting Performance	4	\$1,500,000
	Fundamental Parameters Affecting Curing of HPC	3	1,100,000
	Decision-Support System for Optimized Curing	1.5	400,000
	Short-Term Mechanical Properties	4	600,000
	Long-Term Mechanical Properties	3	700,000
	Formation of Fiber-Reinforced HPC Composites	2	600,000
	Selection of Candidate Methods	1.5	500,000
	Existing Methods for Service Life Prediction	2	250,000
	Detailing Practices for HS Concrete and HS Steel Reinforcement	6	700,000
	Corrosion Resistance	7	1,200,000
Year 1 Total \$7,550,000			
Cumulative Total \$7,550,000			
2	Predicting Performance	4	\$1,400,000
	Fundamental Parameters Affecting Curing of HPC	3	900,000
	Decision-Support System for Optimized Curing	1.5	200,000
	Short-Term Mechanical Properties	4	600,000
	Long-Term Mechanical Properties	3	600,000
	Formation of Fiber-Reinforced HPC Composites	2	500,000
	Selection of Candidate Methods	1.5	250,000
	Existing Methods for Service Life Prediction	2	250,000
	Detailing Practices for HS Concrete and HS Steel Reinforcement	6	700,000
	Corrosion Resistance	7	1,200,000
	Early-Age Thermal History	3	900,000
	Adaptability of Existing Methods	3	1,200,000
	Fatigue of Reinforcing Steel	3	600,000
	Nonmetallic Reinforcement	5	600,000
	Design and Construction Considerations	2	600,000
	Shear and Torsion	3	1,700,000
	Review of Literature and Design of Experiments	3	400,000
Year 2 Total \$12,600,000			
Cumulative Total \$20,150,000			

Year	Project	Duration (in years)	Cost
3	Predicting Performance	4	\$1,400,000
	Fundamental Parameters Affecting Curing of HPC	3	900,000
	Short-Term Mechanical Properties	4	600,000
	Long-Term Mechanical Properties	3	600,000
	Detailing Practices for HS Concrete and HS Steel Reinforcement	6	700,000
	Corrosion Resistance	7	1,200,000
	Early-Age Thermal History	3	900,000
	Adaptability of Existing Methods	3	1,200,000
	Fatigue of Reinforcing Steel	3	500,000
	Nonmetallic Reinforcement	5	600,000
	Design and Construction Considerations	2	500,000
	Shear and Torsion	3	1,700,000
	Review of Literature and Design of Experiments	3	300,000
	In-Place Determination of Mechanical Properties	3	900,000
	Demonstration of Optimized Curing	3	300,000
	Composition-Performance Relationships for Fiber-Reinforced HPC	3	400,000
	Improved Methods for Predicting Service Life	2.5	300,000
	Axial Load and Bending	3	900,000
	Seismic Response	4	1,300,000
Year 3 Total \$15,200,000			
Cumulative Total \$35,350,000			
4	Predicting Performance	4	\$1,400,000
	Short-Term Mechanical Properties	4	600,000
	Detailing Practices for HS Concrete and HS Steel Reinforcement	6	700,000
	Corrosion Resistance	7	1,100,000
	Early-Age Thermal History	3	800,000
	Adaptability of Existing Methods	3	1,100,000
	Fatigue of Reinforcing Steel	3	500,000
	Nonmetallic Reinforcement	5	500,000
	Shear and Torsion	3	1,600,000
	Review of Literature and Design of Experiments	3	300,000
	In-Place Determination of Mechanical Properties	3	900,000
	Composition-Performance Relationships for Fiber-Reinforced HPC	3	350,000
	Improved Methods for Predicting Service Life	2.5	300,000
	Axial Load and Bending	3	900,000
	Seismic Response	4	1,300,000
	Determination of Workability and Placability	3	1,200,000
	Classification of Environments for Service Life Prediction	1.5	600,000
	Knowledge Bases for Use in Materials Selection	2	250,000
	Evaluation of Concepts for Improvement of Existing Products	4	1,250,000
	New Construction Systems	6	1,700,000
	Construction with Cast-in-Place HPC	5	2,400,000
	Demonstration of Optimized Curing	3	300,000
Year 4 Total \$20,050,000			
Cumulative Total \$55,400,000			

Year	Project	Duration (in years)	Cost
5	Detailing Practices for HS Concrete and HS Steel Reinforcement	6	\$ 600,000
	Corrosion Resistance	7	1,100,000
	Nonmetallic Reinforcement	5	500,000
	In-Place Determination of Mechanical Properties	3	800,000
	Composition-Performance Relationships for Fiber-Reinforced HPC	3	300,000
	Improved Methods for Predicting Service Life	2.5	200,000
	Axial Load and Bending	3	800,000
	Seismic Response	4	1,300,000
	Determination of Workability and Placability	3	1,200,000
	Classification of Environments for Service Life Prediction	1.5	350,000
	Knowledge Bases for Use in Materials Selection	2	250,000
	Evaluation of Concepts for Improvements of Existing Products	4	1,250,000
	New Construction Systems	6	1,700,000
	Construction with Cast-in-Place HPC	5	2,400,000
	Environmental Effects on the Life of Fiber-Reinforced HPC Composites	3	350,000
	Validation of Predictive Models	3	600,000
	Strength Potential	3	900,000
	Fire Exposure Experiments	5	950,000
	Construction with Precast HPC Products	6	2,500,000
	Demonstration of Optimized Curing	3	300,000
Year 5 Total \$18,350,000			Cumulative Total \$73,750,000
6	Detailing Practices for HS Concrete and HS Steel Reinforcement	6	\$ 600,000
	Corrosion Resistance	7	1,100,000
	Nonmetallic Reinforcement	5	500,000
	Seismic Response	4	1,300,000
	Determination of Workability and Placability	3	1,100,000
	Evaluation of Concepts for Improvement of Existing Products	4	1,250,000
	New Construction System	5	1,700,000
	Construction with Cast-in-Place HPC	5	2,400,000
	Environmental Effects on the Life of Fiber-Reinforced HPC Composites	3	350,000
	Validation of Predictive Models	3	600,000
	Strength Potential	3	900,000
	Fire Exposure Experiments	5	800,000
	Construction with Precast HPC Products	6	2,500,000
	Recommended Curing Practices	1	450,000
	Simulation of In-Service Conditions	3	1,200,000
	In-Place Evaluation of the Air Void System	3	1,200,000
	Effects of Mixture Proportions on Properties	3	600,000
	Evaluation of Existing Mixing Practices	3	700,000
	The Knowledge Base Structure	1.5	1,300,000
	Condition Assessment	3	300,000
	Buildings	5	450,000
	Highway Structures	5	2,100,000
Year 6 Total \$23,400,000			Cumulative Total \$97,150,000

Year	Project	Duration (in years)	Cost
7	Corrosion Resistance	7	\$1,100,000
	Evaluation of Concepts for Improvements of Existing Products	4	1,250,000
	New Construction Systems	5	1,700,000
	Construction with Cast-in-Place HPC	5	2,400,000
	Environmental Effects on the Life of Fiber-Reinforced HPC Composites	3	350,000
	Validation of Predictive Models	3	550,000
	Strength Potential	3	800,000
	Fire Exposure Experiments	5	800,000
	Construction with Precast HPC Products	6	2,500,000
	Simulation of In-Service Conditions	3	1,200,000
	In-Place Evaluation of the Air Void System	3	1,200,000
	Effects of Mixture Proportions on Properties	3	600,000
	Evaluation of Existing Mixing Practices	3	700,000
	The Knowledge Base Structure	1.5	600,000
	Condition Assessment	3	300,000
	Buildings	5	450,000
	Highway Structures	5	2,100,000
	Design Guidelines for Fiber-Reinforced HPC Composites	2	450,000
	Changes for Codes and Standards	8	90,000
	Degradation Mechanisms	2	250,000
	Service Life Design Code	2	500,000
	Procedure for Optimization of Mixture Design	3	400,000
	Development of Knowledge Base	3	700,000
	Special Structures	5	450,000
	Conveying Techniques	3	1,000,000
Year 7 Total \$22,440,000			
Cumulative Total \$119,590,000			
8	New Construction Systems	6	\$1,600,000
	Construction with Cast-in-Place HPC	5	2,400,000
	Construction with Precast HPC Products	6	2,500,000
	Simulation of In-Service Conditions	3	1,100,000
	In-Place Evaluation of the Air Void System	3	1,100,000
	Effects of Mixture Proportions on Properties	3	600,000
	Evaluation of Existing Mixing Practices	3	600,000
	Condition Assessment	3	300,000
	Buildings	5	450,000
	Highway Structures	5	2,100,000
	Design Guidelines for Fiber-Reinforced HPC Composites	2	450,000
	Changes to Codes and Standards	8	80,000
	Degradation Mechanisms	2	250,000
	Service Life Design Code	2	500,000
	Procedure for Optimization of Mixture Design	3	400,000
	Development of Knowledge Base	3	700,000
	Special Structures	5	450,000
	Conveying Techniques	3	1,000,000
	Fire Exposure Experiments	5	800,000
	HPC Performance Criteria	1	250,000
	Evaluation of Concepts for New Products	5	1,000,000
	Decision-Support System to Aid Mixture Design	3	1,000,000
	Demonstration of the Knowledge-Based System	1.5	500,000
	New Methods for Evaluating Transport Properties	1.5	600,000
Year 8 Total \$20,730,000			
Cumulative Total \$140,320,000			

Year	Project	Duration (in years)	Cost
9	New Construction Systems	6	\$1,600,000
	Fire Exposure Experiments	1	800,000
	Construction with Precast HPC Products	6	2,500,000
	Buildings	5	450,000
	Highway Structures	5	2,100,000
	Changes to Codes and Standards	8	80,000
	Procedure for Optimization of Mixture Design	3	400,000
	Development of Knowledge Base	3	600,000
	Special Structures	5	450,000
	Conveying Techniques	3	1,000,000
	Evaluation of Concepts for New Products	5	1,000,000
	Decision-Support System to Aid Mixture Design	3	900,000
	Demonstration of the Knowledge-Based System	1.5	250,000
	New Methods for Evaluating Transport Properties	1.5	300,000
	Guidelines for Service Life Prediction	1	250,000
	Improved Durability Tests	3	1,200,000
	Improved Mixing Practices	3	700,000
	Long-Term Operation and Maintenance of the System	1	400,000
	In-Place Evaluation of Transport Properties	2	450,000
	Repair of HPC	3	300,000
Year 9 Total \$15,730,000			Cumulative Total \$156,050,000
10	Construction with Precast HPC Products	6	\$2,500,000
	Buildings	5	450,000
	Highway Structures	5	2,100,000
	Changes to Codes and Standards	8*	400,000
	Special Structures	5*	900,000
	Evaluation of Concepts for New Products	5*	3,000,000
	Decision-Support System to Aid Mixture Design	3	900,000
	Improved Durability Tests	3*	2,300,000
	Improved Mixing Practices	3*	1,200,000
	In-Place Evaluation of Transport Properties	2	450,000
	Repair of HPC	3*	600,000
	Fire Design Guidelines for HPC	3*	1,100,000
Year 10 Total \$ 15,900,000			Cumulative Total \$171,950,000
*Project may extend into year 11 and beyond.			

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Chapter 7

High-Performance Hot Mix Asphalt

The United States has approximately 4 million miles of highways, only half of which are paved. **Roughly 94 percent of the paved roads have an asphalt surface.** More than any other single product, asphalt sustains the nation's highways and facilitates the flow of commerce. As the nation increasingly rehabilitates roads, funds spent on asphalt and the importance of this product to the nation's economy increase proportionally.

The annual production of Hot Mix Asphalt (HMA) is estimated at 500 million tons per year, approximately 75 percent of which is public sector work (varies by region of the country). The HMA Industry provides a \$15 billion contribution to the U.S. economy and about 600,000 jobs.

What is High-Performance HMA?

Hot Mix Asphalt (HMA) is a versatile pavement construction material composed of asphalt cement and mineral aggregates. The aggregates are obtained from locally occurring rock sources, sized to meet specific requirements, heated to remove moisture, and then mixed with asphalt cement (a product of the petroleum refining process). Although HMA contains only two principal ingredients, producing and placing HMA pavement requires extensive technical knowledge on many topics.

Major attributes of HMA include:

- Suitability for quality road building
- Ride quality
- Ready availability in large quantities
- Early opening of pavements to traffic
- Cost effectiveness
- 100 percent recyclability
- Ability to use locally available materials
- Well distributed delivery system

For HMA, **high performance** may be defined as pavements that are:

- Durable—the pavement must have appropriate resistance to wear for the loads applied and the climate to which it is exposed
- Smooth—the pavement must have good ride quality for both automobile and truck traffic—low rolling resistance provides both good fuel economy and air quality

*The HMA Industry
provides a \$15 billion
contribution to the U.S.
economy and about
600,000 jobs.*



Approximately 94 percent of all paved roadways in the U.S. are surfaced with Hot Mix Asphalt.

Courtesy of National Asphalt Pavement Association

- Safe—both wet and dry skid resistance of the pavement are important considerations
- Environmentally acceptable—all activities for manufacturing & placement of pavements must be mindful of maintaining clean air and water, minimizing noise impacts, product recyclability, and dust management
- Easily constructed—pavements must be able to be placed such that the flow of traffic will be impacted as little as possible
- Easily maintained—pavements must provide minimum traffic disruption for preventive maintenance and for rehabilitation while offering optimum life cycle cost

Some of the products of the recently completed Strategic Highway Research Program (SHRP) need additional developmental work in order to bring the products to functional application.

Applications of High-Performance HMA

In addition to its use for roads and paving, HMA used in landfill liners and caps provides an impermeable layer to prevent leakage of contaminants into ground-water sources and soils. HMA is used for reservoir liners for drinking water storage, and in permeable bases, HMA can be used to divert water away from pavement foundations to improve structural integrity of pavement systems. HMA can be put to advantageous use in open-graded friction courses as a wearing surface for pavement; this concept provides a “no-spray” pavement in wet conditions (as shown in photo), improves skid resistance, and reduces traffic noise. Noise reductions can be in the range of 3 to 6 DBA. HMA also provides a strong impermeable layer for foundation underlayment in railroad trackbeds.



Two types of Hot Mix Asphalt paving show remarkable differences during a rainstorm. At right, water collects on surface and is thrown up as spray by vehicles; at left, surface with open graded HMA mixture permitting water to drain through surface, virtually eliminating spray.

Development of High-Performance HMA

Some of the products of the recently completed Strategic Highway Research Program (SHRP) need additional developmental work in order to bring the products to functional application. The Federal Highway Administration is currently working on implementation issues for the products. The SHRP products will be central to the development of high performance HMA well into the 21st Century.

A meeting was recently organized by the National Cooperative Highway Research Program (NCHRP) to evaluate the SHRP products and to determine additional research needs in order to implement the products. The NCHRP panel represented both public and private sector personnel. From this meeting, representatives developed a prioritized list of research projects and submitted the list to NCHRP for evaluation.

Constraints to High-Performance HMA Use

Currently, an overall research needs and funding document has not been published for the HMA Industry. Working with a cross-section of HMA industry representatives, research needs statements will be developed. The implementation of SHRP products has captured the attention of most research activities for the last five years. Now that SHRP is completed, a review of product status and future needs will be done. After completion of that needs activity, a prioritization scheme can be developed.

FHWA has developed a series of Technical Working Groups (TWG) and Expert Task Groups (ETG) to review the SHRP products and to develop specific implementation plans for the products. Members of the TWG's and ETG's come from both public and private sectors. As a result of TWG and ETG activity, a Technology Transfer conference was held in Reno, Nevada in October 1994.

THE TWG and ETG concepts have been used as a forum for a wide variety of cooperative technical discussions within the HMA Industry.

The following technical areas would benefit from additional study:

- Performance assessment technology—to predict performance of materials in the laboratory
- Variability of raw materials—to quantify raw material properties and reduce variability
- Susceptibility to environmental deterioration—to understand the mechanisms of oxidation, moisture sensitivity and thermal cracking
- Rapid reliable test methods for process control—to improve overall product quality by better control of the manufacturing process
- Development of performance based specifications—to specify materials that will provide appropriate performance using SHRP products
- Application and use of non-conventional mix types such as open graded friction courses and permeable bases

Potential Federal Agency Partnerships

The Federal Highway Administration (FHWA), the American Association of State Highway and Transportation Officials (AASHTO), and the Transportation Research Board (TRB) are the three principal agencies that are most likely to participate in funding for research activities. FHWA funds research directly, while state departments of transportation through AASHTO provide research funds to TRB who acts as a contract manager. Each of the AASHTO member organizations also has a separate pool of research funds available through the State Planning and Research program.

Private and Public Sector Partnerships

The HMA industry long has recognized the need for strong partnerships and coordination between public and private sectors within the industry. The HMA industry has been developing public and private partnering arrangements for the past several years. The previously mentioned FHWA Technical Working Groups (TWG's) are vital examples of this activity. Recent actions which have been jointly developed include an extensive training program for Hot Mix Asphalt, the first ever Hot Mix Asphalt Textbook and the HMA Paving Handbook. These activities were completed with a strong joint participation.

Activities have begun to extend this partnering approach to the research and technology area. Examples of these activities include the introduction of Stone Matrix Asphalt into the U.S. as a direct result of a European Asphalt Study Tour, and the Technical Working group to develop engineering controls for asphalt paving equipment to improve the overall working environment. In addition, actions for implementation of SHRP have brought public and private sectors together in a very positive way.

Centers for Research, Both Academic and Government Laboratories

National Center for Asphalt
Technology (Auburn, AL)

Center for Aggregates Research
(Austin, TX)

The Asphalt Institute (Lexington, KY)
and numerous university research
centers, to name a few:

Texas A&M University

University of Texas

Purdue University

Oregon State University

University of California - Berkeley

University of Nevada-Reno

*The HMA industry long
has recognized the need
for strong partnerships and
coordination between
public and private sectors
within the industry.*

The HMA Industry must gain a thorough understanding of the SHRP products and use this information to build towards the goal of true performance-based products.

Key Implementation Strategies to Bridge the Research-Implementation Gap

Historically, one of the weakest links in research activities has been the implementation process. The HMA Industry has not been an exception in this area. At best, implementation is very slow and, in some cases, does not occur at all. Making appropriate use of research results is an activity that should provide high return for research investment and improve the performance of HMA.

New activities within FHWA, AASHTO and TRB provide an unprecedented opportunity for public and private sector interests to share concerns and issues. The possibility for improving research products and the implementation process is now available. In addition, the industry has been very active in the support of research and technology as evidenced by the development of the National Asphalt Pavement Association's Research and Education Foundation, the parent organization for the National Center for Asphalt Technology.

Implementing Funding Plans

In the asphalt area, the entire thrust of the Strategic Highway Research Program was to develop performance based tests and specifications for Hot Mix Asphalt Materials. Progress was made in achieving that goal. However, there remains work to be done as identified previously. The HMA Industry must gain a thorough understanding of the SHRP products and use this information to build towards the goal of true performance-based products.

Detailed research and project plans are in the formative stage. The HMA Industry has worked with funding agencies for many years to provide input to research and implementation activities. We look to continue the current process and expand the activity to include development of research needs.

An initial meeting has been held on the research needs issue. Additional forums to develop research agendas are planned.

A ten-year research program, with specific budget outlays, has not been completed at this time.



Bending beam rheometer. Test developed by SHRP to analyze asphalt binders at low temperature.

National Center for Asphalt Technology

Hot Mix Asphalt Working Group Members

Dale S. Decker
Chairperson
National Asphalt Pavement Association

Byron Lord
Federal Highway Administration

Since full and complete industry input was not obtained by the time of publication, the Hot Mix Asphalt chapter should be considered preliminary; the intent is to provide an overview of the evolving HMA perspective. The HMA working group consists of the individuals listed above.

Chapter 8

High-Performance Masonry

Masonry's versatile appearance, long-term durability and high compressive strength have long been recognized. The Great Wall of China, the Roman Colosseum, St. Peter's Cathedral, the Empire State Building—such buildings testify to masonry's durability. The variety of sizes, shapes, colors, and textures evidenced in modern buildings such as the Carnegie Hall Tower or the Exeter Library provide aesthetic variation which enriches our heritage. Moreover, recent advances in resistance to severe environments may increase masonry's value as a building component.

Masonry units are locally produced; raw materials are universally available and abundant. Therefore individual properties of units and mortar must be selected to meet specific design requirements. Masonry is multi-functional: it combines structure and finish; serves as an environmental barrier to thermal changes, noise and fire; is resistant to seismic and wind loads and its hand placement results in site-adaptable construction. High-Performance Masonry (HP Masonry) will result in masonry projects achieving full resistance to severe environments. This resistance to freeze-thaw deterioration, chemical attack, and water penetration will increase HP Masonry's versatility as a building component. A building using HP Masonry may not need repair for 100 years compared to a building with conventional materials which typically needs some type of repair within 30 years.

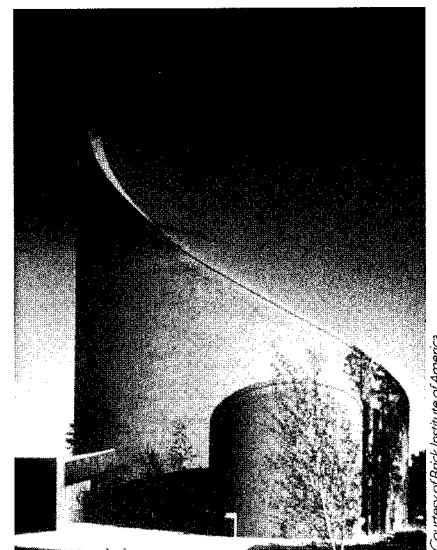
What is High-Performance Masonry?

Masonry, an assemblage of manufactured masonry units normally bonded together with a cement based mortar to act as a single, composite material, serves as a structural element, an architectural element, or both. Primarily, masonry is used as walls in buildings and landscaping, but it serves equally well as foundations, paving and for fireplaces.

HP Masonry optimizes the structural, architectural and construction capabilities of unit masonry by maintaining its current benefits while providing needed improvements in such areas as structural performance and durability. High-performance masonry will improve one or more of:

- Manufacture and quality of materials
- Effectiveness and efficiency of design methods
- Economy and quality of construction
- Structural performance
- Durability and robustness
- Project life span in severe environments

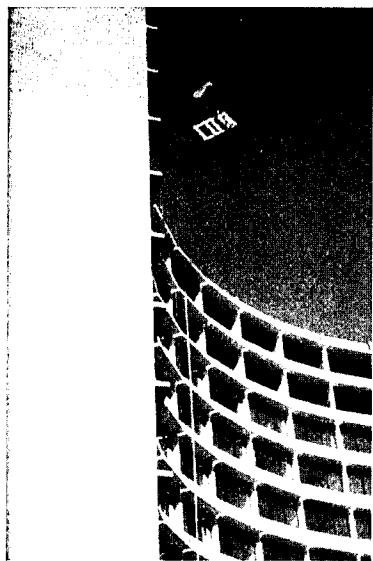
A building using HP Masonry may not need repair for 100 years compared to a building with conventional materials which typically needs some type of repair within 30 years.



Church, Red Deer, Canada. Sculptural forms in structural brick masonry express the architect's design.

Courtesy of Brick Institute of America

...improvements are needed in materials performance, testing procedures, design methods and construction procedures.



The concrete masonry walls on this high rise hotel provide structure, fire resistance, and sound control.

HP Masonry use will retain the best of locally produced materials without compromising the environment. More consistent and predictable performance is considered integral to these improvements.

High-performance design methods optimize the use of these materials in the completed structure and will provide explicit procedures to integrate the masonry with other building components and detail requirements. Moreover, high-performance design methods will enhance the architectural versatility of masonry.

HP Masonry construction procedures improve installation efficiencies and reduce variability. Improvements in material handling systems and alternatives to current procedures of hand placement will be incorporated into construction procedures.

Masonry's high compressive strength makes it an ideal material to resist vertical loads. Its low tensile strength and brittle nature will be overcome in high-performance masonry to result in a material with balanced properties. Horizontal loads will be resisted with the same capacity as that for vertical loads, for example, developing prestressed masonry retaining walls to resist soil pressure or constructing noise barrier walls along highways to resist wind loads. The resulting structures will have the stiffness and robustness to resist all loads with little damage to the structure, the architectural and mechanical components and, without loss of life. Techniques for evaluation completed elements and performance based systems which respond to site conditions provide assurance that the expected structural performance is achieved. Advances in materials, design, analysis, testing and construction are required to achieve this level of structural performance.

Development of HP Masonry

Masonry construction uses materials and construction procedures that are essentially unchanged from those established by experience and tradition over past decades. Thus, masonry materials have gradually evolved to their current status. However, improvements are needed in materials performance, testing procedures, design methods and construction procedures. Key elements in HP Masonry research and deployment include advances in the following areas:

- Mortar bonds strengths which exceed unit tensile strength
- Prestressing with ceramic fibers
- Rapid-firing of ceramic units
- Ultra-light weight concrete masonry units
- Robotic devices for placing units

Although a basis of knowledge about specific materials properties has been developed, the interaction mechanisms of all of masonry materials are not fully understood. The manner in which applied loads are transferred within masonry elements and how these elements react with other structural members needs to be thoroughly documented. Some of the influencing factors related to hand placement and site conditions that affect the quality of masonry have been identified, but methods of controlling many of these parameters have not been developed. Testing procedures have been developed for individual materials but there is a lack of procedures to evaluate the performance capability of in-place masonry.

Current Constraints to High-Performance Masonry Use

Several of masonry's attributes, such as its resistance to seismic and wind loads, are not fully exploited and point to needed improvements. Job-site assembly may lead to inconsistent quality, sensitive to site conditions. The multiplicity of materials makes masonry a complex system for analysis. Due to its brittle nature, masonry requires reinforcement to increase its tensile strength and provide ductility.

Advances in the manufacture of materials are needed to optimize materials. Construction methods and quality control/assurance need to be evaluated and modified to improve the reliability and economy of structures. The historically successful performance of masonry has inhibited the development of documented research on physical properties and behavior. All aspects of masonry materials performance need to be better understood, including the load response of structures; designers, suppliers, and craftsmen who build with masonry are often inadequately informed.

Current Projects Demonstrating HP Masonry's Effectiveness

The overall goal is to develop HP masonry materials and components which fulfill their structural performance requirements at minimum cost to the user and to the environment. Exemplary efforts include the following. The Technical Coordinating Committee for Masonry Research (TCCMaR) is currently engaged in a 12-year study encompassing materials, small scale specimens, building components and combinations, and full size multi-story structures. Dynamic loading, analytical models and design methods are utilized. Under the U.S. Army Corps of Engineers CPAR Program, prestressed brickwork research is currently underway at the University of Nebraska. Lastly, wall systems research at the Center for Engineering Ceramic Manufacturing is investigating new brick unit shapes, mortar materials and means of applying interior finishes.

Development of Research Projects

The research projects outlined on the pages that follow were given highest priority by a steering committee organized by the Council for Masonry Research. The committee met under the auspices of the Advanced Technology Program of the National Institute of Standards and Technology. This committee recognized that technology transfer is as important as practical or conceptual research. Thus, each of the research areas includes a means of applying the accumulated knowledge. Several of these research topics were developed during the successful Technical Coordinating Committee for Masonry Research partially funded through the National Science Foundation. The TCCMaR provided development work which serves as a basis for several topics.

Centers for Research and Technology Transfer

High-Performance Masonry Research

Brick Institute of America

Center for Engineering Ceramic Manufacturing

National Concrete Masonry Association

Portland Cement Association

Atkinson Noland Associates

Robert Nelson & Associates

Wiss, Janney, Elstner Associates

Universities such as California-San Diego, California-Berkeley, Clemson, Colorado, Drexel, Illinois, Maryland, Texas-Austin, Texas-Arlington

Technology Transfer

American Society of Civil Engineers

Brick Institute of America

Council for Masonry Research

International Masonry Institute

National Concrete Masonry Association

The Masonry Society

Trades associations such as Mason Contractors Association of America, National Lime Association, Portland Cement Association

Regional and local promotional groups and masonry institutes

Universities such as California-San Diego, California-Berkeley, Clemson, Colorado, Drexel, Illinois, Maryland, Texas-Austin, Texas-Arlington

MASONRY

Prioritized Research Projects

Research Topic	Research Project	Objective	Approach	Schedule	Budget	Public Agency	Benefits
High-Performance Masonry Structural Behavior	Property Sensitivity Studies	Conduct sensitivity studies to establish the comparative importance of properties for performance objectives.	Identify variables related to raw materials and production methods. Identify variables related to assemblage construction and performance. Analyze influence of variable on units, mortar, grout and assemblages. Knowledge of the sensitivity of performance attributes to the various parameters which affect it will enable measures to be taken to provide and control those which most directly affect performance.	5 years	\$5.75M	HUD GSA USACE NIST	Achieve optimum properties Better control of material properties. Improved quality assurance. Reduced construction costs.
High-Performance Masonry Structural Behavior	Improved Mechanical Properties of Masonry Assemblage	Develop assemblages which provide increased tension, flexural tension, shear and ductility capacity.	Develop material with higher strain capacity. Improve unit/mortar bond strength. Develop alternate grout with no shrinkage or water loss which has adequate bond to units and reinforcement. Investigate grout with tensile capacity to replace or reduce reinforcement needs.	5 years	\$6.0M	Post Office HUD USACE NRC	Brittle materials, such as masonry, are good in compression and an economical form of construction. Optimal utilization requires measures to provide masonry with essentially equal capacity under all stresses. Increased life safety. Reduced property damage.
High-Performance Masonry Structural Behavior	Dynamic Properties	Document and develop dynamic properties of masonry.	Develop reliable procedures for measuring masonry performance under dynamic loads. Evaluate and improve dynamic performance of masonry.	8 years	\$13.5M	FEMA NSF USACE NRC NIST	Design which utilizes material capacity. Increased life safety. Reduced property damage.

Research Topic	Research Project	Objective	Approach	Schedule	Budget	Public Agency	Benefits
High-Performance of Masonry Under Service Conditions	Deterioration Sciences	Affect solutions to mechanisms which cause a deterioration of masonry materials in service.	Link unit and mortar physical properties to durability. Study mechanisms of freeze-thaw and salt-crystallization damage. Examine moisture and humidity movements through masonry. Study means to reduce corrosion. Although masonry is inherently a durable material, certain conditions may cause deterioration with its corresponding undesirable effects upon service life, structural integrity and appearance. The deterioration mechanisms of masonry materials if known and quantified will enable materials to be correspondingly improved.	3 years	\$1.75M	GSA USACE NRC	Reduced maintenance costs Reduced life-cycle costs. Increased life of building.
High-Performance of Masonry Under Service Conditions	Control of Environmental Conditions	Develop design techniques and masonry unit materials/configurations for resistance to heat, fire, sound and water.	Measure and model in order to predict the response of masonry structures to these environmental conditions. Evaluate performance of masonry after fire exposure. Investigate means to improve behavior by new unit materials and configurations. Evaluate how to improve performance in these areas through modifications to current materials properties, design methods, or construction procedures. Masonry must provide desirable performance attributes in addition to structural. An optimal balance of the functional characteristics will lead to more efficient buildings.	8 years	\$10.0M	GSA HUD DOE	Lower building operating costs. Increased safety and comfort for building occupants.
Construction Technology	Improved Construction Techniques	Develop construction techniques which are cost-effective and which have reduced sensitivity to construction variables.	Investigate the effects of moisture content and physical properties of units on performance of the resulting masonry. Document the effects of cold and hot weather. Investigate assembly techniques to reduce sensitivity to worker skills. It has been observed that construction site conditions may affect the quality of masonry. New design methodologies will reward consistent quality of construction by recognizing the improved reliability.	3 years	\$0.75M	USACE	Reduced cost of construction. Reduced time of construction.
Construction Technology	Acceptance of Materials and Workmanship	Develop an effective quality assurance program for high-performance materials and workmanship.	Develop reliable and error free details of construction. Develop real time evaluation methods for construction quality. Develop procedures for establishing reliability based quality assurance program. Improved quality assurance and control combined with improved construction technologies are needed to provide a consistent level of reliability. Again, new design methodologies will reward improved reliability.	4 years	\$1.25M	GSA USACE	Reduced cost of construction. Reduced time of construction. Increased life safety.

Research Topic	Research Project	Objective	Approach	Schedule	Budget	Public Agency	Benefits
Construction Technology	Expert System for Specifications and Construction	An integrated process linking design, specifications and construction.	Identify variables in materials selection and how their use is influenced by construction site variables. Develop a data base and program that links these subjects. Develop application software. Integration of the design-construction process is needed to assure that all aspects are addressed and corresponding requirements are met. A computer-based expert system will optimize this integration.	6 years	\$1.5M	GSA HUD	Reduced design time and costs. Reduce job-site delays. Optimum utilization of materials.
Advanced Masonry Concepts	Preassembly	Determine relative advantages of site-built versus prefabricated masonry construction and develop construction systems and procedures that combine the benefits of both.	Investigate new assembly techniques such as a flexible matrix, mortarless interlocking units or dry-stacked grout injection. Examine techniques for joining prefabricated assemblies. Preassembly may provide higher levels of quality, reliability and cost effectiveness than possible in the field for certain types of masonry components.	8 years	\$8.25M	USACE DOL OSHA NIST	Reduced construction time. Year-round employment.
Advanced Masonry Concepts	Non-Building Applications	Apply masonry's properties and attributes in applications with economy of scale.	Identify needs and match masonry properties for applications such as: retaining walls, environmental remediation facilities, runway underlayment, storage tanks, catalytic surfaces. Masonry construction should be explored for applications other than buildings because it may offer a more reliable and cost-effective approach.	4 years	\$1.5M	FHWA EPA Interior DOT	Reduced structures cost. Better control of environmental concerns.
Advanced Masonry Concepts	Smart Materials and Structures	Materials and structures which respond depending on the conditions.	Develop materials which respond to stimuli such as temperature, stress or moisture and change their resistance to the stimuli. Develop connection devices and materials whose physical properties and response are rate- or direction-sensitive. Develop automatic changes in ventilation which depend on environmental and loading conditions. A given structure may be exposed to a wide variety of environmental and structural environments during its life. Its performance and/or structural integrity may degrade as a result. "Smart" materials and structures would provide means for warning of reduced capacities.	6 years	\$1.9M	EPA DOE	Increased life safety. Reduced property damage.

Research Topic	Research Project	Objective	Approach	Schedule	Budget	Public Agency	Benefits
Advanced Masonry Concepts	Smart Materials and Structures	Materials and structures which respond depending on the conditions.	Develop materials which respond to stimuli such as temperature, stress or moisture and change their resistance to the stimuli. Develop connection devices and materials whose physical properties and response are rate- or direction-sensitive. Develop automatic changes in ventilation which depend on environmental and loading conditions. A given structure may be exposed to a wide variety of environmental and structural environments during its life. Its performance and/or structural integrity may degrade as a result. "Smart" materials and structures would provide means for warning of reduced capacities.	6 years	\$1.9M	EPA DOE	Increased life safety. Reduced property damage.
Advanced Masonry Concepts	Service Life Prediction/Improvement	To provide means of predicting service life considering known and anticipated conditions of service. To identify critical parameters which extend or reduce useful service life to incorporate results into the design, material and construction technologies.	Investigate and quantify maintenance tasks on masonry structures. Identify those parameters and conditions which cause such tasks. Prepare recommendations for material properties, design methods and construction techniques.	6 years	\$1.5M	GSA HUD USACE VA	Reduced maintenance costs Reduce life-cycle costs. Increased useful life of structures.
Instrumentation Monitoring and Structuring	New Test Methods	Develop new means of determining physical properties of masonry and its applications.	Identify current instrumentation and that which must be developed to document stress, strain, temperature and moisture. Establish field tests to verify compliance with contract documents. Develop test methods and criteria for in-situ masonry. Develop nondestructive evaluation test methods to learn current condition and remaining service life. Develop tests which measure actual material assemblage properties, rather than index values, for use in linear and non linear analyses.	7 years	\$7.8M	NIST NSF	Reduced construction costs. Increased useful life of structures.
Instrumentation Monitoring and Structuring	Guides to Design	Instrument masonry buildings and evaluate response to changing conditions.	Identify key structural and environmental control locations in typical buildings. Instrument and monitor stimuli and response. Develop design recommendations based on observed behavior.	7 years	\$7.0M	VA FEMA	Reduced construction costs Increased life safety. Reduced property damage.
Total Program Outlay					\$68.45M		

Masonry Prioritized Timeline and Budget Allocation

Year	Project	Duration (in years)	Cost
1	Property Sensitivity Studies	5	\$1,250,000
	Deterioration Sciences	3	750,000
	Improved Construction Techniques	3	250,000
	Preassembly	8	750,000
	New Test Methods	7	1,000,000
Year 1 Total \$4,000,000			Cumulative Total \$4,000,000
2	Property Sensitivity Studies	5	\$1,000,000
	Dynamic Properties	8	1,500,000
	Deterioration Sciences	3	500,000
	Improved Construction Techniques	3	250,000
	Preassembly	8	1,000,000
	New Test Methods	7	1,000,000
Year 2 Total \$5,250,000			Cumulative Total \$9,250,000
3	Property Sensitivity Studies	5	\$1,000,000
	Dynamic Properties	8	2,000,000
	Deterioration Sciences	3	500,000
	Control of Environmental Conditions	8	1,250,000
	Improved Construction Techniques	3	250,000
	Acceptance of Materials and Workmanship	4	300,000
	Preassembly	8	1,000,000
	Non-building Applications	4	300,000
	New Test Methods	7	1,200,000
Year 3 Total \$7,800,000			Cumulative Total \$17,050,000
4	Property Sensitivity Studies	5	\$1,000,000
	Dynamic Properties	8	1,500,000
	Control of Environmental Conditions	8	1,000,000
	Acceptance of Materials and Workmanship	4	300,000
	Preassembly	8	1,250,000
	Non-building Applications	4	400,000
	New Test Methods	7	1,200,000
	Guides to Design	7	1,000,000
	Service Life Prediction	6	200,000
Year 4 Total \$7,850,000			Cumulative Total \$24,900,000

Year	Project	Duration (in years)	Cost
5	Property Sensitivity Studies	5	\$1,500,000
	Dynamic Properties	8	1,500,000
	Control of Environmental Conditions	8	1,000,000
	Acceptance of Materials and Workmanship	4	300,000
	Expert Systems for Specifications and Construction	6	200,000
	Preassembly	8	1,000,000
	Non-building Applications	4	400,000
	Smart Materials and Structures	6	200,000
	New Test Methods	7	1,200,000
	Guides to Design	7	1,000,000
	Service Life Prediction	6	200,000
Year 5 Total \$8,500,000			
Cumulative Total \$33,400,000			
6	Improved Mechanical Properties	5	\$1,500,000
	Dynamic Properties	8	2,000,000
	Control of Environmental Conditions	8	1,000,000
	Acceptance of Materials and Workmanship	4	350,000
	Expert Systems for Specifications and Construction	6	250,000
	Preassembly	8	1,000,000
	Non-building Applications	4	400,000
	Smart Materials and Structures	6	300,000
	New Test Methods	7	1,200,000
	Guides to Design	7	1,000,000
	Service Life Prediction	6	250,000
Year 6 Total \$9,250,000			
Cumulative Total \$42,650,000			
7	Improved Mechanical Properties	5	\$1,000,000
	Dynamic Properties	8	2,000,000
	Control of Environmental Conditions	8	1,250,000
	Expert Systems for Specifications and Construction	6	250,000
	Preassembly	8	1,250,000
	Smart Materials and Structures	6	400,000
	New Test Methods	7	1,000,000
	Guides to Design	7	1,000,000
	Service Life Prediction	6	250,000
Year 7 Total \$8,400,000			
Cumulative Total \$51,050,000			

Year	Project	Duration (in years)	Cost
8	Improved Mechanical Properties	5	\$1,000,000
	Dynamic Properties	8	1,500,000
	Control of Environmental Conditions	8	1,000,000
	Expert Systems for Specifications and Construction	6	250,000
	Preassembly	8	1,000,000
	Smart Materials and Structures	6	350,000
	Guides to Design	7	1,000,000
	Service Life Prediction	6	300,000
			Year 8 Total \$6,400,000
			Cumulative Total \$57,450,000
9	Improved Mechanical Properties	5	\$1,000,000
	Dynamic Properties	8	1,500,000
	Control of Environmental Conditions	8	1,500,000
	Expert Systems for Specifications and Construction	6	250,000
	Smart Materials and Structures	6	350,000
	Guides to Design	7	1,000,000
	Service Life Prediction	6	300,000
			Year 9 Total \$5,900,000
			Cumulative Total \$63,350,000
10	Improved Mechanical Properties	5	\$1,500,000
	Control of Environmental Conditions	8	2,000,000
	Expert Systems for Specifications and Construction	6	300,000
	Smart Materials and Structures	6	300,000
	Guides to Design	7	1,000,000
			Year 10 Total \$5,100,000
			Cumulative Total \$68,450,000

Masonry Working Group Members

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Chairperson
Council for Masonry Research

J. Gregg Borchelt
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Harry Francis
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Don Grant
Grant Contracting Company

Al Isberner
Consulting Engineer

Richard Klingner
University of Texas-Austin

John Melander
Portland Cement Association

Jim Noland
Atkinson Noland Associates

Paul Stutzman
National Institute of Standards and Technology

Chapter 9

High-Performance Roofing Materials

Annually, the U.S. construction industry spends more than \$16 billion on roofing; approximately 25 percent (\$4.1 billion) is used for residences. Approximately 79 percent (\$13.1 billion) of the total roofing market consists of work on existing buildings (repairs and re-roofing), with the remaining 21 percent for new construction. On many large commercial buildings, the roof accounts for more than one-half of the building's exterior, protecting the building from the elements. Current roofing industry estimates indicate that more than 2 billion square meters (25 billion square feet) of low-slope roofs are in place in the U.S.; in addition, there are roofs on an estimated 100 million homes. Not only are roofs an important and substantial component of the construction industry, but also roofs, more so possibly than any other building component, must withstand moisture, variations in temperature, and wind and building movements. Roofs must also be able to withstand nature's worst disasters, such as fires, hailstorms, hurricanes and earthquakes.

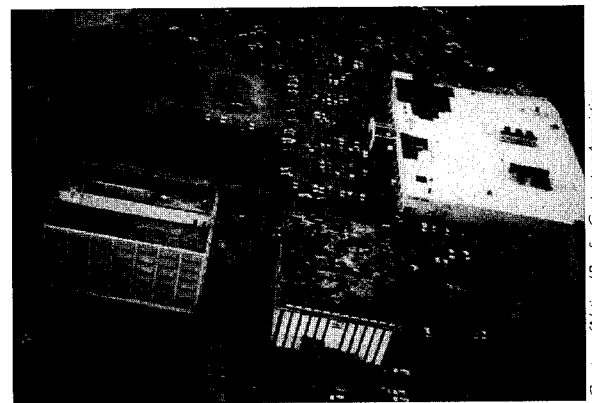
However, Hurricane Andrew and Hugo, as well as the recent tornadoes in Georgia, Illinois, and Texas, have demonstrated that more research and development work must be done on roof systems so that they will perform in high wind situations. As evidenced by the rebuilding required after the storms, current roof systems are insufficient for such significant wind uplift forces. By developing a roofing system that could account for these forces, the U.S. could save billions of dollars in future rebuilding efforts. In addition, other developments in roofing systems may reduce building energy use by up to 50 percent in some southern climates.

Similarly, enormous economic benefits could be realized in the U.S. by extending the average useful life of roofs. The roofing industry estimates that savings in roof replacement costs to building owners of approximately \$8.8 billion could be realized in the U.S. for each year it is possible to extend the average useful life of roofs.

What is a High-Performance Roof System?

We need to look at buildings as long-term investments and need to develop roof systems that will serve for a hundred years or more. A roof can be characterized as a system because it is composed of several materials assembled in separate operations, necessarily at the job site. These materials may include a vapor retarder, thermal insulation, mechanical fasteners or adhesives, the waterproofing membrane, and a surfacing. Thus, the study of superior, high performance roofs should involve the study of the roof as a system.

We need to look at buildings as long-term investments and need to develop roof systems that will serve for a hundred years or more.



Wind-related roof damage from Hurricane Andrew.

Courtesy of National Roofing Contractors Association

Unlike a conventional roof, high-performance roof systems will have such qualities as improved wind and fire resistance, longer service life and lower life-cycle costs, and improved energy efficiency. A high-performance roof system will include one or more of:

Improved Functional Performance

- Enhanced impact resistance
- Enhanced fire resistance
- Enhanced wind resistance
- Improved acoustical properties
- Enhanced weather tightness
- Self-diagnosing and self-healing properties
- Improved predictability
- Improved compatibility with other building components
- Heat reflectivity

Improved Efficiencies

- Easier to transport and store
- Easier to install in all weather conditions
- Easier to inspect
- Easier to maintain
- Easier to repair

Improved Health and Environmental Compatibility

- Improved safety in the manufacturing environment
- Improved safety for applicators
- Improved safety for occupants
- Aesthetically pleasing
- Environmentally friendly

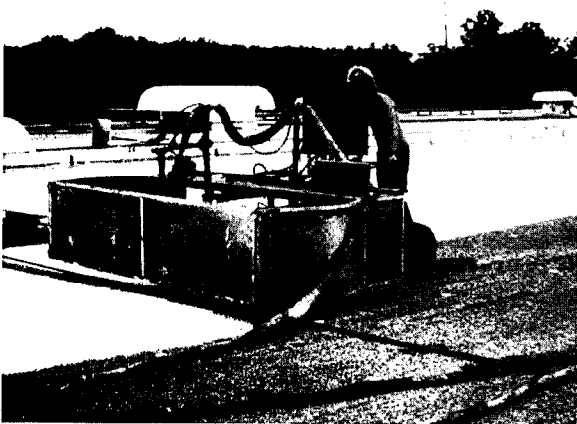
Development of High-Performance Roof Systems

On average, a roof on a typical building has a useful life of approximately 12 to 15 years before repair, if not complete replacement, is necessary. However, it is not unusual to find a roof that has performed satisfactorily for up to 50 years—even longer in some instances.

The performance of roofs has long been regarded to rely heavily on the use of proper roofing materials, and proper design and installation. While it is already possible to produce roofs with a

longer than average service life, roof designers and building owners generally consider the associated costs to be prohibitive. At the same time, the industry has yet to perfect a method to optimize all the factors necessary to consistently produce roofs of a maximum service life potential.

A central source for roofing materials research does not exist in the U.S.



Automated rooftop equipment for the application of sprayed polyurethane foam and coating roofing materials at controlled, uniform rates.

In addition to the attributes necessary for roofs of the past, roofs of today and the future have new demands placed on them, as well. For example, roofs today play a large role in the overall thermal efficiency of buildings, much more so than 25 years ago. Also, roofs must be environmentally safe during manufacture, installation, throughout their service lives, and upon their eventual disposal.

The study of high performance roof systems should be oriented toward optimizing the performance of roof materials, workmanship and design concepts to achieve a maximum service life, while also expanding to address the needs of today and the future.

Current Constraints to High-Performance Roofs

Although the goals for high-performance roof systems are clear, the roofing industry in the U.S. needs research programs to guide it toward high performance roof systems. Currently, the amount of ongoing research in the industry is minimal. There are no industry-specific, university-sponsored research programs in place; thus, only a few of the goals listed above have been met. Furthermore, only a minimal number of programs are underway where roofing is incidental to an overall larger scope.

The roofing material manufacturing community is diverse, and only a few firms have any ongoing research activities. Also, **a central source for roofing materials research does not exist in the U.S.** The need for new direction in roof system research is clear if we are to address the problems that have faced the industry for decades and expand to fit the demands and needs of the future. Currently, industry-sponsored initial research is underway at Colorado State University and Texas Tech University regarding the wind resistance of asphalt shingle roofs and roof edge detailing. Such research should have a notable impact on the wind resistance of roof systems.

Current Projects Demonstrating the Effectiveness of High-Performance Roof Systems

The Lawrence Berkeley Laboratory (LBL) project on cool building materials illustrates the benefits of high performance roof systems. LBL research has shown that cool roof surfaces, those which reflect visible and near infrared radiation, may reduce building energy use by up to 50 percent in some hot climates. Identifying and developing efficient reflective roof materials may result in reduced energy costs. Moreover, these materials, unlike conventional roof materials, may better protect roof surfaces and provide for a long service life.

A joint government and industry-sponsored research program is being conducted at Oak Ridge National Laboratory evaluating the effectiveness of replacement blowing agents for thermal insulation where ozone depleting materials were previously used. This research will result in updated criteria for determining the thermal resistance of certain thermal insulation products and should result in the initial concepts for developing the next generation of thermal insulation materials.

Centers for High-Performance Roofing Materials Research

Clemson University

Colorado State University

Army Construction Engineering Research Laboratory

Army Cold Regions Research & Engineering Laboratory

Lawrence Berkeley Laboratory

National Institute of Standards and Technology

Oak Ridge National Laboratory

Texas Tech University

U.S. Air Force

U.S. Army Corps of Engineers

U.S. Navy

Centers for High-Performance Roofing Materials Technology Transfer

Asphalt Roofing Manufacturers Association

National Roofing Contractors Association

Roof Coatings Manufacturers Association

Roofing Industry Educational Institute

Single Ply Roofing Institute

Various materials manufacturers

ROOFING MATERIALS

Prioritized Research Projects

Research Topic	Research Project	Objective	Approach	Schedule	Budget	Public Agency	Benefits
Service Life	Develop service life predictability methodology	Develop test methodology and mathematical models to predict the service life of existing and newly developed roof materials and systems.	An initial step is to survey existing roofs and develop a sound statistical base of existing roof systems. This statistical information would then be mathematically modeled and tested for accuracy. Based upon the findings of the field investigations, laboratory studies will be initiated to develop evaluation procedures for assessing the capability of materials and systems to resist common modes of roof failure.	10 years	\$ 10.0M	NIST	Service life predictability.
Diagnostic Methods	Develop diagnostic methods	Develop effective means to diagnose roof system problems and predict failure.	Establish a central test center, with a permanent "smart roof" test apparatus where various roof systems and components can be tested. Diagnostic test methods and procedures will need to be developed and refined, but may include electronic sensors embedded into the roof system and monitoring equipment which is readily accessible and capable of making comparative assessments.	10 years	\$ 11.5M	NIST	Failure prediction.
Wind resistance	Develop criteria for wind resistance	Develop methodologies, including loading and testing criteria, and design guidelines to facilitate wind-resistant roof systems.	Three major universities with experience in wind testing, Texas Tech University, Colorado State University, and Clemson University, have been involved in the initial development of a multi-step research program to develop enhanced wind resistance. These steps include, for example, analysis of metal edge flashing details, air permeable roof covering materials, air retarders and dynamic testing of single ply membranes, each which have significant impact on roof performance in high winds, but only limited data is currently available. Implementation of this type of program is essential for the development of dynamic wind resistant roofs.	6 years	\$ 11.0M	NIST	Improved wind resistance.

Research Topic	Research Project	Objective	Approach	Schedule	Budget	Public Agency	Benefits
Application	Develop improved application techniques	Create improved methods of application of roof systems to ensure consistent levels of quality.	Study existing work practices to determine which particular work operations would be best suited to improved methods. Develop appropriate new work methods, and prototype equipment and possibly robotics.	5 years	\$ 10.0M	NIST	Improved application methods.
Health and Safety	Examine health and safety implications	Develop high performance roof system components that are safe to use and environmentally friendly.	Examine health, safety, and environmental issues of existing materials and identify roof system components that would benefit from high performance materials development. Current major existing industry issues include asphalt fuming, VOC compliant materials, and the future replacement of CFC's and HCFC's in high-thermal insulation materials. Development of efficient means of recycling discarded roofing materials is also a high priority.	10 years	\$ 10.0M	DOL	Improved health and safety.
Information Database	Develop a database for roofing information	Establish a single source for information related to roofing technology, and have the information appropriately cataloged and readily accessible.	An initial step is to develop a central database of current roofing information, with the information appropriately studied, cataloged and cross-referenced. Newly produced information can be added on an ongoing basis to keep the database up to date with advancing, high performance technology.	10 years	\$ 13.0M	NIST	Central information source.
Hail Resistance	Develop criteria for hail resistance	Develop high performance roof systems that are resistant to hail damage.	Initial research would concentrate on determining the effect an impact has on the performance of roof systems. Further research would determine if coating performance is impaired by impact. This research would lead to a definition of what constitutes a failure following impact and would provide a basis for the development of appropriate hail resistant materials.	6 years	\$ 10.5M	NIST	Improved hail resistance.

Research Topic	Research Project	Objective	Approach	Schedule	Budget	Public Agency	Benefits
"Cool" Roofing Materials	Develop "cool" roofing materials	Identify and develop roofing materials that will assist in reducing urban heat sinks, especially in warm-weather big cities, and enhance the overall performance of roof systems.	Many roofing materials can be manufactured with reflective surfacings to achieve the objective. Existing roofs can be treated with reflective coatings. Researchers at Lawrence Berkeley Laboratory are proposing a phase-in approach: replacing roofs that fail due to normal attrition with non-absorptive roofs. More data is needed and work will have to be done to identify the desirable properties in coatings and surfacings. In addition, performance considerations will have to be taken into account and will weigh heavily into acceptance of "cool" materials.	6 years	\$ 6.0M	DOE	Improved thermal efficiency.
Thermal Efficiency	Develop criteria for thermally efficient materials	Establish criteria for development of the next generation of energy efficient roof system components.	An initial step is to establish criteria for thermally efficient materials that will suit the objective. Develop prototype materials, and perform testing of mechanical properties and performance.	5 years	\$ 5.0M	DOE	Improved thermal efficiency.
Roof coatings	Develop criteria for high performance roof coatings	Establish criteria for the development of the next generation of protective, energy efficient roof system coating materials.	An initial step is to establish criteria for roof coating materials that will suit the objective. Development of suitable coating materials will need to take place and these new materials will need to be performance tested.	5 years	\$ 5.0M	DOE	Improved service life/thermal efficiency.
Roofing Research	Establish a "Roofing Research Center"	Establish a research center to continue research and development of new roofing materials and technologies beyond the completion of the high performance materials project.	Develop a research center, possibly in conjunction with a research institution or major university, to continue roof system research and development.	8 years	\$11.5M	NIST	Continuation of research.
Total Project Outlay					\$103.5M		

Roofing Material Prioritized Timeline and Budget Allocation

Year	Project	Duration (in years)	Cost
1	Service life	10	\$ 1,000,000
	Diagnostic methods	10	2,500,000
	Wind resistance	6	2,000,000
	Application	5	500,000
	Health and safety	10	1,000,000
	Information database	10	2,500,000
Year 1 Total \$9,500,000 Cumulative Total \$9,500,000			
2	Service life	10	\$ 1,000,000
	Diagnostic methods	10	1,000,000
	Wind resistance	6	2,000,000
	Application	5	500,000
	Health and safety	10	1,000,000
	Information database	10	2,500,000
Year 2 Total \$8,000,000 Cumulative Total \$17,500,000			
3	Service life	10	\$ 1,000,000
	Diagnostic methods	10	1,000,000
	Wind resistance	6	2,000,000
	Application	5	3,000,000
	Health and safety	10	1,000,000
	Information database	10	1,000,000
	"Cool" roofing materials	6	1,500,000
	Roofing research center	8	1,437,500
Year 3 Total \$11,937,500 Cumulative Total \$29,437,500			
4	Service life	10	\$ 1,000,000
	Diagnostic methods	10	1,000,000
	Wind resistance	6	2,000,000
	Application	5	3,000,000
	Health and safety	10	1,000,000
	Information database	10	1,000,000
	Hail resistance	6	2,000,000
	"Cool" roofing materials	6	1,000,000
	Roofing research center	8	1,437,500
Year 4 Total \$13,437,500 Cumulative Total \$42,875,000			

Year	Project	Duration (in years)	Cost
5	Service life	10	\$ 1,000,000
	Diagnostic methods	10	1,000,000
	Wind resistance	6	2,000,000
	Application	5	3,000,000
	Health and safety	10	1,000,000
	Information database	10	1,000,000
	Hail resistance	6	2,000,000
	"Cool" roofing materials	6	1,000,000
	Roof coatings	5	1,000,000
	Roofing research center	8	1,437,500
Year 5 Total \$14,437,500 Cumulative Total \$57,312,500			
6	Service life	10	\$ 1,000,000
	Diagnostic methods	10	1,000,000
	Wind resistance	6	1,000,000
	Health and safety	10	1,000,000
	Information database	10	1,000,000
	Hail resistance	6	2,000,000
	"Cool" roofing materials	6	1,000,000
	Thermal efficiency	5	1,000,000
	Roof coatings	5	1,000,000
	Roofing research center	8	1,437,500
Year 6 Total \$11,437,500 Cumulative Total \$68,750,000			
7	Service life	10	\$ 1,000,000
	Diagnostic methods	10	1,000,000
	Health and safety	10	1,000,000
	Information database	10	1,000,000
	Hail resistance	6	2,000,000
	"Cool" roofing materials	6	1,000,000
	Thermal efficiency	5	1,000,000
	Roof coatings	5	1,000,000
	Roofing research center	8	1,437,500
Year 7 Total \$10,437,500 Cumulative Total \$79,187,500			

Year	Project	Duration (in years)	Cost
8	Service life	10	\$ 1,000,000
	Diagnostic methods	10	1,000,000
	Health and safety	10	1,000,000
	Information database	10	1,000,000
	Hail resistance	6	2,000,000
	"Cool" roofing materials	6	500,000
	Thermal efficiency	5	1,000,000
	Roof coatings	5	1,000,000
	Roofing research center	8	1,437,500
Year 8 Total \$9,937,500 Cumulative Total \$89,125,000			
9	Service life	10	\$ 1,000,000
	Diagnostic methods	10	1,000,000
	Health and safety	10	1,000,000
	Information database	10	1,000,000
	Hail resistance	6	500,000
	Thermal efficiency	5	1,000,000
	Roof coatings	5	1,000,000
	Roofing research center	8	1,437,500
Year 9 Total \$7,937,500 Cumulative Total \$97,062,500			
10	Service life	10	\$ 1,000,000
	Diagnostic methods	10	1,000,000
	Health and safety	10	1,000,000
	Information database	10	1,000,000
	Thermal efficiency	5	1,000,000
	Roofing research center	8	1,437,500
Year 10 Total \$6,437,500 Cumulative Total \$103,500,000			

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Chapter 10

Smart Material Devices and Monitoring Systems

Conventional construction methods for buildings, roads, and bridges do not have the ability to provide data about usage, about remaining life, or about specific areas requiring maintenance. Other than by infrequent on-site inspection, state and local authorities responsible for maintenance and upkeep have little or no access to this crucial information. For example, the U.S. currently has no means to monitor load or evaluate accumulated damage to our more than 575,000 bridges. And annually, an estimated 1,000 bridges will be "lost."

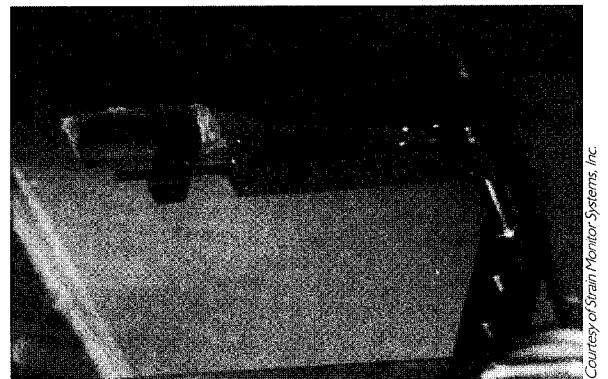
However, by further developing and applying emerging technology in smart materials, together with a communications infrastructure, the United States could better manage its constructed facilities. In particular, bridge management could include remote monitoring to obtain key information concerning bridge health, including water flow rates, scouring effects, and support creep, as well as icing conditions and fatigue and corrosion damage. By incorporating smart materials, a sizable percentage of the interstate system of bridges and highways could be monitored and maintained in a more cost-efficient manner. As an added benefit, the proposed information network that will make this possible could also track much of the hazardous materials transport on our highways.

The promise that smart materials holds for bridge management also holds true for our interstate pipeline and storage tank system. By application of simple materials-based, low maintenance sensor-suites, the integrity of pipelines can be monitored in real-time for impending failure and for efficient, timely deployment of maintenance and repair crews.

What are Smart Material Devices and Monitoring Systems?

Most *smart* or *active* materials are materials different from, but overlapping, new coating materials. They are often integrated into *smart* or *adaptive* systems. These materials are characterized by their ability to change physically in a predictable and measurable way in response to load, temperature, pressure, fatigue, corrosion, and other factors. These materials include an array of technologies from fiber-optic, piezoelectric and chemical sensors to ultraflat antenna to micro-electromechanical devices and microsensors. These may be surface mounted, as on an I-beam or embedded in structural elements, as in concrete or composite building, road, and bridge components. These devices can, for example, measure instantaneous or peak strain in load-bearing members; and detect corrosion, fatigue, or cracking in metal rods and girders; measure ice build-up on bridges; and weigh-in-motion. All the data can be transmitted to remote monitoring sites.

...bridge management could include remote monitoring to obtain key information concerning bridge health, including water flow rates, scouring effects, and support creep, as well as icing conditions and fatigue and corrosion damage.



Savannah River Bridge on I-95, Savannah Georgia. Web deflection sensor installation. The sensor monitors the peak out-of-plane deflection of a girder web.

Courtesy of Strain Monitor Systems, Inc.

Energy Sensor Materials

Material	Device Type	Applications
Piezo and Electrostrictive	Shear, pressure, load sensor. Local stiffening actuator.	Vibration sensing. Load sensing. Noise cancellation. Shear sensing. Cracking. Delamination.
Transducers	Acoustic emission. Surface Wave.	Fatigue and corrosion. Cracking.
Silicon-based devices	Sensors. Data transmission. Communications medium.	Vibration sensing. Temperature sensor. Load sensor. Data transmission uplink. Automated travelers advisories. IVHS data uplink.
Memory metals	Thin film devices. Shape memory actuators and sensors. TRIP steel sensors.	Load sensing. Shape and position restoration. Local stiffening. Peak load storage. Out-of-plane deflections storage. Maximum load storage.
MEMS	Pressure, load sensors. Micromachines.	Load sensing. Micro-repair.
Polymer	Piezopolymer sensors. BST sensors and actuators.	Load and shear sensing. Corrosion. Microcracking.
Active antenna	Integrated sensing. Microwave communication. Information networking.	IDT shear sensors. Corrosion sensors. Local wireless communication. Automated travelers advisories. Satellite uplinks. IVHS data uplink.
Rare earth	Chemical sensing. Magnetostrictive actuation.	Corrosion. Local and global stiffeners.

A substantial part of smart device development, including basic materials composition and device design, has been accomplished within the aerospace industry and national laboratories. Examples include a range of fiber-optical sensors, piezoelectric and electrostrictive devices, electro-rheological fluids, and memory metals. Recently, these materials have formed the basis for a new family of micro-electromechanical systems (MEMS) and ultraflat and conformal microantennas. The sidebar to the left provides a brief synopsis of these materials and their applications.

Applications of Smart Material Devices and Monitoring Systems

Although the construction industry already uses an array of measuring and testing devices, they do not meet the emerging demand for information about our aging infrastructure. They do not satisfy our demands for direct information access posed by road users, construction industries and oversight agencies, and they do not satisfy the federal government's need to improve maintenance procedures. Smart material devices and monitoring systems incorporated into Intelligent Vehicle Highway Systems (IVHS) applications will provide low-cost solutions to maintain the structural integrity of infrastructure. These new materials will monitor the life cycle of our roads, bridges, buildings and pipelines in a non-invasive manner that will make possible more efficient use of our work force and of our maintenance dollars.

Sensors and actuators based upon smart technology encompass a variety of devices and applications from sensors that measure environmental conditions, to structural information actuators that stiffen locally or otherwise alter their structural character on demand. They also include communication devices that exploit unusual optical or electromagnetic properties of certain materials.

Smart material devices and monitoring systems can also provide data about materials (cracking and fatigue), about the environment (icing and water flow rates), and about daily or total use (traffic flow and loading). The data can be transmitted into on-site storage devices or directly down-loaded into state Departments of Transportation (DOTs), where continuous or sequential monitoring of bridges and culverts can be automated. The same data can be coupled

into local area networks and radio transmission to provide automated motorist warnings of impending flooding, icing, or structural failure. Smart materials embedded into concrete roadways can monitor the locations of hazardous materials shipments and that data can be transmitted to responsible parties wherever located. Similarly, information about traffic flow, including speed, loads, and volume can be accumulated and made available to both road users and DOTs. The following figure illustrates such a system.

In addition, smart materials' successful history in aircraft, spacecraft, medical and automotive applications has dispelled concern about how these devices and materials stand up to heavy use and harsh environments. Indeed, typical results indicate that smart material-based devices can be fabricated more cost effectively than existing conventional measurement devices and that such devices can withstand harsh and brutal environments. Typical results indicate that materials-based devices not only last many times longer but also are expected to be smaller, lighter and cheaper than conventional sensors, actuators, and communications systems.

Many smart materials-based devices have proved operational over a range of temperatures and pressures and remain unaffected by local electromagnetic or radio conditions. A number are already commercially available in rugged designs suitable for buildings, roads, bridges, and IVHS applications.

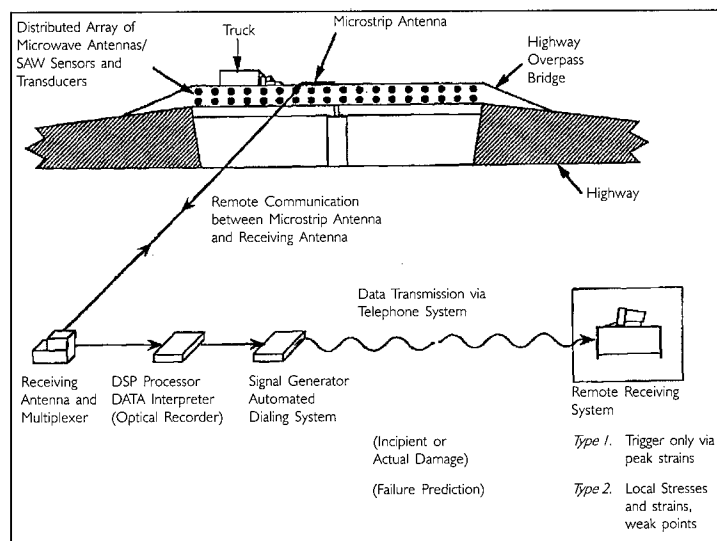
Properties and Benefits of Smart Material Devices and Monitoring Systems

Using smart materials in structural or primary construction components of roads and bridges will substantially improve the monitoring capabilities of the user while simultaneously reducing on-site inspection requirements. For state DOTs, this capability can be integrated easily into automated advisory systems for both local emergency services and the road user. It can also provide early warning of excess loading conditions, catastrophic failure, or unusual environmental hazards.

The obvious value of smart materials and devices is their ability to respond to the environment or to the structural behavior of their host material (the primary or secondary structural element to which they are attached or embedded). For example, "memory metals" such as Transformation Induced Plasticity (TRIP) steel alloys retain information about peak strain for later data retrieval. Similarly, Shape Memory Alloys (SMAs) tend to restore a structural component to its original shape, stiffness, or orientation. This restoration is a function of a metallic memory selected and incorporated in the alloy during its formation.

The following photos illustrate the inclusion of fiber optic-based sensors in the primary load bearing elements of a variety of structures. These silicon-based sensors were incorporated during the construction phases, and now provide both internal load bearing sensor capability and their own data transmission lines from these strategically placed sensor elements.

As high production volumes will likely result from these type of applications, many of these devices should be inexpensive. For example, micro-electromechanical pressure sensors less than 0.02 mm square in size could be produced for less than 20 cents per unit.



Remote Bridge Health Monitoring System



Fiber optic pressure and vibration sensors were placed within the circa 1920 wooden dam (while the dam was being renovated).

Courtesy of University of Vermont

Development of Smart Material Devices and Monitoring Systems

The work yet to be done in this area is extensive. In developing and adapting smart materials for monitoring and evaluating the infrastructure, industry standards for active devices and adaptive materials must be developed. Extensive field testing will be necessary to replicate sensor readings, security and reliability of communications, and effectiveness of data interpretation and evaluation criteria. Microwave, optical, and laser local data gathering systems must be developed, and various methods for long-range data transmission must be tested and adapted. Once the information gathering and transmission "backbone" is established, a decisions process must be developed for the type of information needed. Also, frameworks for usage histories and fatigue patterns must be established.

In addition, quality assurance/quality control manufacturing procedures must be developed to assure smart materials-based devices are both sturdy and accurate. At the same time, production techniques must be developed to assure lowest-cost manufacturing.

To arrive at an integrated information gathering and transmission system that exploits all the recent advances in smart materials and device technologies, the design must accommodate and complement the tools and procedures already established within the construction industry. New diagnostic and repair tools must mesh with methods and processes already in place. Laboratory testing programs must develop techniques usable by the construction engineer to enhance the actual construction process.

Current Constraints to Smart Materials Use

The accessibility of high quality materials and devices, as well as the lack of geographically broad standards, constrain the acceptance and incorporation of smart materials into advanced construction. Although most of the materials currently exist, they are not generally available for commercial use. Only the piezoceramics devices are commercially available. Despite having been developed primarily within U.S. laboratories, these materials are generally available only from the Far East. Even when available, the quality is poor and the costs are high. Consequently, their adaptation into infrastructure applications (including IVHS) is not currently feasible.

Our present lack of investment into key technologies such as self-repairing concretes, micro-electromechanical devices, memory metals and ultraflat antenna devices that can potentially be produced for a few pennies per unit, is the central concern. These technologies may provide substantially longer lives for primary and secondary construction, can reduce or eliminate on-site inspection requirements and can provide affordable monitoring of pavement, bolts, reinforcing rods and all other structural elements. Despite the need and despite the long-term economic gains, the state DOTs cannot provide the level of funding necessary to create this new industry. For these reasons, a timely and substantial infusion of private and public sector funds is critical.

Federal agencies such as NIST, FHWA, and USACE must take the lead in establishing standards for infrastructure applications (roads, railways, bridges, buildings, pipelines, and IVHS) using these emerging smart material devices

Despite having been developed primarily within U.S. laboratories, these materials are generally available only from the Far East.



Close-up showing optical fiber that has been placed within the rebar grid—all of which will be encased within concrete.

and monitoring systems. These standards should address not only the characteristics of the materials and devices themselves, but also the installation and testing procedures to be used off-site and in the field.

Without proper data processing tools, the application of smart material devices and monitoring systems would be of little merit. Basic sensor information must be converted into useful structural, environmental, or usage figures. This is a matter of fundamental research. For example, the newly developed varieties of sensors for detecting corrosion and cracking are of little value without the software routines to determine whether the data actually indicates structural damage or deterioration and, if so, where the damage is located. Processing capability is needed initially to aid construction and enhance quality, and later to support field maintenance and to inform catastrophic failure remotely.

Current Use of Smart Material Devices and Monitoring Systems

Smart materials have already become commonplace in society with examples like shape memory metal eyeglasses, piezoceramic copier devices, viscoelastic brake pads, and active polymeric implants. They are also the key enabling technology in other applications such as electrostrictive devices implementing essential adaptive optics on the Hubble telescope, and correction factors on groundbased telescopes, piezoceramics implementing high-speed data access on optical hard drives, and fiber-optic monitoring of composite cure cycles. These smart materials have revolutionized segments of the medical profession in applications ranging from shape memory catheters to piezoelectric controlled drug delivery systems. The automotive industry is currently incorporating smart materials in low frequency electro-rheological damping and high frequency piezoelectric damping mechanisms, piezoceramically controlled mirror isolation. Viscoelastic brake shoes with piezoelectric sensor modules are now standard on a number of production vehicles. Many other innovations using smart materials are under commercial development such as air bag sensors, impact sensors, local impact stiffeners, active constrained layer damping, active prosthetic materials, disc drive isolation mounts and global positioning systems.

Smart materials have already become commonplace in society with examples like shape memory metal eyeglasses, piezoceramic copier devices, viscoelastic brake pads, and active polymeric implants.

Centers for Smart Materials Research

Pennsylvania State University

Virginia Polytechnic Institute & State University

University of Maryland

Rensselaer Polytechnic Institute

University of Illinois

University of Texas at Arlington

Sandia National Laboratory

Brookhaven National Laboratory

SMART MATERIALS

Prioritized Research Projects

Research Topic	Research Project	Objective	Approach	Schedule	Budget	Public Agency	Benefits
Structural, usage, and environmental instrumentation of critical infrastructure, lifeline, and construction components	Economies, usage and efficiency assessment of integrated diagnostic, measurement and communication systems	To assess the highest potential and lowest risk technologies for diagnostic systems and information transfer as applied to high performance civil infrastructure.	Develop small industry-university teams to evaluate and recommend emerging technologies in materials based sensor systems, communications systems, microelectronics and investigation.	2 years	\$5.0M	ARPA NIST DOT FHWA HUD Bureau of Mines	Optimal investments and economies for limited national investment resources. Early development of integrated long-term system.
Structural, usage, and environmental instrumentation of critical infrastructure, lifeline, and construction components	To provide low cost, reliable, long lifetime sensor materials and interfaces	To develop the necessary materials technology for "smart" materials based and electronic-based sensors.	Identify and develop low cost, long lifetime active materials and electronics materials for custom application.	5 years	\$17.0M	ARPA NIST DOT DOE FHWA Bureau of Mines NSF Army USAF USN HUD FAA	Drastic improvements in materials quantity and performance. Development of material capable of accurately reacting to an array of physical parameters.
Structural, usage, and environmental instrumentation of critical infrastructure, lifeline, and construction components	To provide low cost, reliable, long lifetime instrumentation devices To develop efficient U.S. manufacturing process for high quality, low cost large scale production of data acquisition devices	To develop application specific "smart" materials -based and microelectronics-based devices addressing infrastructure needs.	Develop understanding of application specific device physics. Encourage high quality, low cost fabrication processes. Develop testing procedures and practices for materials-based devices.	7 years	\$15.0M	ARPA NIST DOT DOE FHWA Bureau of Mines NSF Army USAF USN HUD FAA	Increased lifetime of measurement systems. Economies of scale. Reduction in manpower. Pinpointing of structural deficiencies and weak spots. Improved signal capture. Early detection of impending or catastrophic failure.

Research Topic	Research Project	Objective	Approach	Schedule	Budget	Public Agency	Benefits
Structural, usage, and environmental instrumentation of critical infrastructure, lifeline, and construction components	Develop electronics capable of meeting infrastructure conditions and needs	To develop applications specific electronics and electronics interfaces to meet current and future need of the nation's infrastructure in reliable and efficient manner at ever decreasing costs.	Stimulate industry, university and National Laboratory programs in active materials-based microelectromechanical systems.	6 years	\$7.0M	ARPA NIST DOT DOE FHWA Bureau of Mines NSF Army USAF USN HUD FAA OSHA	Increased lifetime of measurement systems. Economies of scale. Reduction in manpower. Pinpointing of structural deficiencies and weak spots. Improved signal capture. Early detection of impending or catastrophic failure.
Structural, usage, and environmental instrumentation of critical infrastructure, lifeline, and construction components	Reliability, lifetime behavior, and environmental compatibility of sensors, sensor electronics and interfaces	To minimize any possible failures, long-term environmental impact, or invalid information transfer.	Stimulate industry, university and National Laboratory programs in lifetime performance and behavior of proposed instrumentation systems.	5 years	\$11.0M	ARPA NIST DOT DOE FHWA Bureau of Mines NSF Army USAF USN HUD FAA OSHA	Provide low cost reliable sensor systems able to detect local and global changes in infrastructure systems without adverse environmental effects. Minimization of device or electronics failure.
Structural, usage, and environmental instrumentation of critical infrastructure, lifeline, and construction components	Constitutive and computational modeling	To enable accurate estimation of physical responses to a wide range of predicted physical excitations over the lifetime of sensor materials and devices developed for infrastructure applications.	Perform extensive laboratory testing and field verification.	4 years	\$12.0M	ARPA NIST DOT DOE FHWA Bureau of Mines NSF Army USAF USN FAA	Accurate prediction of lifetime performance of application specific materials and device technology. Low cost development of aids to field engineers in selection of device systems.

Research Topic	Research Project	Objective	Approach	Schedule	Budget	Public Agency	Benefits
Structural, usage, and environmental instrumentation of critical infrastructure, lifeline, and construction components	Sensor device, electronics and materials standards and practices	To enable standards and procedures for emerging technologies in materials and microelectronics-based technologies as applied to high performance civil infrastructure.	Encourage formation of technical society (e.g. CERF) and oversight agency (e.g. NIST) standards and procedures committees.	3 years	\$8.0M	ARPA NIST DOT DOE FHWA Bureau of Mines NSF Army USAF USN HUD FAA OSHA	Sourcebooks and guidelines for field engineers and infrastructure specialists.
Structural, usage, and environmental instrumentation of critical infrastructure, lifeline, and construction components	Education and information transfer	Provide education and information dissemination on emerging new materials, materials-based devices, microelectromechanical systems, interface and intergration electronics.	Sponsor educational courses provided by leading researchers. Develop and provide databases together with installation and maintenance standards and procedures.	6 years	\$4.0M	ARPA NIST DOT DOE FHWA Bureau of Mines NSF Army USAF USN HUD FAA OSHA	Provision of educated workforce in infrastructure community.

Research Topic	Research Project	Objective	Approach	Schedule	Budget	Public Agency	Benefits
Structural, usage, and environmental instrumentation of critical infrastructure, lifeline, and construction components	Device installation methods and procedures	To develop effective methods for device installation and lifetime monitoring.	Direct extensive laboratory development of application specific installation, testing and evaluation of advances measurement systems under close supervision of appropriate Federal Agencies. Sponsor an extensive program of field installation and testing for critical primary and secondary infrastructure components.	5 years	\$10.0M	ARPA NIST DOT DOE FHWA Bureau of Mines NSF Army USAF USN HUD FAA OSHA	Significant economies in installation costs and maintenance. Enabling of cost effective life extending installation of proposed measurement systems. Development of knowledge base in installation procedures and post-installation monitoring of devices.
Structural, usage, and environmental instrumentation of critical infrastructure, lifeline, and construction components	Databases on environmental influences (e.g. temperature, humidity, corrosion, salt, etc.)	To determine the most critical parameters affecting material aging, device performance and electronics integrity.	Sponsor extensive laboratory simulation and field testing of environmental impact on materials and devices suitable for integration into high performance civil infrastructure.	3 years	\$5.0M	ARPA NIST DOT DOE FHWA Bureau of Mines NSF Army USAF USN HUD FAA OSHA	Significant economies in installation costs and maintenance. Enabling of cost effective life extending installation of proposed measurement systems. Development of knowledge base in installation procedures and post-installation monitoring of devices.

Research Topic	Research Project	Objective	Approach	Schedule	Budget	Public Agency	Benefits
Structural, usage, and environmental instrumentation of critical infrastructure, lifeline, and construction components	Device installation methods and procedures	To develop protection mechanisms for surface mounted and embedded data acquisition devices.	Develop abrasion resistant polymers. Develop protection packaging with high survivability traits.	5 years	\$13.0M	ARPA NIST DOT DOE FHWA Bureau of Mines NSF Army USAF USN HUD FAA OSHA	Significant economies in installation costs and maintenance. Enabling of cost effective life extending installation of proposed measurement systems. Development of knowledge base in installation procedures and post-installation monitoring of devices.
Structural, usage, and environmental instrumentation of critical infrastructure, lifeline, and construction components	Lifetime utility, performance and economies	To determine the ease and cost of access, repair, modification, replacement, and re-installation.	Encourage industry evaluation of competing diagnostic, monitoring and data acquisition technologies for lifetime operation.	3 years	\$7.0M	ARPA NIST DOT DOE FHWA Bureau of Mines NSF Army USAF USN HUD FAA OSHA	Significant economies in installation costs and maintenance. Enabling of cost effective life extending installation of proposed measurement systems. Development of knowledge base in installation procedures and post-installation monitoring of devices.
Global evaluation of large structures	Economies, usage and efficiency assessment of global monitoring of large civil structures	To access the highest potential and lowest risk technologies for diagnostic systems and information transfer as applied to high performance civil infrastructures.	Develop small industry-university teams to evaluate and recommend emerging technologies in IR, microwave, and sound wave testing equipment for in-situ 'end-to-end' evaluation of large structures.	2 years	\$5.0M	ARPA NIST DOE DOT FHWA HUD Turnpike Commission	Optimal investment and economies for limited national investment resources. Early development of integrated systems.

Research Topic	Research Project	Objective	Approach	Schedule	Budget	Public Agency	Benefits
Global evaluation of large structures	Fabrication and testing of global monitoring systems	To fabricate scaled systems for monitoring of large civil structures.	Develop small scale experiments sufficient to prove the concept for larger scale development.	4 years	\$8.0M	ARPA NIST DOE DOT FHWA HUD Turnpike Commission	Low cost verification of capabilities of expensive complex measurement system.
Data acquisition and processing	Local signal processing	To obtain the most useful indicators of structural, environmental or usage parameters from the in situ system. To minimize false alarms. To provide the maximum possible signal correlation and corroboration.	Develop and increasingly sophisticated amalgam of data fusion, neural network, and rule-based processing algorithms. Develop custom processors capable of withstanding environmental conditions associated with civil infrastructures.	3 years	\$4.0M	NSF Army USN USAF DOE DOT ARPA FAA	Provides increasing levels of useable data.
Data acquisition and processing	Network communications	To provide enabling data transfer and storage capabilities able to withstand power failure, catastrophies, and extended use.	Develop (e.g. microwave, cellular, and satellite based) all terrain sytems able to perform in event of power loss or catastrophic events. Develop fiberoptic ground relay systems.	5 years	\$12.0M	NSF Army USN USAF DOE DOT ARPA FAA	Lower cost. Improved reliability. Ability to be incorporated into information highways. Ability to direct emergency services and traffic motion during natural disasters. Ability to track HAZMAT (Hazardous Materials) vehicles.
Data acquisition and processing	Network communications	To provide site specific data storage and transfer mechanisms.	Develop easy access data points adjacent to critical infrastructure elements that contain removable storage mediums.	2 years	\$3.0M	FHWA NIST ONR ARO FAA NSF ARPA DOT DOE	Easy access to time histories of critical components . Aids to visual inspections . Enables long duration analysis of components.

Research Topic	Research Project	Objective	Approach	Schedule	Budget	Public Agency	Benefits
Data acquisition and processing	Data management, information extraction and decision making.	To provide data management systems that convert raw data (either through removable storage or direct access) to user friendly evaluates of critical performance parameters for local DOT's, emergency services, and motorist advisories.	Encourage teaming between Federal, state and local government to develop data management systems.	4 years	\$7.0	FHWA NIST ONR ARO FAA NSF ARPA DOT DOE	Provide useful and usable information to remotely monitor critical sites, emergency services, traveler advisories and inspections.
HAZMAT management. Emergency service management	Monitoring of road conditions and special use	To provide motorist with direct access to road conditions, traffic volume, and life-threatening conditions (e.g. bridge failure). To monitor the use of the nation's roads by special traffic (e.g. HAZMAT vehicles).	Integrate data systems with IVHS or information highway systems.	4 years	\$7.0M	DOE EPA DOT	Enables ability to monitor special uses of nation's transportation infrastructure.
Natural disaster earthquake management	Infrastructure safety and usage	To assess the structural integrity of roads, bridges and lifelines during and immediately after natural disasters. To assist efficient direction of emergency services and safely direct road users during and after natural disasters.	Develop systems level integration of data acquisition and management to enable structural assessments and evaluation of critical structural losses. Develop procedures for conveying structural assessments to emergency services, local agencies, and road users.	3 years	\$6.0M	DOT FHWA OSHA NIST HHS Turnpike Commission	Rapid assessment of structural integration and condition of infrastructure components.
Natural disaster earthquake management	Post disaster structural evaluation	To determine the extent and liability of structural damage caused during a cataclysmic event.	Develop integrated sensors and tools to provide post disaster evaluation of the structural integrity of the structural critical primary and secondary structural elements.	6 years	\$12.0M	DOT FHWA OSHA NIST HHS Turnpike Commission	Ability to assess structural damage to primary and secondary components and building safety. Efficient repair schedules.

Research Topic	Research Project	Objective	Approach	Schedule	Budget	Public Agency	Benefits
Behavior modification and lifetime extension of structural components	Self-repairing systems	To provide automated self-repairing concrete and steel systems.	Identify and develop load-bearing phase transition alloys. Develop self-repairing concretes.	5 years	\$9.0M	ARPA NSF DOE FHA NIST USA-CERL	Delay of the onset of catastrophic failure. Automated structural compensation for erosion and weakening of primary structural members.
Behavior modification and lifetime extension of structural components	High-insulating capacity materials	To develop methods for designing construction materials that have a high insulating capacity to retain or reflect heat.	Investigate design of recycled materials that are environmentally compatible with respect to isotropic or anisotropic behavior so that heat flow can be directed throughout the structure.	8 years	\$7.0M	ARPA NSF FAA FHA NIST ARO ONR DOT	Reduction of stress induced corrosion and cracking. Reduction of extreme excitations due to wind shear, seismic, excess loads, and thermal rates.
Behavior modification and lifetime extension of structural components	Passive damping materials for infrastructure components	To improve the lifetime performance by reducing the stress induced fatigue and corrosion in primary and secondary parts.	Initiate a program to develop low cost damping materials which are environmentally safe and recyclable.	4 years	\$5.0M	ARPA NSF FAA FHA NIST ARO ONR DOT	Reduction of stress induced corrosion and cracking. Reduction of extreme excitations due to wind shear, seismic, excess loads, and thermal rates.
To improve the lifetime performance by actively altering the load dependent dynamical behavior of infrastructure components	To improve the lifetime performance by actively altering the load dependant dynamical behavior of infrastructure components	Initiate a program to develop low cost damping materials which are environmentally safe and recyclable.	Develop laser imaging or electromagnetic imaging systems.	4 years	\$7.0M	ARPA NSF FAA FHA NIST EPA ONR DOT NASA	Early identification and pinpointing of major or catastrophic failures due to scouring, turbulent flow, excess water pressure, excess loading etc. Rapid and accurate post seismic structural integrity evaluation.
Total Program Outlay					\$206.0M		

Smart Materials Prioritized Timeline and Budget Allocation

Year	Project	Duration (in years)	Cost
I	Assessment of potential technologies and systems	2	\$2,100,000
	Development of high sensitivity, durable sensor materials	5	2,500,000
	Development of application specific device technologies	4	2,100,000
	Simulation and analysis	4	2,400,000
	Hardened processing, storage and on-site access	3	1,200,000
	Self-repair systems	5	1,600,000
	Passive and active structural modification	4	2,800,000
	Year I Total \$14,700,000 Cumulative Total \$14,700,000		
2	Assessment of potential technologies and systems	2	\$2,900,000
	Development of high sensitivity, durable sensor materials	5	3,500,000
	Development of application specific device technologies	4	2,700,000
	Development of application electronics	6	1,300,000
	Simulation and analysis	4	3,200,000
	Environmental effects	3	1,500,000
	Device protection	5	2,100,000
	Evaluation of large scale measurement systems	2	2,500,000
	Hardened processing, storage and on-site access	3	1,500,000
	Self-repair systems	5	2,000,000
	Passive and active structural modification	4	3,200,000
	Year 2 Total \$26,400,000 Cumulative Total \$41,100,000		

Year	Project	Duration (in years)	Cost
3	Development of high sensitivity, durable sensor materials	5	\$4,200,000
	Development of application specific device technologies	4	2,500,000
	Development of application electronics	6	1,700,000
	Simulation and analysis	4	3,800,000
	Installation methods	5	1,800,000
	Environmental effects	3	2,400,000
	Device protection	5	3,300,000
	Evaluation of large scale measurement systems	2	2,500,000
	Hardened processing, storage and on-site access	3	1,300,000
	Self-repair systems	5	2,200,000
	High insulating capacity materials	8	900,000
	Passive and active structural modification	4	3,100,000
Year 3 Total \$29,700,000 Cumulative Total \$70,800,000			
4	Development of high sensitivity, durable sensor materials	5	\$3,700,000
	Development of application specific device technologies	4	1,100,000
	Low cost device manufacture	4	1,500,000
	Development of application electronics	6	1,600,000
	Failure analysis	5	1,900,000
	Simulation and analysis	4	2,600,000
	Education and information transfer	6	600,000
	Installation methods	5	2,200,000
	Environmental effects	3	1,100,000
	Device protection	5	3,200,000
	Local area networks	5	2,300,000
	Site specific data access and transfer	2	1,500,000
	Self-repair systems	5	1,700,000
	High insulating capacity materials	8	1,000,000
	Passive and active structural modification	4	2,900,000
Year 4 Total \$28,900,000 Cumulative Total \$99,700,000			
5	Development of high sensitivity, durable sensor materials	5	\$3,100,000
	Low cost device manufacture	4	2,000,000
	Development of application electronics	6	1,200,000
	Failure analysis	5	2,200,000
	Device standards and practices	3	2,600,000
	Education and information transfer	6	700,000
	Installation methods	5	2,400,000
	Device protection	5	2,400,000
	Access and repair issues	3	2,000,000
	Local area networks	5	2,700,000
	Site specific data access and transfer	2	1,500,000
	Natural disaster management	3	2,000,000
	Post-disaster evaluation and repair scheduling	6	1,700,000
	Self-repair systems	5	1,500,000
	High insulating capacity materials	8	1,200,000
Year 5 Total \$29,200,000 Cumulative Total \$128,900,000			

Year	Project	Duration (in years)	Cost
6	Low cost device manufacture	4	\$2,000,000
	Development of application electronics	6	700,000
	Failure analysis	5	2,600,000
	Device standards and practices	3	3,200,000
	Education and information transfer	6	1,000,000
	Installation methods	5	2,100,000
	Device protection	5	2,000,000
	Access and repair issues	3	3,100,000
	Local area networks	5	2,600,000
	Data management systems	4	1,500,000
	Natural disaster management	3	2,000,000
	Post-disaster evaluation and repair scheduling	6	2,100,000
	High insulating capacity materials	8	1,100,000
Year 6 Total \$26,000,000 Cumulative Total \$154,900,000			
7	Low cost device manufacture	4	\$1,100,000
	Development of application electronics	6	500,000
	Failure analysis	5	2,200,000
	Device standards and practices	3	2,200,000
	Education and information transfer	6	800,000
	Installation methods	5	1,500,000
	Access and repair issues	3	1,900,000
	Investment in large-scale diagnostic systems	4	2,300,000
	Local area networks	5	2,200,000
	Data management systems	4	2,300,000
	Road monitoring	4	1,500,000
	Natural disaster management	3	2,000,000
	Post-disaster evaluation and repair scheduling	6	2,300,000
	High insulating capacity materials	8	900,000
Year 7 Total \$23,700,000 Cumulative Total \$178,600,000			
8	Failure analysis	5	\$2,100,000
	Education and information transfer	6	500,000
	Investment in large-scale diagnostic systems	4	2,400,000
	Local area networks	5	2,200,000
	Data management systems	4	2,100,000
	Road monitoring	4	2,100,000
	Post-disaster evaluation and repair scheduling	6	2,200,000
	High insulating capacity materials	8	700,000
Year 8 Total \$14,300,000 Cumulative Total \$192,900,000			

Year	Project	Duration (in years)	Cost
9	Education and information transfer	6	\$400,000
	Investment in large-scale diagnostic systems	4	2,100,000
	Data management systems	4	1,100,000
	Road monitoring	4	2,100,000
	Post-disaster evaluation and repair scheduling	6	2,000,000
	High insulating capacity materials	8	600,000
Year 9 Total \$8,300,000			
Cumulative Total \$201,200,000			
10	Investment in large-scale diagnostic systems	4	\$1,200,000
	Road monitoring	4	1,300,000
	Post-disaster evaluation and repair scheduling	6	1,700,000
	High insulating capacity materials	8	600,000
Year 10 Total \$4,800,000			
Cumulative Total \$206,000,000			

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Chapter 11

High-Performance Steel Products

Steel is one of the major construction materials used today; almost every constructed facility, including bridges, buildings, houses, and pipelines, contains steel. Construction consumes approximately 30 percent of the 80-90 million tons of steel produced each year in the U.S.—representing more than a \$10 billion dollar investment in materials. **The estimated world market value for construction steel in the year 2000 will be \$500 billion.** As a construction material, steel is well suited for a variety of applications because of such properties as high strength-to-weight ratio, high stiffness, ductility, toughness and weldability. High-performance steel will improve these properties so that future steel structures will perform better under adverse conditions such as earthquakes, fires, and corrosive environments; be safer and more reliable; be less costly to fabricate and construct; and be more efficient and durable. Over the last few decades, significant advancements have been made in steel production and fabrication technologies. However, more can still be done to develop improved steels for construction applications.

The estimated world market value for steel in the year 2000 will be \$500 billion.

What is High-Performance Steel?

Steel is a designer material; new High-Performance Steel (HPS) will be tailored to meet the needs of specific construction applications using a variety of alloying and processing approaches. Advanced steelmaking practices including “clean steel” technology, microalloying, and process control technology. Steel produced as plate, hot-rolled shapes, and sheet is included. By using HPS, the building, refurbishing, or replacement of structures will result in improved performance as measured by initial costs, ease of maintenance, and increased service life.

High-Performance steel (HPS) can demonstrate enhancements in:

- Weldability
- Toughness
- Corrosion resistance
- Ductility
- Fatigue resistance
- Fire resistance
- Formability
- Strength

Applications of High-Performance Steel

Despite significant progress in the development of new materials such as advanced composites and ceramics, it is anticipated that the demand for steel



Roize bridge, outside Grenoble, France. Underside of completed bridge with view of five 12-strand tendons.

Courtesy of J. Muller International

Advancements in steel construction technology will enhance America's infrastructure in three key areas: design, constructability and life-cycle performance.



Paris Landing Bridge, Tennessee.

Courtesy of U.S. Steel

will continue to increase through new applications and a significant role in rebuilding the infrastructure. The growth and maintenance of structures in the U.S. will continue to create demand for steel products. Building frames, building envelope (roofing, siding), bridges, offshore structures, pipelines, water and underground tanks, pressure vessels, mechanical tubing, earthmoving equipment, construction and mining equipment, railway and transportation equipment, and shipbuilding--all of these represent potential and current applications for HPS. Expanded potential applications of HPS include roofing, house framing, and short span bridges.

Properties and Benefits of High-Performance Steel

Advancements in steel construction technology will enhance America's infrastructure in three key areas: design, constructability and life-cycle performance.

High-performance steel with enhanced strength and weldability will reduce the material and fabrication costs of new structures. Structural steel production processes that are more efficient (e.g., near net shape casting) and more flexible (e.g., custom rolling of shapes) will reduce material costs and improve material use. Advanced processing will provide superior high-performance steel materials with significant improvements in weldability and toughness. New fabrication technologies, such as high-heat input and laser welding will greatly increase the ease with which structures can be fabricated.

The potential cost savings offered by the development of improved steels for military and commercial ships, for bridges and pipelines, and for transportation and infrastructure use is great. In the shipbuilding market, for instance, the London-based International Maritime Organization (IMO) and the U.S. Oil Pollution Act of 1990 have mandated that by 2015 the world's tanker fleet must be replaced with double-hull construction. Thus more than 1,200 new commercial tankers will be required over the next decade. If 100 tankers are U.S. built, an economy of \$125 million is possible. HPS with improved fabricability can help to achieve this potential.

New, optimized structural steel shapes including light-gage sections will further improve material use and costs. Automated and more agile fabricated operations will reduce fabrication cost and time, and will improve fabrication productivity. Innovative designs using HPS can reduce the weight of structures, thereby making them more efficient. An example of the benefits of using higher strength steel is the Paris Landing Bridge in Tennessee. This bridge has a 160m (525 foot) main span and was designed using 480 MPa (70 ksi) material to reduce the weight of the structure which allowed the bridge to be fabricated with a more economical, constant depth cross-section. A 32 percent cost saving resulted from using HPS instead of conventional steel. The time and cost required for steel erection will also be reduced by automated erection methodologies enhanced by new joining and fastening technology.

Development of High-Performance Steels

The development of high-performance steel construction technology will enable advances in the design of steel structures that exploit these innovations. The weldability improvements result from new alloying and processing,

initially developed in laboratory studies and implemented in full-scale production facilities. Research activities throughout the world are focusing on new steels that are tailor-made for the strength, durability and corrosion demands of a given application.

The continuing emphasis on life-cycle costing will make first cost less important, thus higher valued steels with better performance throughout the life of the structure will be desired. New stainless steels which can be produced efficiently (lower cost) will begin to find their way into future structures.

Constraints to High-Performance Steel Use

Development of HPS faces both technical and non-technical barriers. Over the past few years, Japanese and European producers have reported significantly improved mechanical properties for steels produced using special thermomechanical controlled processing (TMCP), and they have installed the facilities to produce these steels. TMCP uses controlled rolling and accelerated cooling to produce high-performance steel; this steel has in turn improved the efficiency of ship fabrication. However, in the U.S. although the potential for TMCP has been widely studied in the laboratory, the required facilities have not been installed. (One steel company will be installing them in 1995). Japanese and European facilities were justified by strong markets in ship and linepipe construction during the 80's. Those markets are only now beginning to be significant in the U.S. New computer modeling software reflecting new design approaches will be required to use high-strength HPS efficiently. Furthermore, the fabrication methods must be optimized and/or new technologies established.

In the public policy area, decision-makers in both industry and government need to agree upon design standards and contracting and procurement procedures that will facilitate innovation in steel construction technology. For example, there is currently a lack of standard systems for house framing. In addition, builders are often unfamiliar with HPS technology; thus, the industry should be reeducating the consumer or the user of this technology. In bridges, for example, the current steel grades have been in use for over 30 years. Replacing those bridges with HPS will require significant qualification efforts to satisfy federal, state and local transportation officials of their suitability. In deciding to use HPS, decision-makers must also look beyond initial costs of use to life-cycle costs.

The following research projects indicate the breadth of current HPS research:

- Double hull welding system using one-sided welding
- Bridge using new girder system with pipe and plate (ATLSS and FHWA programs)
- Thermomechanical controlled processing
- New sensor process control and modeling technology
- New steels for bridges with new design concepts for their use
- Electroslag welding, high-heat input welding, laser welding
- Fabrication robotics
- Research on coatings technology for longer service life

Centers for Research Technology Transfer

Materials

University of Pittsburgh

National Institute of Standards and Technology

NSF Center for Advanced Technology for Large Structural Systems (ATLSS)

Colorado School of Mines

Northwestern University

Welding and Joining

Oregon Graduate Institute

Ohio State-Edison Welding Institute

ATLSS-Lehigh

American Welding Society

Products and Systems-Virginia Tech

Design

University of Texas at Austin

ATLSS-Lehigh

University of California at Berkeley

Cornell University

University of Minnesota

University of Illinois

Virginia Tech

University of Missouri-Rolla

Fabrication and Erection

NIST

ATLSS-Lehigh

Life Cycle Performance

University of Kansas

Infrastructure Institute

ATLSS - Lehigh

STEEL

Prioritized Research Projects

Research Topic	Research Project	Objective	Approach	Schedule	Budget	Public Agency	Benefits
Materials	Predictability	To produce economically new high performance, low carbon steels which have more predictable properties.	Investigate both alloy development and process control as mechanisms to improve the reliability and uniformity of steels with respect to strength and toughness.	5 years	\$15.0M	NIST FHWA DOE	Economy, more reasonable codes.
Materials	Weldability	To improve the weldability of steels through variations in chemistry and processing.	Define key controlling weldability characteristics for various high performance steel strength levels and establish chemistry and processing required to maximize fabrication productivity. Carry out full scale tests.	4 years	\$8.4M	NSWC DOE NIST FHWA	Ease of fabrication, economy.
Materials	Corrosion Resistance	To develop improved corrosion-resistant steels and coatings for various environments.	Investigate both alloy development and the use of coatings to optimize long-term performance and test using laboratory samples and other appropriate testing methods.	6 years	\$9.6M	FHWA DOE EPA NIST	Improved durability, less maintenance.
Products & Systems	New Structural Systems	To develop new structural systems for buildings and bridges which employ high performance steel.	Classify improved characteristics of HPS. Evaluate different types of structural components and assemblies. Develop new systems to optimize performance of HPS. Perform studies to establish performance enhancements. Design prototype structures.	5 years	\$30.0M	NIST FHWA	Optimize use of HPS. Efficiently use HPS in design.
Products & Systems	Innovative Structural Shapes	To explore innovative shapes for construction products to take advantage of HPS.	Investigate innovative shapes to enhance the strength and performance of structures. Explore near net shape casting technology.	4 years	\$8.4M	NIST FHWA	Improved economy, appearance. More efficient use of HPS.
Fabrication & Erection	Welding Processes and Consumables	To develop welding processes and consumables with sufficient weldability, toughness and strength for commercial conditions.	Determine the effect of coatings on weld metal and Hazardous Materials. Determine feasibility of under-matching weld metal. Develop new materials. Conduct tests of prototype applications.	4 years	\$8.4M	NIST FHWA NSWC DOE EPA	Economy, faster fabrication and erection.

Research Topic	Research Project	Objective	Approach	Schedule	Budget	Public Agency	Benefits
Fabrication & Erection	Automated Systems	To develop cost effective automated fabrication and erection systems.	Review automation concepts and techniques of other industries and other countries. Determine opportunities for automation and integration of key phases of construction. Develop automation systems to address and coordinate fabrication and erection operations.	8 years	\$28.5M	NIST USACE NSF	Faster erection, economy, safety.
Fabrication & Erection	Connection Systems	To develop connection systems to increase performance of HPS.	Evaluate different types of construction details and develop suitable geometries as well as appropriate connections to be coupled with new structural systems to improve structural performance.	8 years	\$8.4M	NIST USACE NSF	Faster erection, improved seismic performance.
Analysis & Design	Fire Performance	To evaluate fire performance of HPS structural systems.	Explore the fire performance of prototype HPS building systems and develop code provisions and design guides.	5 years	\$6.0M	NIST NSF USACE	Better performance in fires, improved codes.
Analysis & Design	Serviceability/Reliability Definition	To develop performance criteria for serviceability including deflections, vibrations (motion perception), etc. and evaluate overall structural reliability of HPS systems.	Research elements affecting structural serviceability, integrate knowledge of material behavior, structural loads, and deterioration and develop acceptable performance levels for serviceability. Develop probability based methods to assess structural reliability.	8 years	\$7.8M	NIST FHWA	Better user comfort, improved codes.
Analysis & Design	Advanced Analysis Methods	To develop the analytical capability for predicting the full-range of behavior of structures and structural components of high-performance steel and integrate into design standards.	Employ micro and macro-modelling approaches to study the rotation capacity and cyclical resistance of HPS sections, the possibility of extending present limits on the use of inelastic analysis, and the resistance of thin HPS members thru the effective width concept and interactive computer graphics programs. Develop associated design provisions.	6 years	\$8.16M	NIST NSF FHWA	Efficiently use HPS Improve codes and standards.
Life Cycle Performance	Service Life Evaluation	To develop methods to evaluate the service life of high performance steel structures and systems.	Characterize HPS response to extreme loadings through laboratory testing. Determine acceptable or threshold damage levels, develop remaining life assessment techniques.	4 years	\$12.0M	NIST FHWA	Quick assessment of existing structures.
Life Cycle Performance	Renovation and Retrofit	To develop methods to strengthen existing structures using high performance steel.	Develop and evaluate methods of attaching HPS to conventional steel including modular systems. Develop field methods to evaluate the strengthening methods.	4 years	\$9.0M	NIST FHWA	Retrofitting of current structures.

Research Topic	Research Project	Objective	Approach	Schedule	Budget	Public Agency	Benefits
Life Cycle Performance	Life Cycle Cost Analysis	To develop procedures for predicting life cycles and conducting life cycle cost analysis of high performance steel structures.	Incorporate information on the durability of materials and systems, the role of design details, maintenance requirements of systems and materials, environmental factors, projected changes in service conditions, political decisions affecting the structure into a comprehensive life cycle cost plan.	4 years	\$12.0M	NIST FHWA	Lower and more predictable lifecycle costs.
High Performance Composite Steel Systems	Composite Systems Load Transfer Models	To develop behavioral and load transfer models for high performance materials in composite systems and to develop appropriate design standards.	Establish a research program to study the behavior mechanism in high performance materials by reviewing basic force transfer mechanisms between materials for both connections and members including cyclic loading conditions, and assessing the influence of detailing.	5 years	\$7.8M	NIST FHWA	Incorporate strengths of other materials with HPS, economy.
High Performance Composite Steel Systems	Innovative Composite Systems	To develop composite steel-concrete structural systems to utilize HPS in building systems.	Review present composite systems for functionality, reliability, ductility, durability, cost and structural efficiency. Target potential systems utilizing HPS. Conduct performance analyses and structural tests. Develop design tools for the new systems.	5 years	\$10.5M	NIST USACE	Provide optimal use of each material.
Total Program Outlay					\$190.56M		

Steel Prioritized Timeline and Budget Allocation

Year	Project	Duration (in years)	Cost
1	Materials Predictability	5	\$3,000,000
	New Structural Systems	5	6,000,000
	Welding Processes and Consumables	4	2,100,000
	Fire Performance Analysis and Design	5	3,000,000
	Service Life Evaluation	4	3,000,000
	Composite Systems Load Transfer Models	5	1,560,000
Year 1 Total \$18,660,000			
Cumulative Total \$18,660,000			
2	Materials Predictability	5	\$3,000,000
	Improved Materials Weldability	7	1,200,000
	New Structural Systems	5	6,000,000
	Welding Processes and Consumables	4	2,100,000
	Automated Shop Fabrication and Erection	8	3,000,000
	Fire Performance Analysis and Design	5	900,000
	Service Life Evaluation	4	3,000,000
	Composite Systems Load Transfer Models	5	1,560,000
Year 2 Total \$20,760,000			
Cumulative Total \$39,420,000			
3	Materials Predictability	5	\$3,000,000
	Improved Materials Weldability	7	1,200,000
	New Structural Systems	5	6,000,000
	Welding Processes and Consumables	4	2,100,000
	Automated Shop Fabrication and Erection	8	3,000,000
	New Connections	8	1,050,000
	Fire Performance Analysis and Design	5	900,000
	Design for Serviceability	8	900,000
	Service Life Evaluation	4	3,000,000
	Composite Systems Load Transfer Models	5	1,560,000
Year 3 Total \$22,710,000			
Cumulative Total \$62,130,000			

Year	Project	Duration (in years)	Cost
4	Materials Predictability	5	\$3,000,000
	Improved Materials Weldability	7	1,200,000
	New Structural Systems	5	6,000,000
	Welding Processes and Consumables	4	2,100,000
	Automated Shop Fabrication and Erection	8	4,500,000
	New Connections	8	1,050,000
	Fire Performance Analysis and Design	5	900,000
	Design for Serviceability	8	1,500,000
	Advanced Analysis Methods	6	1,350,000
	Service Life Evaluation	4	3,000,000
	Composite Systems Load Transfer Models	5	1,560,000
Year 4 Total \$26,160,000			
Cumulative Total \$88,290,000			
5	Materials Predictability	5	\$3,000,000
	Improved Materials Weldability	7	1,200,000
	Improved Corrosion Resistance	6	1,500,000
	New Structural Systems	5	6,000,000
	Automated Shop Fabrication and Erection	8	4,500,000
	New Connections	8	1,050,000
	Fire Performance Analysis and Design	5	900,000
	Design for Serviceability	8	900,000
	Advanced Analysis Methods	6	1,350,000
	Renovation and Retrofit Techniques	4	2,250,000
	Life Cycle Cost Analysis	4	3,000,000
	Composite Systems Load Transfer Models	5	1,560,000
Year 5 Total \$27,210,000			
Cumulative Total \$115,500,000			
6	Improved Materials Weldability	7	\$1,200,000
	Improved Corrosion Resistance	6	2,100,000
	Innovative Structural Shapes	4	2,100,000
	Automated Shop Fabrication and Erection	8	4,500,000
	New Connections	8	1,050,000
	Design for Serviceability	8	900,000
	Advanced Analysis Methods	6	1,410,000
	Renovation and Retrofit Techniques	4	2,250,000
	Life Cycle Cost Analysis	4	3,000,000
	Innovative Composite Systems	5	2,100,000
Year 6 Total \$20,610,000			
Cumulative Total \$136,110,000			

Year	Project	Duration (in years)	Cost
7	Improved Materials Weldability	7	\$1,200,000
	Improved Corrosion Resistance	6	1,500,000
	Innovative Structural Shapes	4	2,100,000
	Automated Shop Fabrication and Erection	8	3,000,000
	New Connections	8	1,050,000
	Design for Serviceability	8	900,000
	Advanced Analysis Methods	6	1,350,000
	Renovation and Retrofit Techniques	4	2,250,000
	Life Cycle Cost Analysis	4	3,000,000
	Innovative Composite Systems	5	2,100,000
Year 7 Total \$18,450,000			
Cumulative Total \$154,560,000			
8	Improved Materials Weldability	7	\$1,200,000
	Improved Corrosion Resistance	6	1,500,000
	Innovative Structural Shapes	4	2,100,000
	Automated Shop Fabrication and Erection	8	3,000,000
	New Connections	8	1,050,000
	Design for Serviceability	8	900,000
	Advanced Analysis Methods	6	1,350,000
	Renovation and Retrofit Techniques	4	2,250,000
	Life Cycle Cost Analysis	4	3,000,000
	Innovative Composite Systems	5	2,100,000
Year 8 Total \$18,450,000			
Cumulative Total \$173,010,000			
9	Improved Corrosion Resistance	6	\$1,500,000
	Innovative Structural Shapes	4	2,100,000
	Automated Shop Fabrication and Erection	8	3,000,000
	New Connections	8	1,050,000
	Design for Serviceability	8	900,000
	Advanced Analysis Methods	6	1,350,000
	Innovative Composite Systems	5	2,100,000
Year 9 Total \$12,000,000			
Cumulative Total \$185,010,000			
10	Improved Corrosion Resistance	6	\$1,500,000
	New Connections	8	1,050,000
	Design for Serviceability	8	900,000
	Innovative Composite Systems	5	2,100,000
Year 10 Total \$5,550,000			
Cumulative Total \$190,560,000			

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Chapter 12

High-Performance Wood Products

More buildings are constructed of wood than any other building material. Over 90 percent of all single family homes, as well as many small office and commercial buildings, are constructed with wood structural framing. Many buildings with concrete and masonry walls use wood floor and roof systems. In addition, some cities, counties, and states are specifying the use of modern timber bridges as alternatives to steel and concrete bridges on low to medium volume roads. Although U.S. construction projects consume more than 40 billion board feet of timber annually, wood is a renewable resource. Wood is an attractive material choice because of its ease of construction, especially on-site, and because it provides the highest strength-to-weight ratio of traditional building materials. The use of newer, high-strength, lightweight engineered wood products such as glued laminated beams, wood I-joists, and structural composite lumber is increasing dramatically.

What is High-Performance Wood?

High-performance wood products are characterized by enhanced performance in one or more of the following:

- Fire resistance
- Strength and/or stiffness
- Creep resistance
- Decay resistance
- Serviceability

The term high performance wood products does not just mean that these products are more durable and serviceable—it means that these products are engineered to perform better. For example, polymers and wood fiber may be used to increase material strength.

Applications of High-Performance Wood

While the use of engineered wood products represents a small portion of today's wood products market, decreased availability of large dimension timber combined with the environmental benefit of continuing to use a renewable resource makes their increased use and continued development necessary. Some of these products (such as I-joists and box beams) use different types of wood, while others incorporate laminations of wood (such as glued laminated beams and certain types of structural composite lumber). There is also increasing use of composites which use wood along with non-wood products such as fiber reinforced glued laminated beams and

While the use of engineered wood products represents a small portion of today's wood products market, decreased availability of large dimension timber combined with the environmental benefit of continuing to use a renewable resource makes their increased use and continued development necessary.



Soaring glued-laminated beams give this U.S. Ski Hall of Fame in Ishpeming, Michigan its dramatic ski-jump effect.

Courtesy of Southern Forest Products Association

wood trusses which incorporate metal webs. All of these engineered wood products use our natural resources efficiently.

Modern timber bridges, structural frames of commercial buildings, and roofing systems—this list demonstrates a few applications of high-performance wood products. High-performance wood is especially adaptable for use in commercial buildings as well as in public infrastructure applications.

Properties and Benefits of High-Performance Wood

Compared to traditional systems, the benefits of using high-performance wood include low initial building costs, increased service life with reduced maintenance, and efficient use of natural resources.

Wood has excellent qualities for heat transfer. Wood stress-skin panels offer hope for providing low-cost, energy efficient, yet structurally sound housing. These systems can be used for walls as well as roofs. Improved coatings and preservatives will enhance the performance of wood products on building sidings.

The need to provide low-cost housing for the economically disadvantaged can be fulfilled in part by using promising light-weight building materials which can be pre-assembled in plants.

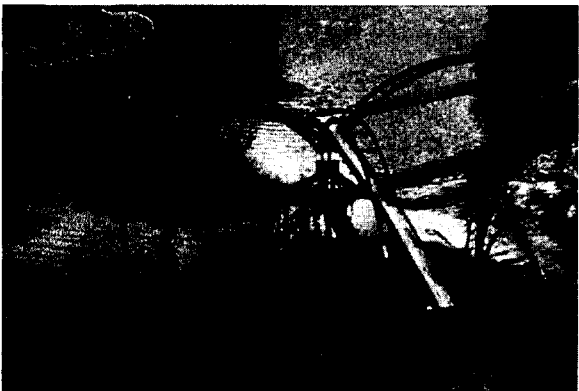
Because wood has a high strength-to-weight ratio, the use of engineered wood products only increases efficiency in resource utilization. Engineered wood products which are reinforced with synthetic fibers and wood composites will enable designers to increase floor loads or spans for wood systems. The need to provide low-cost housing for the economically disadvantaged can be fulfilled in part by using promising light-weight building materials which can be pre-assembled in plants and transported to building sites for final assembly. Along with the incorporation of engineered wood products described above, stress-skin wall and roof systems which sandwich insulation between wood structural-use panels, are both light-weight and strong. All of the materials can be easily transported to a building site and assembled using light construction equipment and nonspecialized labor.

State and local jurisdictions strapped for adequate funds to maintain and repair deteriorating bridges recognize the use of modern timber bridges to rebuild and improve the nation's highway infrastructure. Nationwide, approximately 230,000 bridges are either structurally or geometrically deficient, and an estimated 150,000 of these bridges could use modern timber replacements. These modern designs using panelized assemblies and/or engineered wood products allow local jurisdictions to replace deficient bridges using their own personnel and construction equipment, which will save both time and money.

Development of High-Performance Wood

The development of high-performance wood members and systems is in its infancy; however development of non-wood products to reinforce wood members is well underway. Poly-

mer strands incorporated into the cross-sections of glued laminated beams, much as steel reinforcing bars are used in concrete beams, increase strength and stiffness. Similar reinforcement for other engineered wood products holds promise. For example, the use of wood fiber to reinforce non-wood materials is being researched. The performance of these members and assemblies, especially in harsh environments, needs to be evaluated.



COURTESY OF AMERICAN INSTITUTE OF TIMBER CONSTRUCTION

Three span constructed "tridge."

In addition, the development of modern timber bridge designs is well underway. In fact, guardrail systems for these bridges have been tested and approved. In support of this effort, the U.S. Department of Agriculture Forest Service has published and distributed a design manual for such structures. Also, the American Association of State Highway and Transportation Officials (AASHTO) will incorporate load and resistance factor design provisions for timber bridges in its standard.

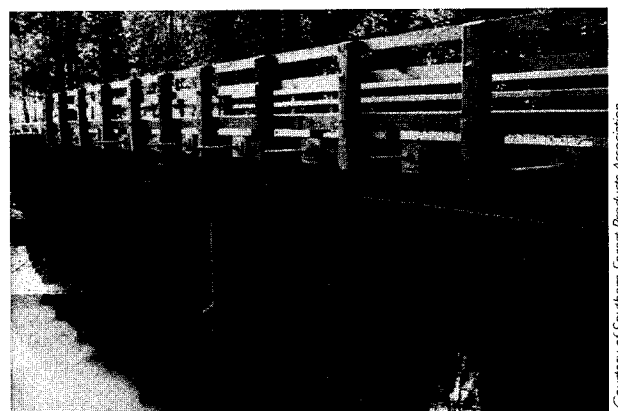
Constraints to High-Performance Wood Use

Although high-performance wood research and use appear promising—modern timber bridges being one good example—barriers to increased use of these engineered wood products include prescriptive building codes and limited funding for fire modeling and load and resistance testing. Historically, building codes have contained prescriptive provisions covering the design and construction of single family residential structures.

These prescriptive provisions, sometimes referred to as conventional construction, incorporate long-standing “rules-of-thumb” used by the construction industry. These building code provisions have proven to be adequate for most parts of the country. However, in coastal areas where high winds associated with hurricanes are possible, and in some areas of high seismic activity, legislators are revising building code requirements to mandate engineered design of homes where conventional construction provisions have previously been accepted. The use of customary engineering methodology to design redundant member systems (such as traditional wood framed floors, walls and roofs) results in substantially increased costs for residential structures. Thus, research needs to resolve two main issues: fastener performance, and development of “system factors.” Some of this research requires full-scale testing of wood frame structures, assemblies, and subassemblies. Data from full-scale tests will be used to derive system factors which in turn can be used by designers to calculate the performance of conventional wood frame structures accurately. Cyclic testing of assemblies is necessary to assess the performance of fasteners traditionally used in light-frame residential construction. Data gathered from cyclic tests will be used to substantiate the performance of wood frame assemblies under high wind and seismic conditions. All of this research will require substantial funding; however, significant savings in construction costs will benefit the ultimate consumer. Engineered wood products are now being specified in place of dimension lumber for long span applications and certain multi-member subassemblies (such as headers) in conventional construction.

Fire modeling is an important continuing segment of wood products research. Building codes specify fire performance criteria which reference fire test standards for all structural assemblies. Since wood systems can be made up of a variety of construction materials, testing every possible combination which can be used in buildings is costly and time consuming. With the development of each new wood product, the number of possible combinations increases. Therefore, fire modeling procedures must be developed to depict the performance of wood products and assemblies specified in fire test standards. Computer models must be validated by conducting

...barriers to increased use of these engineered-wood products include prescriptive building codes and limited funding for fire modeling and load and resistance testing.



Timber bridges are an important option for improving our nation's road system.

Courtesy of Southern Forest Products Association

Centers for Research and Technology Transfer

Research

American Forest & Paper Association
USDA Forest Service Forest Products Laboratory
National Institute of Standards and Technology
Oregon State University
Pennsylvania State University
Texas A&M University
Virginia Polytechnic Institute and State University
University of Wisconsin
West Virginia University
American Institute of Timber Construction
American Plywood Association
Structural Board Association

Technology Transfer

American Society of Civil Engineers
USDA Forest Service Forest Products Laboratory
Federal Highway Administration
Forest Products Society
American Forest & Paper Association
American Institute of Timber Construction
American Plywood Association
Southern Forest Products Association
Structural Board Association
Western Wood Products Association

costly full-scale fire tests. However, limited research funds have slowed the completion of wood industry computer fire models. These computer models, when developed and accepted, will significantly reduce the time and costs associated with demonstrating fire performance of systems and assemblies.

Also, serviceability limit states are being discussed for inclusion in future editions of load standards. Serviceability includes member and assembly deflection and vibration. Research to better quantify the long term creep (deflection) characteristics of wood assemblies, as well as floor vibration design are important to satisfy serviceability concerns of designers.

Industry sponsored research will soon result in the issuance of a load and resistance factor design (LRFD) standard for engineered wood construction. Although the U.S. is considered to be the world leader in development of LRFD principles for wood construction, research is needed to continue this work to develop true reliability-based design (RBD) procedures. RBD procedures will result in more accurate estimations of building systems performance. Such research will maintain this country's lead in the development of true RBD methodology and will encourage other countries to adopt this methodology into their design codes.

Current Industry Sponsored Projects

Currently, universities and government agencies are conducting the following research projects:

- Tests to determine the cyclic and dynamic performance of wood connections and assemblies at Virginia Polytechnic Institute and State University.
- Research to determine the shear resistance of various configurations of perforated shearwalls.
- Guardrail testing for various timber bridge sections, sponsored by the USDA Forest Service and conducted at the University of Nebraska.
- Timber bridge research sponsored by the Federal Highway Administration and the Forest Service to develop new designs being conducted at West Virginia University.
- Research to determine directional wind pressures on low-rise structures at the University of Western Ontario. This project is sponsored by the Canadian Wood Council and American Forest & Paper Association. Additional research anticipated on repetitive member systems (conventional construction).
- Development of structural fire performance models at the American Forest and Paper Association, University of Wisconsin, and USDA Forest Service Forest Products Laboratory.

WOOD

Prioritized Research Projects

Research Topic	Research Project	Objective	Approach	Schedule	Budget	Public Agency	Benefits
Materials	Composite Lumber Products	Develop high strength, high performance composite lumber products.	Review potential and current materials used in composite lumber products and identify those materials best suited for increased strength and performance. Investigate and test combinations of new or existing materials and fabrication processes to improve strength and performance characteristics.	6 years	\$6.0M	USDA	Improved performance of lumber products and efficient use of wood fiber.
Materials	Composite Wood Panel Products	Develop high strength, high performance wood composite panel products.	Review potential and current materials used in composite wood panel products and identify those materials best suited for increased strength and performance. Investigate and test combinations of new or existing materials and fabrication processes to improve strength and performance characteristics.	6 years	\$6.0M	USDA	Improved performance of panel products and efficient use of wood fiber.
Materials	Fire Resistance	Improve fire resistance characteristics of wood products.	Investigate use of alternative chemicals, coatings and protective membranes to increase performance and test using appropriate testing methods.	5 years	\$6.5M	USDA	Improved fire resistance.
Products And Structural Systems	Structural Systems	Develop new structural systems for buildings and bridges which use traditional and composite wood products.	Design, test and evaluate prototype structures using wood composite and traditional wood products. The prototype structures will utilize the enhanced properties of composite wood products.	5 years	\$9.5M	FHWA USDA	Improved performance of structural systems.
Products And Structural Systems	Structural Shapes	Develop efficient shapes for wood composite products.	Identify and test efficient shapes for wood composite products for use in buildings and bridges.	3 years	\$3.6M	USDA	Efficient use of wood fiber.

Research Topic	Research Project	Objective	Approach	Schedule	Budget	Public Agency	Benefits
Connections	Connections for Wood composite products	Develop connection systems for wood composite lumber products and composite wood panel products.	Identify and test various connection geometries and methods to utilize the enhanced properties of composite lumber products.	8 years	\$4.0M	USDA	Improved performance of wood products.
Connections	Connections for Structural Assemblies	Develop connection systems for structural assemblies.	Identify and test various connection geometries and method to improve the performance of the structural systems and assemblies.	8 years	\$4.0M	USDA	Improved performance of structural assemblies.
Fabrication And Erection	Automated systems	Develop cost effective automated fabrication and erection systems.	Investigate current automation techniques and concepts and identify areas where there are opportunities for automation. Develop automation systems where opportunities are available.	8 years	\$10.0M	USDA	Efficient fabrication and erection systems.
Analysis And Design	Fire Performance	Determine the fire performance of composite wood products and structural systems.	Investigate the fire performance of wood composite products wood composite structural systems through the use of appropriate testing procedures. Develop analysis procedures to predict material performance.	7 years	\$5.25M	USDA	Improved fire performance of wood products and systems.
Systems Analysis And Design	Serviceability	Develop performance criteria for serviceability of wood composite products and wood assemblies.	Develop performance criteria for serviceability based on knowledge of loads and material behavior.	8 years	\$3.0M	USDA	Improved performance of wood assemblies.
Systems Analysis And Design	Systems Analysis	Develop methods for predicting the behavior of wood structural systems.	Design, test and evaluate prototype wood structural systems. Develop empirical and computer models for predicting performance of structural systems.	5 years	\$3.5M	USDA	Improved performance of wood assemblies.
Life Cycle Analysis	Service Life Evaluation	Develop methods for predicting the service life of composite wood structural systems.	Investigate service life of wood composite structural systems through appropriate testing and modeling.	3 years	\$3.6M	USDA	Improved performance of wood assemblies.
Life Cycle Analysis	Life Cycle Cost Analysis	Develop a life cycle cost plan.	Evaluate information about the conditions of use of wood composite products and systems to develop a life cycle cost plan.	4 years	\$1.0M	USDA	Improved performance and use of wood products.

Research Topic	Research Project	Objective	Approach	Schedule	Budget	Public Agency	Benefits
Life Cycle Analysis	Renovation And Retrofit	Develop methods to strengthen and replace components of existing structures with wood products.	Identify areas where wood products can be used to strengthen or replace existing structures. Develop methods to allow the use of wood products for strengthening or replacing components of existing wood, steel and concrete structures.	5 years	\$4.0M	USDA	Improved methods to renovate existing structures.
Total Project Outlay					\$ 69.95M		

Wood Prioritized Timeline and Budget Allocation

Year	Project	Duration (years)	Cost
1	Composite Lumber Products	6	\$1,000,000
	Composite Wood Panel Products	6	1,000,000
	Fire Resistance	5	1,300,000
	Structural Systems	5	1,900,000
	Fire Performance	7	750,000
	Wood Composite Connections	8	500,000
	Structural Assembly Connections	8	500,000
	Service Life Evaluation	3	1,200,000
Year 1 Total \$8,150,000 Cumulative Total \$8,150,000			
2	Composite Lumber Products	6	\$1,000,000
	Composite Wood Panel Products	6	1,000,000
	Fire Resistance	5	1,300,000
	Structural Systems	5	1,900,000
	Systems Analysis	5	700,000
	Fire Performance	7	750,000
	Service Life Evaluation	3	1,200,000
	Wood Composite Connections	8	500,000
	Structural Assembly Connections	8	500,000
Year 2 Total \$8,850,000 Cumulative Total \$17,000,000			
3	Composite Lumber Products	6	\$1,000,000
	Composite Wood Panel Products	6	1,000,000
	Fire Resistance	5	1,300,000
	Structural Systems	5	1,900,000
	Systems Analysis	5	700,000
	Fire Performance	7	750,000
	Service Life Evaluation	3	1,200,000
	Wood Composite Connections	8	500,000
	Structural Assembly Connections	8	500,000
	Serviceability	8	375,000
	Automated Systems	8	1,250,000
Year 3 Total \$10,475,000 Cumulative Total \$27,475,000			

Year	Project	Duration (years)	Cost
4	Composite Lumber Products	6	\$1,000,000
	Composite Wood Panel Products	6	1,000,000
	Fire Resistance	5	1,300,000
	Structural Systems	5	1,900,000
	Systems Analysis	5	700,000
	Fire Performance	7	750,000
	Wood Composite Connections	8	500,000
	Structural Assembly Connections	8	500,000
	Serviceability	8	375,000
	Automated Systems	8	1,250,000
Year 4 Total \$9,275,000			Cumulative Total \$36,750,000
5	Composite Lumber Products	6	\$1,000,000
	Composite Wood Panel Products	6	1,000,000
	Fire Resistance	5	1,300,000
	Structural Systems	5	1,900,000
	Systems Analysis	5	700,000
	Fire Performance	7	750,000
	Wood Composite Connections	8	500,000
	Structural Assembly Connections	8	500,000
	Serviceability	8	375,000
	Automated Systems	8	1,250,000
Year 5 Total \$9,275,000			Cumulative Total \$46,025,000
6	Composite Lumber Products	6	\$1,000,000
	Composite Wood Panel Products	6	1,000,000
	Systems Analysis	5	700,000
	Fire Performance	7	750,000
	Wood Composite Connections	8	500,000
	Structural Assembly Connections	8	500,000
	Serviceability	8	375,000
	Automated Systems	8	1,250,000
	Renovation And Retrofit	5	800,000
	Life Cycle Cost Analysis	4	250,000
Year 6 Total \$7,125,000			Cumulative Total \$53,150,000
7	Fire Performance	7	\$750,000
	Wood Composite Connections	8	500,000
	Structural Assembly Connections	8	500,000
	Serviceability	8	375,000
	Automated Systems	8	1,250,000
	Renovation And Retrofit	5	800,000
Year 7 Total \$4,425,000			Cumulative Total \$57,575,000

Year	Project	Duration (years)	Cost
8	Wood Composite Connections	8	\$500,000
	Structural Assembly Connections	8	500,000
	Serviceability	8	375,000
	Automated Systems	8	1,250,000
	Renovation And Retrofit	5	800,000
	Structural Shapes	3	1,200,000
	Life Cycle Cost Analysis	4	250,000
Year 8 Total \$4,875,000			
Cumulative Total \$62,450,000			
9	Serviceability	8	\$375,000
	Automated Systems	8	1,250,000
	Renovation And Retrofit	5	800,000
	Structural Shapes	3	1,200,000
	Life Cycle Cost Analysis	4	250,000
Year 9 Total \$3,875,000			
Cumulative Total \$66,325,000			
10	Serviceability	8	\$375,000
	Automated Systems	8	1,250,000
	Renovation And Retrofit	5	800,000
	Structural Shapes	3	1,200,000
Year 10 Total \$3,625,000			
Cumulative Total \$69,950,000			

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Chapter 13

Ensuring Program Success: Forging an Industry-Government Partnership

The case for the CONMAT program is powerful; the nation's infrastructure **must** be transformed. The CONMAT program, costing a tiny fraction of the annual construction put in place, has the opportunity to bring forth such a transformation, utilizing tomorrow's high-performance materials and systems. In a very short time, ten different sectors of the construction materials industry have come together to pursue this goal.

The Role of Industry

In order for the CONMAT program to succeed, a number of steps must be undertaken. **First, and most importantly, CONMAT must continue to be an industry-led program.** The ten material groups which came together to produce this report are committed to:

First, and most importantly, CONMAT must continue to be an industry-led program.

- **Cooperative action.** The commercial opportunities are so great that all material groups recognize the virtue of cooperative ventures in areas beyond their current market niche. CONMAT participants understand that the research and technology deployment activities will be periodically reviewed and updated, as the needs of the construction community and the nation's infrastructure are regularly reassessed.
- **Industry leadership.** Construction industry leaders must direct the implementation of the CONMAT program, demonstrating how it directly responds to the needs and vision of the construction community. These leaders will strengthen the CONMAT program by establishing partnerships and collaborative efforts where appropriate.
- **Financial commitment.** CONMAT must truly become a dynamic cooperative effort between the public and private sectors. The program will succeed only if there is active industry participation, including cash and in-kind support, and oversight.
- **Implementation and technology deployment.** Industry is well positioned to take the results of the CONMAT program to the marketplace. CONMAT will succeed only if it can develop and demonstrate practical, commercially-viable applications.

The Role of the Federal Government

Active participation by the federal government is essential to the success of CONMAT. The Administration and Congress should support the CONMAT program by:

- **Endorsing the concept and objectives of the CONMAT program**, recognizing it as an essential element of this nation's commitment to upgrade the nation's civil infrastructure.
- **Supporting the establishment of CERF's National Construction Materials Coordinating Council (NCMCC)** to have authority for program implementation.
- **Directing all Federal agencies to consider the budget and program objectives outlined herein** when developing their respective program budgets. The strength of the CONMAT program will be in its ability to leverage private and public sector funds to most efficiently accomplish its goals.
- **Continuing to provide a construction program focus** through the National Science and Technology Council (NSTC) and the Office of Science and Technology Policy (OSTP).
- **Ensuring Federal support through such cost-sharing/support mechanisms** as the Technology Reinvestment Project (TRP), Manufacturing Extension Partnership (MEP), the U.S. Army Corps of Engineers Construction Productivity Advancement Research (CPAR) programs and Cooperative Research and Development Agreements (CRDA), the Advanced Technology Program (ATP) and other programs as appropriate.
- **Continuing to modify user agency procurement policies** to encourage the inclusion of innovative technologies in new and rehabilitation construction projects. As a major customer, Federal support is essential for many of the key CONMAT demonstration projects.
- **Facilitating the CONMAT effort to reduce barriers to commercialization** by supporting new approaches in such areas as new product evaluation, life cycle costing, contract/bid systems, tort liability and regulations which affect the introduction of innovation into the construction industry.

Active participation by the federal government is essential to the success of CONMAT.

The need to implement a research, development and deployment program to exploit the potential of high-performance materials and systems is clear.

The need to implement a research, development and deployment program to exploit the potential of high-performance materials and systems is clear. We must seize this opportunity and ensure that the CONMAT program is implemented. The quality of life that we demand for ourselves and expect for our children requires no less.