HIGH-PERFORMANCE Construction Materials and Systems

Building an Infrastructure for the 21st Century

RICHARD A. BELLE

A pundit once observed that politics makes for strange bedfellows. Recent developments suggest that this may happily also be true for the design and construction industry. A clear recognition of the need to repair and rehabilitate the nation's rapidly deteriorating infrastructure has brought together diverse organizations representing 10 different material groups that traditionally compete for market share. The material scientists and engineers working with these different basic construction materials—aluminum, coatings, fiber-reinforced polymer composites, concrete, hot mix asphalt, masonry, roofing materials, "smart" material devices and monitoring systems, steel, and wood—have come together to craft a program that will help create a new infrastructure for the next century. The 10-year effort, known as CONMAT ("construction materials") is a $2 billion national program of technological research, development, and deployment to accelerate the commercialization of high-performance construction materials and systems. CONMAT was formally presented to the Clinton administration and Congress in December 1994. The key elements of the program and its implications for the highway community are highlighted in this article, which describes the plan presented in a recent publication, *Materials for Tomorrow's Infrastructure: A Ten-Year Plan for Deploying High-Performance Construction Materials and Systems (1).*

The ultimate goal of CONMAT is to create the materials and systems for an entirely new generation of constructed facilities. Rapid advances in material science and engineering, computing and telecommunications, building materials research, and other emerging technological innovations make it possible to realize this ambitious national goal. Merely articulating societal needs and possessing technical capabilities is insufficient, however. CONMAT's chances for success rest on three elements: a detailed, step-by-step implementation plan; a dedicated national leadership; and broad support from the design and construction industry. Without these elements in place, the program will have little chance to succeed.

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MASTER BUILDERS, INC.

Parking structure at Denver International Airport is predominantly precast concrete containing corrosion-inhibiting admixture to help increase service life.

Magnitude of Problem

Readers of *TR News* understand better than most observers how fragile is our nation's infrastructure. The major domestic 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 dramatically highlighted the limitations of the nation's built environment. The situation is perhaps even more daunting when one reviews the catalogue of problems facing our nation's infrastructure under the best of circumstances, when nature is not playing an extraordinary role. Many of the nation's bridges, highways, buildings, pipelines, and other structural supports are falling below capacity or are in need of immediate repair or replacement. Consider these examples *(2-5)*:

- Approximately 230,000 of the nation's 575,000 bridges are structurally deficient or functionally obsolete; 143,000 of these 575,000 bridges are 50 years old or more and unsuitable for current or projected traffic demands.
- Ten percent (96 561 kilometers or 60,000 miles) of the federal-aid roadway pavements require immediate repair or replacement. The American Association of State Highway and Transportation Officials 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 requires 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.
- One study estimates that by 2005 the traffic delays caused by inadequate roads will cost the nation $50 billion a year in lost wages and wasted fuel. A comparable study calculates that the delays due to highway congestion in 15 major U.S. cities cost the nation more than $30 billion in traffic delays, excess fuel consumed, and higher insurance premiums.


HARDCORE COMPOSITES, LTD.

New high-technology composite marine fenders outperform traditional materials in energy absorption and are immune to marine wood borer attack.

A guiding assumption of the CONMAT program is that major public and private investments in technology for infrastructure renewal will directly benefit the private sector. For example, the construction of the Interstate highway system led to the development of new concretes and steels and of new design technologies with direct application to commercial structures. New materials and systems that 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. The development of expertise in the application of high-performance materials and systems will help to restore the United States to its leadership position in world construction markets.

Research and development (R&D) pertinent to infrastructure improvement currently amounts to a miniscule percentage of public works budgets. As a result R&D activities have been narrowly focused and predominantly short term. A continuing underinvestment in R&D and a reluctance to address long-term goals have resulted in the current dismal state of the public works infrastructure. For example the total public capital investment in the transportation infrastructure (as a percentage of the gross domestic product) has declined almost 40 percent since 1960 *(6)*. In fact, R&D investment by the construction community, reflecting both public- and private-sector commitments, is approximately one-seventh of the U.S. all-industry investment rate average *(7)*. The CONMAT program budget of $2 billion over the next 10 years is ambitious. Yet viewed as an annual investment of $200 million, this represents a financial commitment by all elements of the industry of slightly less than one-twentieth of 1 percent of the annual construction put-in-place *(8)*. Many of the necessary funds are potentially already available; the CONMAT program provides a structure and template for previously uncoordinated materials programs.

Characterizing High-Performance Construction Materials and Systems

What do the program participants mean by the term "high-performance construction materials and systems"? After all, a program of infrastructure renewal could use traditional, present-day materials and processes. Such an effort would address some of the immediate needs and be better than no program at all, but using traditional materials and systems 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. It would also be difficult to effect significant improvements in durability, constructability, and maintainability. The CONMAT program stresses that the nation's constructed facilities, whether in public or private hands, need the benefits inherent in high-performance construction materials and systems.

Significant advances have been made in materials science and structural analysis during the past two decades. The challenge for CONMAT is making certain that these advances leave the laboratory to become effectively commercialized. When developed, elements of a high-performance infrastructure will be characterized by one or more of the following types of improvement:

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

These performance capabilities, when achieved, will dramatically transform the current approach to design and construction. For example, designing a bridge with a life-cycle expectancy of 50, 100, or even more years will forcefully change expectations for maintenance, repair, and a host of related issues. An examination of the performance expectations of each materials group will lead to a better understanding of what "high-performance" means for the next generation of bridges, highways, buildings, pipelines, and other key components of a 21st-century infrastructure. The report on which this article is based presents dozens of specific research projects for each of the 10 groups. One or two exemplary projects or families of projects per material group are presented here.

Aluminum

Without any rebuilding of the foundations or girders systems, the load-carrying capacity of posted bridges could be upgraded by 30 to 40 percent through decks replaced with long-life, corrosion-resistant, high-performance aluminum. These decks can be erected within days instead of weeks or months, greatly reducing the expense, roadway restrictions, and driver inconvenience of the repair. The net reduction in bridge replacement costs could be significant.

Coatings

Hundreds of thousands of bridges, water towers, and other public structures are coated with paint containing lead. The need to protect the environment and public health has increased the maintenance costs of vital structures three- to four-fold during the past decade. New equipment and procedures are urgently needed to make paint removal, waste separation, abrasive recycling, and dust control more cost-effective and less disruptive to the public. This effort will focus on high-performance coating systems using robotics and remote-control sensing, processes that are also being used in other areas of CONMAT research.

Fiber-Reinforced Polymer Composites

The potential for factory assembly and the light weight of composites offer significant potential for reduced construction times. One possibility is the goal of a new generation of vehicular bridges. The initial costs of these bridges will be competitive with those of traditional prestressed and precast concrete bridges. Composite bridges will be factory-produced for exceptional quality control, and can be transported over the road and opened to traffic within eight hours. A second area of effort is the unique contribution composites can make to high-performance concrete construction. Potential composite products include dowel rods, reinforcing bars (rebars), tendons for prestressed and precast concrete structures, and cable stays. Composite reinforcements for concrete do not corrode and can be fabricated into sophisticated shapes for greater strength and higher job site productivity.

Concrete

Workable high-performance concrete with a compressive strength approaching 140 MPa (20 ksi) is currently commercially available in some areas; researchers predict that strengths of 200 MPa (29 ksi) will be achievable without the use of exotic materials and special processes. If high-strength concrete can be successfully commercialized and used for such applications as bridges and high-rise buildings, the industry will be able to design and build major structures with significantly reduced mass. The lighter weight will greatly reduce the costs of materials and simplify the design and construction of foundations.

Hot Mix Asphalt

Several research projects are under way to develop modified asphalt cements to improve performance. These modified asphalt cements are more flexible than conventional asphalt cements at low temperatures to prevent cracking. Ongoing and future research work will produce a number of modifiers with the potential to improve the performance of hot mix asphalt significantly.

Masonry

Perhaps more than other subjects of research, preassembly offers greater potential for high visibility and significant payoff. New techniques of assembling and joining masonry elements will remove the constraints of individual masons and site weather conditions. The masonry construction seasons will be extended to the full year, an increase of one-third in the northern United States. Advances in materials, robotics, and control systems are available for investigation. The scope of this project is not easily addressed by the separate components of the masonry industry. The oversight of the CONMAT program is needed.

Roofing Materials

Developing the methodologies to estimate more accurately the useful lifetimes of roofs and introducing new diagnostic methods to predict roof failure are critical. More accurate life-cycle and failure data will make it possible to develop and use high-performance materials, application techniques, and design methods to extend the average useful life of roofs. Enormous economic benefits can be realized from these efforts: building owners could save approximately $8.8 billion for each year of additional roof life.


NATIONAL ASPHALT PAVEMENT ASSOCIATION

Traffic lanes surfaced with open-graded hot mix asphalt permit water to drain through surface, virtually eliminating spray at high speeds *(left)*. Water collects on surface of traffic lanes treated with conventional hot mix asphalt *(right)*.

Smart Material Devices and Monitoring Systems

Engineers and scientists have recently developed a number of highly reliable devices built on microwave, acoustic, optical, and transducer principles. Wide-area communication networks will convey information acquired by smart material sensors. State and local authorities that are monitoring structures remotely can be warned almost immediately of threats to the structural health of every bridge, roadway, or pipeline in the system. This technology will enable historical data on buildings and bridges to be available to oversight agencies that provide early warnings of imminent catastrophic failure. Such a communication net will be implemented using a combination of microwave, micrometeor trellite, fiber optic relays, and conventional ground line components.

Steel

Improved knowledge of the effects of welding processes on steel will allow the development of new high-performance steel with significantly improved welding capability. Improved welding electrodes and processes will be developed concurrent with this steel advancement. Both of these activities will permit more productive practices such as one-sided and field welding, which will result in lower costs and shorter erection times for bridges. Another approach to this goal for high-performance steel systems is the use of automated fabrication and erection techniques. Integrated design and fabrication will further improve the total quality of constructed facilities. Development of new connection systems will aid in this automation. Construction will become less labor-intensive, more economical, and more reliable.

Wood

Numerous state and local jurisdictions that lack adequate funds to maintain deteriorating bridges now recognize the potential usefulness of modern timber bridge designs. An estimated 150,000 substandard bridges in the United States could use these designs. Panelized assemblies and engineered wood products allow local jurisdictions to replace deficient bridges using their own personnel and construction equipment. Wood industry experts estimate that construction time for these bridges could be reduced by as much as 50 percent, compared with traditional products and practices *(9)*.

Formation of National Construction Materials Coordinating Council

Publication of the CONMAT plan in December 1994 was only the first step: implementation of the plan requires an ongoing joint private and public sector effort. The key challenge has been to develop an institutional mechanism that ensures effective implementation of the research and commercialization program. The collective responsibilities and need for consensus among the program participants led to the establishment of the National Construction Materials Coordinating Council (NCMCC) in spring 1995 as a mechanism to coordinate both day-to-day and long-term activities. NCMCC is an industry-led group that works closely with federal agencies, academic institutions, and federal laboratories. The key members of the council are the basic material groups that have developed and are regularly updating and modifying the program's research agenda. Public sector experts have observer status. NCMCC has one overriding mandate: to facilitate the implementation of the CONMAT program. The council provides outreach on a regular basis to the construction community.

NCMCC will document and measure program implementation against the published 10-year plan. These efforts will be reflected in reports to Congress and the Administration and in reports to the private sector. NCMCC will also work to ensure that the CONMAT research, development, and deployment efforts are comprehensive and that they address critical technical concerns, building codes, and other issues.

The challenge is a dynamic one because CONMAT will be constantly evolving, with possible additions to its membership (for example, groups representing the geotextiles, rock/aggregate, and gypsum industries) and increased visibility in the construction community. NCMCC will ensure that duplicate research projects are avoided and that the maximum potential for collaboration is realized. Day-to-day activities of NCMCC are coordinated through the Civil Engineering Research Foundation (CERF). The plan recognizes that each material group will pursue its own market objectives and work with NCMCC on crosscutting projects and technology deployment issues that are common to more than one group.

Program Budget

In preparing the report participants closely reviewed the program objectives and the specific aims of their particular research and commercialization plan. Table 1 presents the 10-year budgets for each group, with some of the key objectives established to advance knowledge and use of each material. Table 1 also presents an eleventh line item for those technology deployment activities that cut across two or more material groups and are directed through 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 and deployment estimates in the 1993 volume, *High-Performance Construction Materials and Systems: An Essential Program for America and its Infrastructure,* in which the CONMAT steel and concrete agenda was initially presented *(4)*. Table 2 presents the annual budgets, by material group, for each of the next 10 years. As with Table 1, a separate line item has been assigned to the NCMCC technology deployment activities.

Emphasis on Technology Deployment

The R&D program is only one element of the implementation plan. Although many of the projects are interrelated (i.e., the successful completion of one project provides the necessary data to initiate a follow-on effort), there will be no effective improvement in the nation's infrastructure if the projects remain in the laboratories or are restricted to the text of a report that stays on the bookshelves.

Many of the elements that will ensure successful commercialization are common to all materials and may be classified under the term technology deployment. The United States has often been negligent in moving the results of R&D into the mar-

Ten-Year Implementation Plan

CONMAT is envisioned as a 10-year program of R&D and technology deployment. If research achievements are not translated into changes in the way the marketplace perceives and uses construction materials, then CONMAT will not succeed in its fundamental mission. The implementation plan is designed to disseminate research findings and commercialize new products and processes and rests on four operating principles: leadership, cooperation, technology deployment, and an orientation toward results.

Industry Leadership

Although active cooperation and partnership with academia and the public sector are sought and are critical to the success of CONMAT, the program will fall short of its goals if it is not driven by industries that can support and benefit from program implementation. The program is not simply a wish-list for industry representatives to pass on to government officials. Industry is expected to take the lead in identifying not only research needs and challenges, but also creative and effective ways to respond to these opportunities.

Cooperation

The material groups represented in the CONMAT plan are and will remain frequent competitors for the same niche markets and research funds. Nonetheless the CONMAT implementation strategy must pursue opportunities that require the active cooperation of these competing groups. This collaboration may take the form of cooperative funding on research projects of overlapping interest. It may also be reflected in the realization of mutual technological deployment objectives such as the creation of an integrated knowledge system or the training and retraining of engineers and technicians in the construction community.

Deployment

The implementation plan focuses not only on identifying specific research needs but also on overcoming the knowledge gaps and institutional barriers that currently limit the construction industry's use of high-performance materials and systems. A variety of proactive strategies promoting changes in product evaluation and contracting processes and establishing evaluation and demonstration projects are critical to CONMAT's success. These activities, relevant to the needs of all material groups, define the specific ways to deploy new technology.

Results Orientation

Initial successes will create incentive, enthusiasm, and energetic support for follow-up projects. Some projects are specifically designed as near term or intermediate term, and their successful completion is a prerequisite for subsequent projects.

TABLE 1 Proposed 10-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 affordablity	$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

ketplace—for example, the series of technological innovations in the electronics industry that were initiated in U.S. research laboratories but commercialized far more successfully in Japan and elsewhere. This inability to commercialize promising research discoveries and innovations applies equally to construction materials and systems. The active deployment of new technologies and processes, including the removal or reduction of barriers that limit the exploitation of new products and systems, is central to the CONMAT implementation plan.

Five key technology deployment activities are essential. First, the program will develop a clearinghouse to ensure that reliable data about the composition, properties, and performance of these materials and systems will become available to owners, designers, contractors, and the construction community. Second, because significant advancements in construction materials and systems research that occur outside the United States are not routinely captured or uniformly retained, CONMAT will ensure that knowledge of ongoing foreign developments is systematically obtained and disseminated. The program must also contribute to training and retraining engineers and technicians in the newest and most effective design, fabrication, and construction technologies. The program will strive to break down some of the barriers that consistently impede technology deployment, particularly in such areas as new product evaluation, life-cycle costing, and contract-bid systems. Finally, a key element of the CONMAT plan is prototype demonstration (evaluation) projects documenting the real-world benefits of using high-performance materials and systems. Prototype demonstration projects serve to change the paradigm and prove that major innovations are credible, efficient, and cost-effective in the long term.

Open Invitation

CONMAT must continue to be an industry-led program to maintain its initial success. The 10 material groups that produced the CONMAT report are committed to cooperative action, industry leadership, financing research and deployment efforts, and deploying the new technologies.

The commercial opportunities are so great that all material groups recognize the virtue of cooperative ventures in areas beyond their current market niche. 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.

Construction industry leaders will direct the implementation of the program, demonstrating how it directly responds to the needs and vision of the construction community. These leaders will establish partnerships and collaborative efforts where

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*	120.37	174.37	240.29	363.26	374.68	265.88	184.58	152.01	118.76	86.90	2081.05

* Totals may differ slightly from sum of yearly outlays, due to rounding.
** Specific funding levels have not been established at this time.

appropriate. CONMAT must 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.

Industry is well positioned to take the results of the CONMAT initiative to the marketplace. The program must develop and demonstrate practical, commercially viable applications.

The key to success is knowledgeable and enthusiastic participation from a broad spectrum of the materials community. Ten different sectors of the construction materials industry have come together quickly to pursue a goal of significantly transforming how the design and construction industry develops and uses advanced materials and technologies. To continue the momentum and to ensure program success, the participant groups must be expanded. Readers of this article who work in steel, concrete, aluminum, composites, or any of the other groups described should take the opportunity to become involved with their respective material group. The CONMAT program welcomes the interest of participants representing other basic material groups such as gypsum, plastics, or geomaterials.

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lanes, or support improved and increased ferry service.

The principle is simple: an increase in the gas tax is not an increase in taxes but in the fee for using the highways. The gas tax and tolls appear to be the simplest and fairest ways to collect the fee. Improvements to transit, ferries, and highways are simply improvements to specific parts of the whole system. Improvements to any one part make the whole system work better, which makes it better for each user.

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EDITOR'S NOTE: The letter above presents one reader's view on the costs of transportation improvements and how they can be financed. *TR News* welcomes the comments of others on this topic.

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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, NSF; 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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