Roadmap 2030:
The U.S. Concrete Industry Technology Roadmap

(Version 1.0)

December 2002

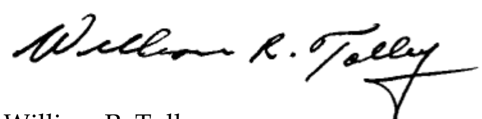
This document was facilitated by the Strategic Development Council

FOREWORD

Roadmap 2030 tracks the eight goals defined in the Strategic Development Council's (SDC's) *Vision 2030: A Vision for the U.S. Concrete Industry*, defines where enabling research is needed, and proposes areas where governmental-industrial-academic partnerships are required. The guiding force behind this initiative is the Strategic Development Council, an industry-led forum established by senior executives to focus on partnerships for accelerating adoption of new technologies for the benefit of society. In addition to this significant contribution, the Council provides a strategic voice in the concrete industry and facilitates a number of research consortia that examine a variety of subjects across the industrial spectrum. These include advanced cement manufacturing, high-performance concrete, automated construction systems, survivability and sustainability, and the predictive modeling of service life.

Roadmap 2030 is a living document (hence, the Version 1.0 designation) designed to continually address technical, institutional, and market changes. It highlights existing state-of-the-art technologies and emerging scientific advances that demonstrate or promise high potential for innovation and predicts future technological needs. The selected existing and needed technologies define the pathways to achieve *Vision 2030*.

SDC gratefully acknowledges the financial support provided by the U.S. Department of Energy (DOE) in developing this first version of *Roadmap 2030*. It is the intent of SDC to work with public and private sector organizations so that future versions of *Roadmap 2030* will continue to address the changing needs of the concrete industry for the public good.



William R. Tolley
President
Concrete Research and Education Foundation

Roadmap 2030 was developed in cooperation with the U.S. Department of Energy (DOE) Office of Energy Efficiency & Renewable Energy and the Strategic Development Council (SDC). SDC is a council of the Concrete Research and Education Foundation (ConREF), a subsidiary of the American Concrete Institute (ACI). *Roadmap 2030* does not represent the views of SDC, ConREF or ACI. Multiple organizations and unaffiliated people from the concrete industry participated in five technical reviews and/or the drafting of this document from May 2001 until completion of the final draft in November 2002.

Questions about *Roadmap 2030* or its intended use should be directed to William H. Plenge, Managing Director, Strategic Development Council, phone (410) 867-9702 or e-mail at bill.plenge@concrete.org.

Table of Contents

List of Exhibits

I. INTRODUCTION

The value of concrete as an essential material for modern society cannot be overestimated. Concrete forms the backbone of our nation's infrastructure and has impacted almost everything we encounter in daily life. Concrete is the most widely used man-made product in the world and is second only to water as the world's most utilized substance. Slightly more than a ton of concrete is produced every year for each human on the planet—over six billion tons a year—and our society uses more, in excess of 2.5 tons annually per American. The use of concrete as an affordable, reliable material in our nation's construction, industrial, transportation, defense, utility, and residential sectors is so pervasive that it is taken for granted. It is an almost absolute probability that anyone reading this document is located within one meter of some form of concrete.

While there is a healthy diversity of services within the concrete industry, its participants share a common objective—to deliver a high-quality, long-lasting, competitive, and sustainable product. *Vision 2030: A Vision for the U.S. Concrete Industry* outlines consensus goals established by industry leaders to improve their products' levels of performance, quality, and competitiveness. *Vision 2030* goals are as follows:

Process Improvements – The industry will make processing improvements throughout the life cycle of concrete. These will include design, manufacturing, transportation, construction, maintenance, and repair. *By 2030, concrete will be a significantly more cost-effective material for construction.*

Product Performance – The industry will make improvements in concrete's strength, durability, and other aspects of its performance to increase its use and quality. *By 2030, concrete will be the prime construction material selected on the basis of life-cycle cost and performance.*

Energy Efficiency – The concrete industry will continue to identify methods for improving energy efficiency in all stages of the product's cycle. *By 2030, the industry will have reduced the consumption of traditional energy resources from current levels by 50 percent per unit of output.*

Environmental Performance – The concrete industry will continue to increase its use of recycled waste and by-product materials, originating within the industry and from other sources, in concrete manufacturing. *By 2030, the concrete industry will achieve zero net waste.*

Technology Transfer – It typically takes about 15 years for new concrete technology to become widely available to the marketplace. *By 2030, the industry will reduce the time required for the acceptance of new technology to two years.*

Institutional Improvements – The industry will address the needs to reduce organizational fragmentation and to work together toward common goals. *By 2030, the industry will be cohesive and will demonstrate strong leadership, pursuing a fully integrated and well-defined strategic vision.*

Education and Employment – To attract more skilled workers, from laborers to engineers to executives, the industry will place increased emphasis on education. *By 2030, the concrete industry will be seen as a source of safe, well-paying, and challenging careers, resulting in the creation of a committed, diverse, and skilled workforce.*

Industry Image – With process and product improvements, as well as greater education and outreach to the public, the industry will make significant strides in improving its image with the populace at large. *By 2030, concrete will be recognized as an environmentally friendly material that is durable, versatile, and aesthetically pleasing.*

Whereas the *Vision 2030* goals provide a broad framework for the industry to follow over the next 30 years, *Roadmap 2030: The U.S. Concrete Technology Roadmap* presents a more detailed strategic plan for turning the *Vision* into reality. In producing this roadmap, industry experts that have a broad range of expertise and experience identified four distinct categories of critical research areas necessary to propel the industry forward. These categories are mapped to the present base of knowledge, research, and technology to illustrate the opportunities for advancement. Whether in the embryonic or growth stages, these opportunities possess great potential for short- and long-term economic impacts. The four categories, which are not independent, are:

Design and Structural Systems – Research to improve the design of and technology associated with concrete structures is vitally important. Through better understanding and control of material behavior, structural characteristics, and the construction processes involved, all elements of a concrete system can be enhanced. Research activities that address design and structural systems are grouped into seven classifications: structural concrete; reinforced concrete; modeling and measurement; high-performance concrete; technology transfer; fire-, blast-, and earthquake-resistant materials; and crosscutting innovations.

Constituent Materials – Constituent materials are those physical ingredients that make up the concrete mixture to achieve the performance desired. They include water, cement, aggregates, chemical admixtures, supplementary cementitous materials, and reinforcing materials, including fibrous reinforcement. There are a variety of research needs relating to constituent materials that, if met, will improve energy efficiency, productivity, and the performance of concrete and concrete products. These research needs are grouped into three classifications: new materials; measurement and prediction; and reuse and recycling.

Concrete Production, Delivery, and Placement – The concrete production, delivery, and placement category includes those activities associated with the mixing, transporting, placing, consolidating, and curing of concrete. Careful selection, proportioning, and mixing of the constituents, in addition to skilled forming, placing, consolidation, finishing, and curing of the concrete, are essential to producing concrete with the desired attributes (e.g., strength, durability, survivability). A properly proportioned concrete mixture will possess the desired workability when fresh and will have the intended durability and strength when cured. There are a variety of research requirements for improving energy efficiency, productivity, and performance in the processes for concrete production, delivery, and placement. Research activities are grouped into four classifications: information and control; production, delivery, and placement enhancements; test methods and sensors; and energy and environment.

Repair and Rehabilitation – Many of the nation's existing structures, such as bridges, roads, water and sewer pipes, dams, parking garages, concrete pressure vessels, and other vital constructions, are in need of repair or rehabilitation. Future concrete works, as in every form of construction, will almost without exception have to be repaired over their intended lives. Many older structures must be retrofitted to meet current standards, and functionally deficient structures must undergo renovation to meet capacity demands. There are a wide range of R&D prospects that, if addressed properly and brought into practice, can improve energy efficiency, environmental performance, health and safety, and productivity for the concrete industry. These are grouped into three classifications: new repair materials; assessment tools and modeling/measurement technologies; and field process technologies.

The following sections and exhibits provide a brief overview of the industry, followed by a discussion of research needs for each of the categories identified above. Although some items cross over into related categories, many are discussed in only one section. The listing of research needs is not intended to be exhaustive because this roadmap is a dynamic document to be updated as needs, technologies, and requirements change.

II. INDUSTRY OVERVIEW

In its simplest form, concrete is a mixture of cement paste and aggregates. The paste, composed of cementitious materials and water, coats the surface of fine and coarse aggregates (sand, gravel, and other materials) and binds them together as it cures and hardens into a rock-like mass known as concrete. A key advantage to the use of concrete is that it can be molded or formed into virtually any shape when newly mixed, and is strong and durable when hardened. These qualities explain why concrete can be used to build skyscrapers, bridges, sidewalks, superhighways, houses, and dams.[1] Although concrete is widely used today, concrete technology continues to advance. As these technologies develop and the industry becomes more advanced, the industry's energy efficiency and clean production and transportation should also improve. This roadmap is one way to ensure that these advances occur simultaneously.

Americans rely on concrete everyday in ways hardly noticed. Concrete is an affordable and reliable substance that builds the infrastructure of our nation's construction, industrial, transportation, defense, utility, and residential sectors. Concrete sustains our homes, our roads, our bridges, our buildings, and our lives. In essence, concrete is the fabric and foundation for the growth and prosperity of our nation.

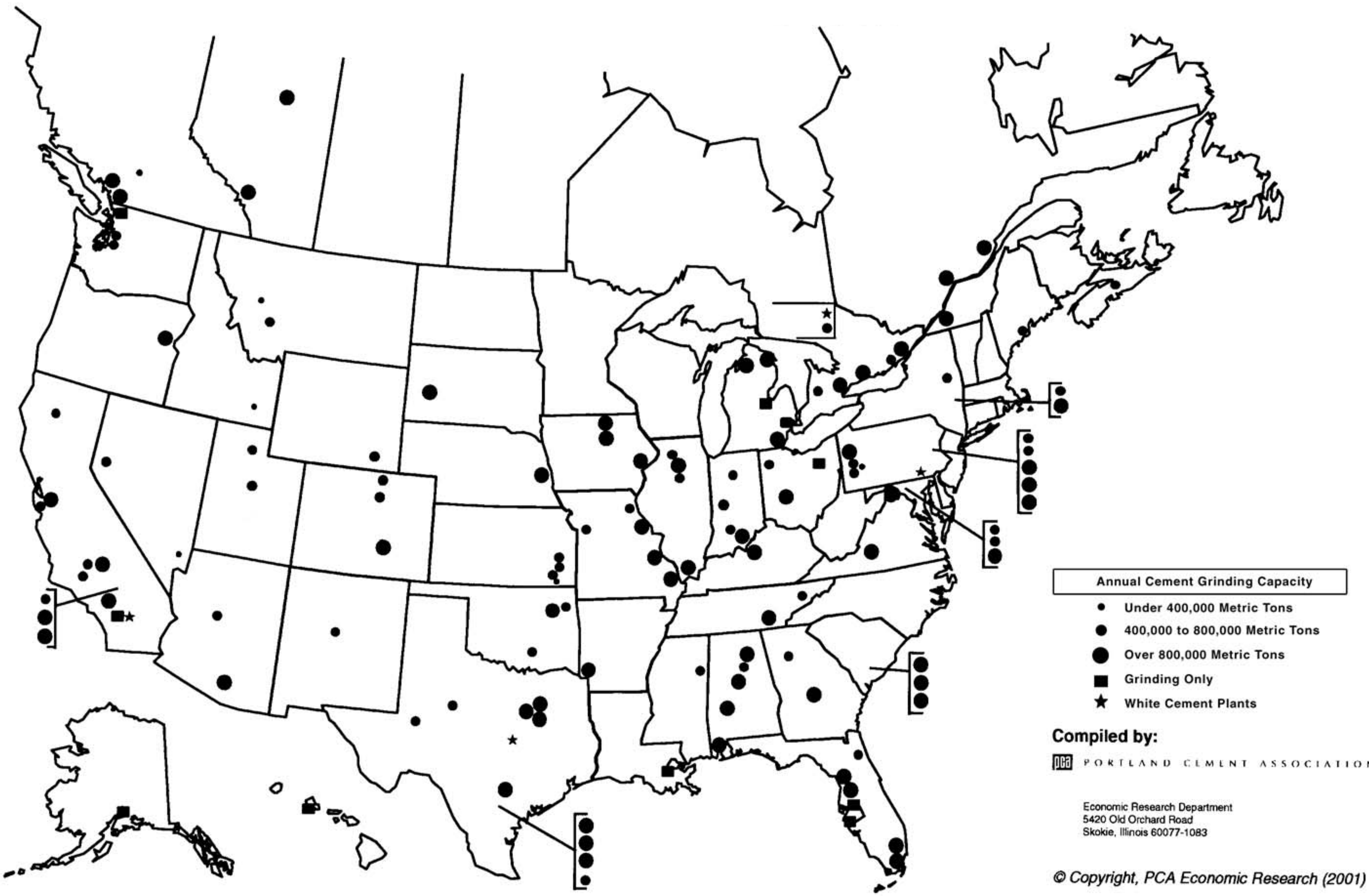
The concrete industry is vital to economic development and employment in communities across the country. The industry is a diverse one, consisting of thousands of concrete operations across the nation, and more than 95 percent of concrete-related companies employ fewer than 100 people. Also, the U.S. concrete industry is the largest manufacturing sector in the United States. Within the industry, thousands of companies manufacture cement, ready mixed concrete, concrete pipe, concrete block, precast and prestressed concrete, and other concrete products, and they employ over 220,000 people. If aggregate and other material suppliers, designers, haulers, constructors, and repair and maintenance companies are included, over two million jobs are related directly to the U.S. concrete industry. Overall, the value of shipments of cement and concrete production manufacturing exceeds $42 billion annually,[2] and the value of concrete placed each year exceeds $100 billion.

The concrete industry is nationwide. As shown in Exhibit 1, portland cement is produced in nearly every state. Similarly, as illustrated in Exhibit 2, every state in the nation has a ready mix concrete plant within its borders. Major states include Florida, California, Texas, Georgia, Arizona, Illinois, Michigan, Ohio, and Pennsylvania.

---

1. Portland Cement Association, *Concrete Basics.*
2. U.S. Department of Commerce, U.S. Census Bureau, *Annual Survey of Manufactures*, Geographic Area Statistic: 2000, NAICS code: Cement & concrete production manufacturing (3273).

Exhibit 1- United States and Canadian Portland Cement Plant Locations
Data as of December 31, 2000



Used with permission from Portland Cement Association

Exhibit 2 - Ready Mix Concrete Production by State—2000
Industrial Data Survey

State	2000 Production, cy*	Plants by State	State	2000 Production, cy*	Plants by State
Alabama	5,752,000	100	Montana	1,169,000	20
Alaska	467,000	10	Nebraska	3,964,000	70
Arizona	11,889,000	200	Nevada	7,214,000	120
Arkansas	3,499,000	60	New Hampshire	985,000	20
California	46,537,000	780	New Jersey	7,037,000	120
Colorado	9,543,000	160	New Mexico	3,053,000	50
Connecticut	3,078,000	50	New York	11,704,000	200
Delaware	606,000	10	North Carolina	10,158,000	170
District of Columbia	653,000	10	North Dakota	1,131,000	20
Florida	28,269,000	480	Ohio	14,355,000	240
Georgia	12,618,000	210	Oklahoma	5,220,000	90
Hawaii	1,060,000	20	Oregon	3,686,000	60
Idaho	2,049,000	30	Pennsylvania	12,396,000	210
Illinois	14,093,000	240	Puerto Rico	7,178,000	120
Indiana	8,111,000	140	Rhode Island	566,000	10
Iowa	6,283,000	110	South Carolina	4,843,000	80
Kansas	5,473,000	90	South Dakota	1,588,000	30
Kentucky	4,857,000	80	Tennessee	7,704,000	130
Louisiana	6,575,000	110	Texas	42,420,000	710
Maine	812,000	10	Utah	5,262,000	90
Maryland	4,896,000	80	Vermont	533,000	10
Massachusetts	5,804,000	100	Virginia	8,143,000	140
Michigan	12,818,000	220	Washington	7,409,000	120
Minnesota	7,385,000	120	West Virginia	1,531,000	30
Mississippi	3,440,000	60	Wisconsin	8,029,000	130
Missouri	9,414,000	160	Wyoming	909,000	20
			TOTAL	**395,614,000**	**6,650**

Source: Used with permission from National Ready Mix Concrete Association
* cy: cubic yards

The cement and concrete product manufacturing industry is a large consumer of energy, spending approximately $1.5 billion on purchased fuel and electricity in 2000, representing approximately 7.5 percent of material cost. Fifty-three percent of energy expenditures were for purchased fuels and 47 percent were for purchased electricity.[3] Cement manufacturing consumed 355 trillion Btu in 1998, representing an estimated two-thirds of total energy consumption in cement and concrete manufacturing.[4] These data do not include energy consumed in the placement of concrete in its many applications in construction, road building, and other uses.

The concrete industry continues to make giant strides in reducing energy consumption. For example, the cement manufacturing sector, which accounts for about 80 percent of the industry's total use of electricity, has just completed an intense 30-year effort that has reduced fuel and electricity consumption by 50 percent. As the nation's construction material of choice, concrete actually helps reduce energy consumption through life-cycle savings inherent in concrete construction as compared to systems using other materials. For example, concrete paving offers lower rolling resistance than asphalt to vehicles on U.S. roads and streets, thus contributing significantly to the nation's fuel savings.

3. U.S. Department of Commerce, U.S. Census Bureau, *Annual Survey of Manufactures*, Statistics for Industry Groups and Industries: 2000, Tables 2 and 4, NAICS code: Cement & concrete production manufacturing (3273).

4. U.S. Department of Energy, Energy Information Administration, *Manufacturing Energy Consumption Survey*, Table N3.1, Fuel Consumption, 1998, NAICS code: Cements (327310).

III. DESIGN AND STRUCTURAL SYSTEMS

Structural design necessarily precedes concrete construction. Before beginning the design, certain material properties must be assumed, such as compressive strength of the concrete and the yield point of steel reinforcement as well as how these characteristics can change in reaction to various environmental exposures or loadings. Based on an understanding of the material properties and how different materials interact under a wide range of conditions, a structure can be designed to resist anticipated environmental exposures and load conditions over its useful life, while providing satisfactory performance with a minimum amount of structural maintenance. Proper consideration of the following physical parameters is foremost in the design process as they are determinants for usable space, durability, survivability, maintainability, and useful life:

Compressive Strength – Compressive strength is the maximum resistance of a concrete to axial compression loading, expressed as force per unit cross-sectional area. Increased compressive strength and/or flexural strength can lead to smaller structural cross-sections that can translate into increased usable areas.

Shear – Shear is the internal force tangential to the plane on which it acts.

Ductility – Ductility is the property of a material by virtue of which it may undergo large deformation without rupture.

Tensile Strength – Tensile strength is the maximum stress that a material is capable of resisting under axial tensile loading, based on cross-sectional area of specimen before loading, expressed as force per unit cross-sectional area.

Research leading to tools that enhance the design process and technologies that expand design parameters through better understanding and control of structural characteristics and construction processes will increase the applicability, performance, and use of concrete systems. Exhibit 3 shows research needs within the Design and Structural Systems category.

Exhibit 3 - Design and Structural Systems Research Needs*

Design and Structural Systems	
Structural Concrete	· ***System survivability (different than durability or sustainability)*** · Chemical and mechanical bonds between concrete, reinforcement, and connectors · Time-dependent changes due to relaxation, creep, and shrinkage · Environmental and chemical factors such as freeze/thaw, chlorides, and sulfates · Layout and specification of reinforcement · Ratio determination of concrete to reinforcement volumes · Size/configuration of reinforced concrete elements · Relative direction, speed, location, and cycling of external loading or internal forces · Location and classification of cracks · Type and size of connections between structural elements · Interaction of elements within structural system
Reinforced Concrete	· ***Design methodologies for reinforcement and fibrous concrete*** · Coated and corrosion-free steel reinforcement · Nonmetallic reinforcement · Enhanced design procedures for shear reinforcement · Improved ductility of structural systems and high-performance concrete · Corrosion- and reinforcement-free bridge deck designs · Total precast bridge deck system · Permanent cementitious form systems · Electrically conductive concrete
Modeling and Measurement	· Service life design models – all applications · Durability models that predict interaction of stresses and environmental factors - all applications · Monitoring and embedded sensors – all applications · Smart materials that monitor, predict, and adjust (see Constituent Materials)
High-Performance Concrete	· Placing, finishing, and curing technologies · Field expedient, accurate testing of HPC · Advanced testing methods for HPC · HPC mixture optimization software · HPC designs for residential housing · Manufacturing processes for fiber-reinforced HPC components
Technology Transfer	· ***Comprehensive plan for accelerating technology transfer times from 15 to 2 years*** · ***Greater use of appraisal services by standards and codes bodies***
Fire-, Blast-, and Earthquake-Resistant Materials and Systems	· ***Rational (smart) systems for design of fire-, blast-, and heat-resistant alternative reinforced structures*** · ***Survivability research*** · Fire-resistant, high-strength concrete (see New Materials)
Crosscutting Innovations	· Adaptation of improved forming technologies used by other industries · Research that considers concrete as part of a multi-material constructed system · Adaptation of industrial sensing/testing devices used by other industries (see Test Methods and Sensors)

*High-priority research needs are in ***bold italics***

The following describes design and structural systems research classifications in broad terms.

A. Structural Concrete

Structural concrete has historically been reinforced with steel, which carries tensile forces that are internally generated when the structure undergoes elastic and inelastic deformations and movements. The strain and force equilibrium interactions within reinforced concrete structures involved are highly complex.

Factors that affect these interactions include:

- Chemical and mechanical bond and interface between the concrete and the reinforcement
- Time-dependent changes to the concrete and reinforcement material properties due to relaxation, creep, and shrinkage
- Introduction of environmental factors to the concrete over time, such as freezing and thawing and chemicals such as chlorides and sulfates
- Relative geometric configuration, distribution, and detailing of the reinforcement within or outside the reinforced concrete element
- Absolute ratio of concrete volume to reinforcement volume
- Relative size and configuration of the reinforced concrete element
- Relative direction, speed, location, and cycles of external loading or internal forces
- Location, length, and width of cracks
- Type and size of connections between structural elements
- Interaction of elements within the structural system

Research is needed to advance the understanding of each of these factors, both individually and as they relate with each other in structural concrete systems. The public, which takes little note of these factors, is quick to react when structures fail or come under threat, as in the present world terrorism situation. However, whether a structure degrades naturally or from abrupt, unpredictable insult, it does not change the fact that these interdependent factors are all working in structural concrete and will always require systematic research and innovation.

B. Reinforced Concrete

Steel reinforcement is commonly incorporated into the design of concrete structures to carry the tensile forces. However, concrete permeability, the resultant corrosion of steel reinforcement, and the associated tendency of concrete to lose bond or composite action with imbedded reinforcement reduce structural performance over time. Cooperative research is needed from their respective industry sectors to develop economical, thermodynamically durable metallic and non-metallic, corrosion-resistant reinforcements.

Appropriate research would advance, for example, the work already done on reinforcement-free bridge decks and that is being incorporated into the ACI design guide for this type of construction. Widespread use of these technologies, which have been researched for many years, will lead to additional refinements, such as the further development of FRP bars with a useful form of psuedo-ductility so as to make full use of their strength (see Constituent Materials).

Developments of design methodologies for corrosion-resistant steel and continuous and short-fiber reinforcements are *high-priority* research areas that could contribute to a significant decrease in life-cycle costs. In addition, enhanced design procedures that increase shear capacity are necessary to address the high-punching shear stresses encountered around columns or piles by thin concrete flat slabs, especially those with longer spans. Improvements in this area could significantly increase the use of concrete flat slabs as an economic form of construction. Research to boost the ductility of concrete could lead to the reduction or elimination of conventional continuous reinforcement in concrete structures.

C. Modeling and Measurement

The ability to predict the performance of structural systems is critical to meeting service life requirements. A comprehensive durability (service life) design model for cracked and uncracked structures that fully addresses multiple chemical and physical environments could result in extended structural life, lower life-cycle cost, and increased energy efficiency. New families of embedded sensors and monitoring devices could be developed to provide the base data necessary to build and validate these predictive design models. New “smart” materials technologies could result in higher-quality assurance and further increase the knowledge base (see Constituent Materials). The development of revolutionary, field-expedient, in-situ, non-destructive test methods for structural performance will present the opportunity to improve upon current methods of acceptance testing and quality assurance.

D. High-Performance Concrete

High-Performance Concrete (HPC) is designed to optimize performance in specific applications. As examples, more durable or higher-strength concretes may be developed by drawing on the latest knowledge when conventional concrete will not do or when improved performance would provide significant benefits. Often HPC is composed of essentially the same materials as normal concrete, only proportioned differently to yield improved performance.

In flatwork applications, research to improve the placeability and finishability of HPC could result in faster construction, increased durability, and reduced life-cycle cost (see Concrete Production, Delivery, and Placement). Industry and society could benefit from the efficiencies made possible by using new HPC designs for safe, rapid, and low-cost residential housing. Houses utilizing new fiber-reinforced HPC components that are manufactured using innovative and economical processes, e.g., extrusion and pultrusion, could perform better than those constructed with conventional materials such as wood by providing increased hardening against disaster and protection from economic loss. A corrosion-inhibiting admixture should be considered part of HPC in bridges subjected to harsh weather conditions. Methods for quick and reliable quality assurance of HPC at the job site need to be developed. Advanced testing methods, such as proton response testing or ultrasonic shear wave reflection – while certainly far from field expedient today – could be of great value if practically harnessed as an on-site means for achieving HPC. These also promise to enhance the industry’s knowledge base and lead to the development of high-technology equipment and testing methodologies.

E. Technology Transfer

Typically, and for a number of reasons, it now takes more than 15 years for commercialization of new concrete technology, a well-known vulnerability of concrete as it competes for market share against other construction materials groups. The structural design community would be well served if the concrete industry were to develop and implement a consensus plan for expediting the code approval process – without compromise of comprehensiveness and quality. Reducing the time between completion of new concrete technologies and their availability to the design community is a *high-priority*. Greater use and expanded development of existing appraisal and evaluation services in the concrete industry to produce work product compatible with the needs of industry standards development organizations (which themselves need to become more responsive to the accelerated rate technology development) is required as concrete competes with other materials industries.

F. Fire-, Blast-, and Earthquake-Resistant Materials

Systems for designing structures with low risk of damage by fire, blast, and earthquake are of critical importance to the public and the concrete industry. Survivability is as important as durability and sustainability. This has been underscored by the present world terrorism situation. Structural designs that incorporate new fire-resistant, high-performance concrete can lower economic and social costs and, therefore, are *high-priority* research items. Research that will lead to an increased ability of constructed facilities to survive natural and man-caused attacks is a *high-priority*, both near-term and well into the twenty-first century.

G. Crosscutting Innovations

Research focused on development of crosscutting innovations (i.e., those with applicability in other construction materials groups) can benefit design of constructed facilities. Improved forming technologies such as extrusion, pultrusion, and injection molding could significantly enhance design capabilities and result in new applications for concrete, as well as adoption by other industries. Research leading to improved shear, tension, and torsion performance of constructed systems will positively impact all facets of structural design and help maintain concrete as the prime construction material of choice. An aggressive pursuit of crosscutting innovations is exemplified by the development of a new generation of engineered systems using inorganic materials specifically tailored for residential construction and transforming that construction through the use of micro- and nano-structural engineering to develop materials, sensors, components, and systems with new and presently unrealized properties that improve the construction process and provide important new benefits to the homeowner.

Exhibit 4 - Research Pathways for Design & Structural Systems

(High-priority research pathways are in ***bold italics***)

Design & Structural Systems	Short-Term R&D Activities (0 - 3 Years)	Mid-Term R&D Activities (4 - 18 Years)	Long-Term R&D Activities (19 - 28 Years)
Stuctural Concrete	· ***System survivability (different than durability or sustainability)*** · Environmental and chemical factors such as freeze/thaw, chlorides, and sulfates · Layout and specification of reinforcement · Ratio determination of concrete to reinforcement volumes · Size/configuration of reinforced concrete elements	· Type and size of connections between structural elements · Relative direction, speed, location, and cycling of external loading or internal forces · Chemical and mechanical bonds between concrete, reinforcement, and connectors · Location and classification of cracks	· Time-dependent changes due to relaxation, creep, and shrinkage · Interaction of elements within structural system
Reinforced Concrete	· ***Design methodologies for reinforcement and fibrous concrete*** → · Nonmetallic reinforcement → · Coated and corrosion-free steel reinforcement · Enhanced design procedures for shear reinforcement	· Improved ductility of structural systems and high-performance concrete · Corrosion- and reinforcement-free bridge deck systems · Total precast bridge deck system · Permanent cementitious form systems · Electrically-conductive concrete	
Modeling and Measurement	· Durability models that predict interaction of stresses and environmental factors—all applications → · Service life design models—all applications	· Monitoring and embedded sensors—all applications · Smart materials that monitor, predict, and adjust (see Constituent Materials)	
High-Performance Concrete	· HPC mixture optimization software → · Placing, finishing, and curing technologies	· Field-expedient, accurate testing of HPC · Advanced testing methods for HPC · HPC designs for residential housing	· Manufacturing processes for fiber-reinforced HPC components
Technology Transfer	· ***Comprehensive plan for accelerating technology transfer times from 15 to 2 years*** · Greater use of appraisal services by standards and codes bodies		
Fire-, Blast-, and Earthquake-Resistant Concrete	· ***Survivability research***	· ***Rational (smart) systems for design of fire-, blast-, and heat resistant alternative reinforced structures*** · Fire-resistant, high-strength concrete (see New Materials)	
Crosscutting Innovations		· Research that considers concrete as part of a multi-material constructed system	· Adaptation of improved forming technologies used by other industries · Adaptation of industrial sensing/testing devices used by other industries (see Test Methods and Sensors)

IV. CONSTITUENT MATERIALS

Constituent materials are those materials incorporated in concrete mixtures to achieve the desired performance. They include cement, aggregates, chemical admixtures, supplementary cementitious materials, reinforcing materials, water, and air. A description of all but the last two of these constituents follows:

Cement – Portland cement is the most widely used cementitious constituent in concrete, but blended cements, which may be viewed as optimized blends of portland cement with supplementary cementitious material, are growing in importance because of the benefits they can offer in regard to certain aspects of performance, conservation of energy in manufacture, protection of the environment, and cost.

Aggregates – Aggregates are essentially inert granular materials such as sand, ground sand, gravel, crushed stone, recycled crushed concrete, or manufactured aggregates that are an essential ingredient of concrete. Typically, they occupy 60 to 75 percent of total volume. As such, the aggregate materials have a significant influence on the concrete (e.g., mechanical and physical properties, dimensional stability, wear resistance, and cost). For a "good" concrete mixture, aggregates must be clean, hard, and strong particles free of absorbed chemicals or coatings (e.g., clays and other fine materials) that could be detrimental to the performance of the concrete.

Chemical Admixtures – Chemical admixtures are the materials other than the cement, water, and aggregates that are added to the concrete mixture, usually in very small quantities, immediately before or during mixing. Most admixtures are organic materials. They are used primarily to reduce the cost of concrete construction by ensuring the quality of concrete during mixing, transporting, placing, and curing to overcome certain emergencies during concrete operations, to improve the properties of hardened concrete, and to improve its durability.

Supplementary Cementitious Materials – Supplementary cementitious materials are often referred to as mineral admixtures. While not normally used as cements by themselves, when used in blends with portland cement they make a significant cementing contribution to the properties of hardened concrete through hydraulic or pozzolanic activity. Some common supplementary cementitious materials are natural pozzolans, fly ash, ground granulated blast-furnace slag, and silica fume.

Reinforcement – Reinforcements, most commonly steel, are materials in shapes with high-aspect ratios embedded in concrete to increase its resistance to tensile forces. Reinforcements are needed principally because concrete, sufficient as it is for strength, is relatively weak in tension.

The following are examples of research needed in the area of constituent materials. If sufficiently researched, they will lead to improved energy efficiency and productivity in the manufacture of concrete and concrete products; they are also likely to improve the technical performance and life-cycle cost of concrete and concrete products and to reduce their life-cycle environmental impacts. Exhibit 5 shows research needs within the Constituent Materials category.

Exhibit 5 - Constituent Materials Research Needs*

Constituent Materials	
New Materials	· ***Noncorroding steel reinforcement*** · ***Families of innovatively manufactured concrete with predictable performance*** · ***New materials to reduce shrinkage and cracking*** · ***Reduction of alkali-silica reactions in concrete*** · Fiber-reinforced composites · Rebar and welded wire reinforcement, four categories: (a) stainless steel, (b) zinc - coated, galvanized, and epoxy-coated (c) epoxy-coated, and (d) combination zinc- and epoxy-coated · Materials for active and passive corrosion prevention · New aggregate sources and types, including compatible lightweight aggregates · Methods for accurate characterization of aggregate shape and size · Reactive powder concretes · New admixtures and cementitious materials · Cements of specified performance · Corrosion-inhibiting admixtures · Smart materials · Self-consolidating, self-leveling concrete · Cement produced with improved energy efficiency and reduced environmental impact (see Energy & Environment) · Alternative fuels used in production of constituent materials · Optimized use of cementitious materials · Advanced concrete mixtures to reduce dependence on reinforcement · Advanced mixtures to promote internal curing and prevent shrinking and cracking · Acid-, fire-, and heat-resistant cementitious composites · Sulfate- and alkali-silica-resistant concrete · Moisture-insensitive mastics · Controlling vapor migration in slabs · Guidelines for concrete to be used in impervious overlays · Performance-based standards · New materials from novel waste streams · Supercritical carbon dioxide research for rapid strength
Performance Measurement and Prediction	· ***Prediction methods and models for permeability, cracking, durability, and performance (including environmental interactions)*** · ***Tools and data for quantifying benefits of using alternative materials*** · Tests for alternative reinforcement materials · Prediction model for exposed structures with >2" cover over black steel rebar and welded wire reinforcement · Models for predicting the performance of zinc-coated, epoxy-coated, combination zinc- and epoxy-coated, and stainless steel reinforced concrete structures · Measurement and prediction of self-desiccation in concrete · Multi-scale modeling to connect microstructure with engineering properties · Joint concrete and steel industry research to minimize corrosion of reinforcing steel · Predictive models to augment/replace QC tests
Reuse and Recycling	· ***Reuse of high-alkali wastewater*** · Aggregate recycling · Incorporation of waste and by-product materials from other industries · Reuse of cementitious materials, cement kiln dust, and other waste products

*High-priority research needs are in ***bold italics***

Selected constituent materials research topics are shown in broad classifications as follows.

A. New Materials

Better metallic reinforcement materials are needed, such as steels that are less prone to hydrogen embrittlement and corrosion as well as stainless steels and steels with improved corrosion-protective coatings. Better active and passive corrosion prevention means, such as cathodic prevention of mild steel, need to be developed and refined as well (cathodic prevention of mild steel reinforcement keeps reinforcement passive by producing hydroxyl ions on the reinforcement surface while anodic current retards diffusion of dangerous anions, such as chloride and sulfate, deeper in the concrete). Furthermore, reliable models need to be developed to predict the effectiveness of better metallic reinforcements and corrosion inhibiting admixtures. Existing models, such as those that predict performance and life of concrete with a specified thickness of cover over metallic reinforcement, need to be validated and refined.

Alternatives to traditional reinforcements, such as non-metallic reinforcing bars in the form of fiber-reinforced plastics (FRP), are needed to make reinforced concrete members that are not susceptible to damage by corrosion of the reinforcement. Worldwide interest in the use of FRP and carbon fibers in concrete structures as alternatives to traditional steel reinforcement has increased in recent years. However, research is needed to improve present technology FRP and carbon fiber reinforcements, which lack the ductility and load-deflection capability of traditional steel and are subject to deterioration when exposed to ultraviolet light. On the other hand, they exhibit high strength and noncorrosivity. While types of FRP reinforcement have been used experimentally in bridges, there is significant potential for use of nonmetallic reinforcement in residential and commercial applications, such as multi-story buildings, parking garages, and industrial structures, providing that the disadvantages cited, plus low-fire resistance, can be overcome. More research is needed before FRP and carbon fibers can be considered for wide application as primary reinforcements of concrete. The major technical challenge is how to retain structural ductility with carbon fiber reinforcement, an inherently brittle system, and achieve adequate strength with FRP. If this can be solved, FRP and carbon fibers can join stainless and coated steels as options for the elimination of corrosion in concrete in wide-ranging applications.

Additionally, research is needed to develop and validate alternatives to and advanced variations of traditional concretes that use alternative and traditional reinforcements. One example is reactive powder concrete reinforced with chopped, small diameter steel wires. New technology concretes open endless possibilities for the use of existing and new technology reinforcements.

The rheological research that has enabled production of reactive powder concretes of very high strength will also enable production of self-consolidating and self-leveling concrete. Industry and code acceptance of self-consolidating concrete will reduce labor costs, save space, and increase energy efficiency. Rheological research is also needed to explore possibilities for improving concrete characteristics by coating the aggregates chosen.

Aggregates are costly to transport, and the distances necessary for transportation of material are growing larger as nearby source locations are lost to urbanization. The result is increased energy use and associated environmental impacts of emissions and dust. Research is needed to develop close-in sources of aggregates that are acceptable to local communities. Research is also needed to develop new, lightweight aggregate materials that are less costly to transport, not as difficult to obtain, and that reduce energy use.

Advances are needed in the science and technology of fire resistance of high-strength concrete to ensure that structures will retain adequate strength in case of fire. New materials to reduce shrinkage and cracking are needed to make concrete more reliable and enduring. Research is also needed that will lead to the routine production of crack-free concrete. Crack-free concrete is a *high-priority* need, particularly in structures exposed to harsh environments.

Research is needed to address the phenomena of water vapor migration in concrete slabs with coatings such as membranes, tile, and carpeting. Design guidelines are needed for such applications. New mastics with high degrees of insensitivity to moisture are also required. New admixtures and cementitious materials will increase the durability, sustainability, and performance of concrete in existing and new applications. Lightweight concretes are needed to broaden the use of concrete as a residential building material. Research could lead to entire families of innovatively manufactured concretes with predictable performance. This is a *high-priority* research need.

Optimizing the use of cementitious materials can improve design, energy, and environmental efficiency in concrete manufacturing and use. However, cementitious materials research is also needed in relation to the concrete mixture itself. This can reduce dependence on reinforcement. Development of acid-resistant concrete is needed. There is a need for biogenic, sulfuric acid-resistant concrete made with improved constituent materials that will facilitate the use of concrete under more extreme environmental conditions. Attention is needed to the development of user-friendly performance specifications and tools for predicting performance for the full family of cementitious materials.

The treatment of cementitious materials with gaseous carbon dioxide to achieve rapid development of strength has been known for many years. Advances have been made recently in the treatment of cementitious materials that will facilitate the use of supercritical carbon dioxide to achieve a ten-fold reduction in permeability, while strength increased by several fold. With further research, it is likely that this process could lead to the development of new materials from novel waste streams and accelerate the development of new and improved concrete mixtures.

Smart materials are needed to improve the performance and service life of concrete systems. These might range from basic, sensor-laced concrete to hybrid concrete that performs independently and optimally in response to changes in the environment. Research is needed to develop smart materials that will reliably warn of failure and other safety dangers. Beyond this, smart materials will become active in combating problems detected. The use of smart materials in concrete will broaden the residential and commercial market applications in which inexpensive concrete can be used as the primary construction material.

A strong technological base exists in research on the behavior of concrete's constituent materials. Recent advances in computational material science have given concrete industry scientists a promising new suite of tools for materials research. In many respects, the chemical and physical changes that occur in the development of a cement-based composite resemble those that occur in natural environments. Most materials in a composite like concrete are either earth materials or derivatives. Likewise, the processes that occur during cement hydration or as the composite interacts with its environment have geological analogs. Hence, the methods used to describe geological materials and processes at a fundamental level may contribute to the foundation for a mechanistic approach to concrete technology. This could form the basis for a geochemical model of the evolution of cement-based composites. Such a model would predict how a concrete mixture would perform in a particular environment, making it possible to optimize mixture design. Proper attention to this area could enable the concrete industry to avail itself of a number of geochemical and geophysical methods for the characterization of cement-based composites.

B. Performance Measurement & Prediction

There are many research needs for improving the characterization of constituent materials and prediction of their performance in concrete. Existing and to-be-developed tests need to be approved by code bodies for validating the fire endurance of fiber-reinforced concrete. Tests for characterizing fibers and other substitutes for steel reinforcement in concrete are needed. The results of these tests will not only help make concrete design more flexible, but will also aid the development of better and more cost-effective materials for reinforcement. Industry acceptance of the results of fire-resistant plastic will ensure reliability and consistency in the use of these materials in concrete. Also, industry development of models for predicting performance will increase the knowledge of concrete systems. In fact, the long delay in getting new materials accepted in the marketplace, 15 years or more, could be attributed directly to the fact that the basic materials science of the material is not known, and its life-cycle performance, therefore, not predicted so that a long period of time is necessary for people to feel confident with the material. Sound scientific knowledge, combined with performance-based tests and quantitative, accurate modeling and performance prediction, should drastically shorten these acceptance times as well as lead to increased optimization of materials.

Industry needs to quantify benefits of using alternative materials for energy reduction, waste reduction, and utilization. This will allow concrete to become more competitive as a construction material. Better methods for prediction of cracking and durability are also needed. With these, the concrete industry could produce a more reliable and durable product. Research in measurement and prediction of self-desiccation could lead to better means for predicting the failure of concrete in any environment. Design specifications and well-conceived performance criteria for performance-based concrete will also help ensure the consistency and reliability of concrete. The acceptance of specifications for concrete is a *high-priority* that requires the development of tools for measurement and prediction of performance.

The fact that the constitution of concrete is complex, with characteristic features on several very different length scales, can lead to confusion about concrete's performance. A concrete modeling initiative aimed at producing a meso-to-macro statistical performance prediction model could greatly benefit the concrete industry by connecting the macro behavior in specific applications to the underlying meso-scale processes associated with the concrete constituents and their production. Studies of concrete failure tend to focus on gross-macro features, whereas the underlying physical processes causing failure are often best related on the nano-to-meso scale. For this reason, modeling of mechanical failure phenomena usually focuses on the large structural extent, whereas composition designers tend to focus on nano-scale chemical constituent materials and additives. The latter focus includes porosity and leaching around grains of finely crushed rock or other gravel-sized aggregates. A standard methodology for bridging this gap and enhancing understanding of the physics of concrete performance will lead to improved concrete designs and applications. This methodology will be, of course, dependent on computational capabilities. The continuing development and application of three-dimensional modeling is essential to advancing the knowledge of concrete performance.

One suggested methodology would be validation of meso-scale models of concrete mixtures against specific performance-based experiments using hybrid computational techniques. This would include (1.) explicit representation of cement pore space, grains, water, and other filler material combined with its individual constitutive relationships, chemical reactions, and interface conditions; (2.) implementation of new statistical methods to define metrics that can represent damage and behavior from simulations of those observed empirically; (3.) applications of the correlated model to other types of loading and environment; and (4.) correlation of damage metrics from meso-scale simulations to a damage mechanics based on constitutive models for macro-scale applications. These will improve knowledge of concrete performance that can be directly related to the characteristics of the individual mixtures.

Development and validation of predictive modeling methodologies are needed for augmenting or replacing existing quality control tests. Predictive modeling is not a new concept, but it has never been fully developed into a widely accepted, practical tool. Moreover, predictive models need to be adaptable to advancements in concrete technology. Multi-scale models are needed to predict and guide the entire concrete "process," from microstructure to performance. Industry-wide acceptance of these models is-a *high-priority*.

C. Reuse and Recycling

Disposal of washwater from concrete construction sites has always been a high-cost, environmentally sensitive problem. There are few uses for this high-alkali water. Research, particularly with admixtures, could lead to the development of chemical means for reducing alkali content, making possible new alternative uses for treated water. This could open the way for the elimination of alkali limits on cements, thus making the application of concrete more desirable from an environmental perspective. This is a *high-priority* research need.

Economic and environmental benefits can also be derived from more research in recycling concrete as an inexpensive, readily available aggregate source. There is an associated need to research the means for determining the age at which aggregates derived from recycled concrete may be used inertly in new concrete. Finally, research promises to find ways to produce or salvage cementituous materials from waste stream materials from the concrete and other industries. Success in these three areas alone could increase recycling by 30 to 50 percent.

Overall, research is needed to optimize the use of all constituent materials in order to minimize the use of other materials needed in concrete mixtures. This research will lead to a higher level of recycling, resulting in concrete that is more energy-effective, cost-effective, and environmentally benign.

Exhibit 6 - Research Pathways for Constituent Materials

(High-priority research pathways are in ***bold italics***)

Constituent Materials	Short-Term R&D Activities (0 - 3 Years)	Mid-Term R&D Activities (4 - 18 Years)	Long-Term R&D Activities (19 - 28 Years)
New Materials	· ***Noncorroding steel reinforcement*** · Fiber-reinforced composites · Rebar and welded wire reinforcement, four categories: (a) stainless steel, (b) zinc-coated, galvanized and epoxy-coated, (c) epoxy-coated, and (d) combination zinc-and epoxy-coated · ***New materials to reduce shrinkage and cracking*** · ***Reduction of alkali-silica reactions in concrete*** · Methods for accurate characterization of aggregate shape and size · Self-consolidating, self-leveling concrete · Alternative fuels used in production of constituent materials · Optimized use of cementitious materials · Advanced concrete mixtures to reduce dependence on reinforcement · Moisture-insensitive mastics · Controlling vapor migration in slabs · Guidelines for concrete to be used in impervious overlays · Supercritical carbon dioxide research for rapid strength	· Materials for active and passive corrosion prevention · Performance-based standards · New aggregate sources and types, including compatible lightweight aggregates · New admixtures and cementitious materials · Sulfate- and alkali-silica-resistant concrete · Smart materials	· ***Families of innovatively manufactured concrete with predictable performance*** · Corrosion-inhibiting admixtures · Acid-, fire-, and heat-resistance cementitious composites · New materials from novel waste streams · Advanced mixtures to promote internal curing and prevent shrinking and cracking
Measurement and Prediction	· Models for predicting the performance of zinc-coated, epoxy-coated, combination zinc- and epoxy-coated, and stainless steel reinforced concrete structures · Joint concrete and steel industry research to minimize corrosion of reinforcing steel · Prediction model for exposed structures with >2” cover over black steel rebar and welded wire reinforcement	· Tests for alternative reinforcement materials · Measurement and prediction of self-desiccation in concrete	· ***Prediction methods and models for permeability, cracking, durability, and performance (including environmental interactions)*** · ***Tools and data for quantifying benefits of using alternative materials*** · Multiscale modeling to connect microstructure with engineerging properties · Predictive models to augment or replace QC tests
Reuse and Recycling	· ***Reuse of high-alkali wastewater*** · Aggregate recycling · Incorporation of waste and by-product materials from other industries · Reuse of cementitous materials, cement kiln dust, and other waste products		

V. CONCRETE PRODUCTION, DELIVERY, AND PLACEMENT

Concrete production, delivery, and placement encompass those activities associated with the mixing, transportation, placement, finishing, consolidation, and curing of concrete. The key to achieving a strong, durable concrete rests not only in the careful proportioning and mixing of the ingredients but in all the other parameters, as well. A properly designed mixture will possess the properties for desired workability for the fresh concrete and the required durability and strength for the hardened product. Basic elements of concrete production, delivery, and placement include:

Mixing – Concrete mixtures are precisely specified to achieve suitable rheological properties in fresh concrete and the required mechanical properties in the hardened product. Typical volumetric concrete mixtures are 10 to 15 percent cement, 60 to 75 percent aggregate, and 15 to 20 percent water. Entrained air in certain concrete mixes may take up another 5 to 10 percent with a corresponding volumetric reduction in constituent mixture.

Placement – Transporting and handling of concrete should be carefully coordinated with placing and finishing operations. Concrete should not be deposited more rapidly than it can be spread, struck off, consolidated, and floated. Concrete should be deposited continuously as near as possible to its final position.

Consolidation – The objective is to produce a dense, well-consolidated concrete free of accidentally entrapped air voids within and on the surface of the exposed material. Proper consolidation will ensure a more aesthetically pleasing structure with higher strength, lower permeability, and greater durability.

Finishing – Proper finishing produces a consolidated, well-graded surface suitable for the conditions of service. Proper finishing can help ensure a maintenance-free concrete but will not compensate for negative properties induced by improperly designed mixtures. Flat work (slabs, floors, walks, driveways, roads, etc.) must be "finished." Finishing involves bringing the surface to proper grade, forming the edges, removal of latent moisture, precise surface compaction, and removal of evident imperfections.

Curing – Concrete curing is defined to begin after the exposed surfaces of the concrete have hardened sufficiently to resist marring. Curing ensures the continued hydration of the cement (which begins as soon as the cement is exposed to water) and the associated strength development. The longer the concrete is kept moist during curing, the stronger and more durable it will become. The rate of hardening depends upon the composition and fineness of the cement, mixture proportions, and moisture and temperature conditions. Most of the hydration and strength gain take place within the first month of concrete's life cycle, but hydration continues for many years at a slower but measurable rate.

A wide range of research is needed to improve efficiency and performance in concrete production, delivery, and placement. Successfully directed research will enable the industry to meet society's needs. Exhibit 7 shows research needs within the Concrete Production, Delivery, and Placement category.

Exhibit 7 - Concrete Production, Delivery, and Placement Needs*

Concrete Production, Delivery, and Placement	
Information and Control	· ***Intelligent, integrated, interoperable knowledge systems*** · ***Improved control over non-specified (general application) concrete*** · ***On-line batching control*** · Techniques to optimize, predict, and verify concrete performance · Modeling and measurement systems to predict and control properties
Production, Delivery, and Placement	· ***Increased applications for robotics and automation*** · Improved surface modification and finishability of high-performance concrete · Advanced precast, prestressed concrete techniques · Advanced forming technologies, such as extrusion · Lightweight components for residential construction · Controlling curing · DEF as relates to accelerated curing · Prevention of slab delamination
Test Methods and Sensors	· ***Improved sensing technologies, including portability*** · ***Procedures and technologies for ensuring performance requirements are met*** · ***Non-destructive test methods – all applications*** · Procedures and technologies for tests in the curing process · Improved on-site monitoring of concrete during early age · Tests and models to predict cracking and strength development immediately after setting · Time-lapse migration imaging · Tests for fundamental rheology properties · Computer-based systems to monitor properties during delivery · Continuous test for rheology and air in plastic concrete
Energy and Environment	· ***Aggregate and alkaline water reuse (see Constituent Materials)*** · ***Reduction of transportation energy use*** · ***Increased use of waste streams from crosscutting technologies from other industries via the use of validated, integrated models to optimize concrete formulation*** · ***Life-cycle model for carbon dioxide impact*** · "Cradle to grave" assessments · Recycling of concrete · Carbon dioxide utilization · Carbon dioxide reduction · Life-cycle model for carbon dioxide impact · Admixtures to eliminate steam cleaning/curing of precast · Frost-resistant, non air-entrained concrete · Waste heat power recovery from kiln and cooler exhaust gasses as an additional power source · Greater thermal efficiency in cement manufacturing process

*High-priority research needs are in ***bold italics***

Selected concrete production, delivery, and placement research topics are shown in broad classifications as follows.

A. Information and Control

Improvements in information, data, and control technologies and systems are needed to facilitate substantial advances in concrete production, delivery, and placement. These are required for maximum interconnectivity and control. Reliable knowledge systems will enable producers to meet specific performance parameters for concrete products with great accuracy. The performance database and quantitative, science-based models are the backbone of the knowledge system from which the appropriate ingredients and mixture proportions are selected.

To improve control over concrete that is placed, performance must be verified. Therefore, there is a need to develop modeling and measurement systems that identify, predict, and control properties, including reliable models for validating performance. One working component of control systems is the achievement of on-line batching control for the maintenance of required properties. Improved control over the quality of concrete placed will improve the quality and performance of end products, thereby positively affecting the public image of concrete and the industry.

Improved control over non-specified concrete (general application concrete) is a *high-priority* need. This will include strengthening certification and/or performance-based contracting procedures. The goal is to replace non-specified concrete with default specifications supported by research and analysis that maintain a certain level of performance.

Intelligent control systems will assist the industry in eliminating material rejection at the job site. Performance models will also significantly reduce the need for concrete repairs during the useful life of structures and pavements.

B. Production, Delivery, and Placement Enhancements

Research could extend production, delivery, and placement technologies beyond traditional surface modifications to reduce cracking and permeability. Research is needed to understand the cause and prevention of delamination in slabs. Research is also needed to improve the placement, finishing, and conditioning of high-performance flatwork to reduce tearing. Additional research needs to focus on controlling curing, including more study on the phenomenon of delayed ettringite formation (DEF) as related to accelerated curing. Internal curing research is needed to define lightweight aggregate requirements at various water/cement ratios and their effects on performance.

The current state-of-the-art production, delivery, and placement performance needs to be benchmarked. This is a *high-priority* because improved industry performance standards cannot be defined unless acceptable performance levels are documented.

There also is a need for continued research of promising forming technologies, such as extrusion and pultrusion. Manufacturing enhancements have the potential for significant cost reductions, particularly important in price-sensitive new markets such as residential construction.

Construction robotics and automation research, identified as a *high - priority* by industry, can also increase the time- and cost-competitiveness of concrete from production to placement, as well as improve quality. Increased automation is an especially ideal goal for construction that utilizes precast components. Computer-based systems are needed to monitor properties during delivery and to adjust concrete mix mixtures automatically to ensure that required specifications for workability and performance are met. Continuing advances in the technology and use of robotics in high-volume warehousing require degrees of floor level and surface preparation that are becoming increasingly difficult for contractors to meet. Significant investigation is required.

C. Test Methods and Sensors

Better sensing and measuring technologies can improve the efficiency of concrete production and placement and greatly enhance concrete performance. Research is needed to adapt and improve existing industrial sensing technologies for concrete applications. For example, sensors are needed that can be embedded in concrete structures to monitor the maturation and strength of concrete immediately after placement and to measure moisture during curing, though more is understood about the latter. These are *high-priority* needs.

Adoption of time-lapse migration imaging technology can provide a technological base for initiating research to sense and measure in-situ condition of concrete. This technology has the capability of monitoring the status of the condition of concrete structures by detecting damage as soon as it occurs and thereby enabling actions to prevent further damage. Acoustic migration imaging has been successfully used by the petroleum industry for exploration and monitoring of oil and gas reservoirs. Acoustic/elastic data collected by embedded sensors and other monitoring devices in a concrete structure can be used for migration imaging. Time variations can be used to locate and classify damage (cracking, spalling, disintegration, etc.) in the cross section so that appropriate repair methods can be selected. The scope and quality of data collected by embedded sensors would be considerably better than that available in earth applications where only surface sensors are possible. Therefore, such migration data in concrete promises to provide a higher imaging quality, which may be needed for the smaller flaw sizes in concrete compared to, for example, reservoir rock. Diffraction tomography should also be developed as a complimentary imaging tool.

New testing means will always be needed to ensure that required concrete properties are attained and performance criteria are met as new concrete innovations become proactive. The development of portable testing technologies for use at the job site is a *high-priority* research need. For example, technologies could be developed that change the color of concrete if it fails to meet required specifications. Research is needed to develop a reliable, rapid test method to predict potential concrete strength immediately after setting. Field tests are needed to measure fundamental rheological properties of fresh concrete.

D. Energy and Environment

There is a need for a cradle-to-grave assessment of the full cycle of concrete manufacturing, placement, lifetime service, demolition, and recycling in order to accurately portray the total energy and environmental performance of concrete-constructed systems. This assessment must begin with the production of cement and other constituent materials, encompass the entire useful life of the constructed work, and include recycling after useful life. Only from this full-cycle baseline can the full effect of energy and environmental improvements be quantified.

Research is needed to improve kiln and cooler thermal efficiencies in cement manufacturing in order to take greatest advantage of vast quantities of heat energy contained in combustion gases discarded to the atmosphere in present-day cement production. As costs of fuel and electricity will outstrip improvements in productivity in the foreseeable future, it follows that any new utilizations of "free" energy available from cement production represent the most viable approach to keeping manufacturing costs down and curtailing use of purchased energy.

Reducing energy loss from material transportation is a *high-priority*. Transportation energy efficiency must be researched in order to achieve greater energy conservation. Larger transport distances and extended haul times require more fuel consumption as well as threaten the quality of fresh concrete mixture delivered to the job site. Transportation efficiency can be achieved in many ways, e.g., engines that are more fuel-efficient and trucks with greater load capacity. Admixtures need to be developed to optimize mixture properties at point of delivery and to reduce the incidence of wastewater. “Delivery” is actually a system of parameters working together to get good product on site; therefore, systems research is required. Alternate methods to reduce transportation energy use include a greater utilization of precast concrete and new, more efficient process technologies (e.g., modularized mixing units) that facilitate on-site production of concrete.

Research is needed to achieve 30 to 50 percent recycling of concrete with an ultimate goal of 100 percent. Economical systems are needed for reuse of wash water and recycled aggregates. The ready mixed concrete industry has identified water and aggregate reuse as *high priorities* (see Constituent Materials).

Exhibit 8 - Research Pathways for Concrete Production, Delivery, and Placement

(High-priority research pathways are in *bold italics*)

	Short-Term Impact by 2005 (0 - 3 Years)	Mid-Term Impact by 2020 (4 - 18 Years)	Long-Term Impact by 2030 (19 - 28 Years)
Information and Control	· ***Improved control over non-specified (general application) concrete***	· Techniques to optimize, predict, and verify concrete performance · Modeling and measurement systems to predict and control properties	· ***Intelligent, integrated, interoperable knowledge systems***
Production, Delivery, and Placement Enhancements	· Prevention of slab delamination · Improved surface modification and finishability of high-performance concrete · DEF as relates to accelerated curing	· ***On-line batching control*** · Advanced precast, prestressed concrete technique · Advanced forming technologies, such as extrusion · Controlling curing · Lightweight components for residential construction	· ***Increased applications for robotics and automation***
Test Methods and Sensors	· ***Non-destructive test methods—all applications***	· ***Procedures and technologies for ensuring performance requirements are met*** · Procedures and technologies for tests in the curing process · Tests and models to predict cracking and strength development immediately after settling · Tests for fundamental rheology properties · ***Improved sensing technologies, including portability*** · Improved on-site monitoring of concrete during early age · Time-lapse migration imaging · Computer-based systems to monitor properties during delivery · Continuous test for rheology and air in plastic concrete	
Energy and Environment	· Recycling of concrete	· ***Reduction of transportation energy use*** · ***Life-cycle model for carbon dioxide*** · Carbon dioxide utilization · Waste heat power recovery from kiln and cooler exhaust gasses as an additional power source · ***Aggregate and alkaline water reuse (see Constituent Materials)*** · ***Increased use of waste streams from crosscutting technologies from other industries via the use of validated, integrated models to optimize concrete information*** · "Cradle-to-grave" assessment · Admixtures to eliminate steam cleaning/curing of precast · Frost-resistant, non air-entrained concrete · Greater thermal efficiency in cement manufacturing process	· Carbon dioxide reduction

VI. REPAIR AND REHABILITATION

Repair and rehabilitation of concrete structures, already a substantial part of the concrete industry, will continue to gain importance as domestic infrastructure changes to meet the needs of a demanding populace. An increasing number of the nation's vital structures – bridges, roads, water and sewer pipes, dams, parking garages, and runways – are in need of repair or rehabilitation. Deteriorated and damaged structures must be repaired, older structures must be retrofitted to meet current standards, and functionally deficient ones must undergo renovation or replacement to enhance capacity.

A concrete structure may deteriorate from one or many of a number of processes. Characterizations include electrochemical (e.g., corrosion of steel), physical (e.g., cyclic freezing and thawing), chemical (e.g., acid attack, sulfate attack, and alkali-aggregate reaction), and mechanical (e.g., fatigue cracking). Typically, these processes are manifested physically in concretes as shrinkage or expansion, usually followed by cracking and/or spalling. To date, the industry strategy has been to repair and rehabilitate rather than replace. Repairs can range broadly from elementary corrections of form-related defects to complex rehabilitations of load-bearing structures.

Repair techniques usually focus on restoration of structural integrity and shape. These generally involve the removal of damaged concrete, replacement or cleaning and coating of existing steel reinforcing, and placement of new concrete. The critical step in executing a proper repair is to accurately determine the cause of damage and to select an effective remedy that will remove or lessen the chance of recurrence. Unfortunately, even the best repair methods are ineffective against causes of deterioration if proper forensics have not been carried out. For example, simple repairs of reinforcing steel corrosion typically fail prematurely if the cause of failure is not properly diagnosed and nothing is done to mitigate or arrest the mechanism of primary deterioration.

Proper rehabilitation, in addition to restoring structural integrity and shape, slows or stops the harmful processes responsible for damage. When rehabilitation addresses the "disease" as well as the "symptoms," repairs last significantly longer. Rehabilitation is also an acceptable means for upgrading constructions to higher levels of performance, e.g., upgrading a structure to accept higher loads when current demands exceed the requirements of the original design.

Current repair and protection techniques for rehabilitation of deteriorated structures have been derived largely from methods used in new construction. However, these are not always suitable as rehabilitation differs from new construction in many important aspects, such as magnitude, accessibility, ambient conditions, and interactive processes associated with the repair.

The general procedure for evaluating and correcting deficiencies of a concrete structure is empirical and begins with the use of the best diagnostic tools and practices reasonably available and accessible to the location of the suspected damage. Short of what specialized instruments can reveal, initial diagnosis is most often based on visual observations and supporting data on the mechanism or mechanisms that caused the damage. Repair plans often change as damage is exposed. However, most repair situations can be properly diagnosed with a high degree of confidence.

The next step is selecting appropriate repair materials and methods suitable for achieving the expected life of the repair. For ease of selecting repair methods and materials, it is helpful to consider the possible approaches as from two general categories: those more suited for cracked concrete and those more suited for spalled and disintegrated concrete. Cracking, which can originate for a number of reasons, is the primary cause of virtually all deterioration in reinforced concrete structures. Due to the wide variety of crack types and causes, there is no single repair method that will work in all situations. On the other hand, spalling and disintegration are only symptomatic of many types of concrete distress.

A basic understanding of the underlying causes of concrete deficiencies is essential. The repair method chosen depends on the extent of deterioration that has already occurred, whether a permanent or short-term repair is desired, time to completion, and the expected life of the repair. Examples of currently recognized concrete repair and rehabilitation methods include crack arrest, unbonded overlay, stitching, additional reinforcement, flexible sealing, slabjacking, drilling and plugging, routing and sealing, judicious neglect, autogenous healing, removal and replacement, epoxy injection, grouting, corrosion-inhibiting post treatment, partial replacement, dry packing, jacketing, preplaced aggregate concrete, polymer impregnation, overlay, shotcrete, underwater replacement, high-strength concrete, and surface coatings and overlayments. The science of repair and protection will continue to challenge the concrete industry as technology, applications and user needs increase. A wide range of research needs exist that, if met, can improve energy efficiency, environmental performance, health and safety, and productivity. Exhibit 9 shows research needs within the Repair and Rehabilitation category.

Exhibit 9 - Repair and Rehabilitation Research Needs*

Repair and Rehabilitation	
New Repair Materials	· ***New repair materials and applications technologies*** · ***Self-repairing (damage-insensitive) concrete*** · Heat-resistant pavements · Zinc-coated and epoxy-coated steel reinforcement to repair or replace existing steel · Stainless steel as new reinforcement · Non-metallic reinforcement (polymer-reinforced concrete) · Adhesives to improve bond between repair layers and substrate · New fiber-reinforced cement-based composites · Hardening rehabilitation for survivability · New fiber-reinforced, cement-based composites · Repair of sulfate damage with sulfate-resistant concrete
Assessment Tools and Modeling/ Measurement Technologies	· ***Nondestructive testing for stress in existing structures*** · ***Long-term monitoring of structures*** · Model development · Corrosion cancellation and avoidance technologies · Non-impact removal techniques · Low-maintenance, long-life repair techniques for concrete · Costing model for non-corrosive steel reinforcement systems vs. non-metallic, alternative reinforcement systems · Remaining life determination of existing reinforcement · Use of laser as assessment tool
Repair Field Process Technologies	· ***Mitigation of alkali-silica reactivity in existing structures*** · ***Corrosion-canceling technologies*** · ***Low-maintenance, long-life repair of concrete for corrosion protection of embedded steel*** · Robotic and laser non-impact repair techniques · Applications for reconstituted/recycled concrete · Admixture research to stay abreast of changing performance requirements · Field mitigation means for existing ASR damage

*High-priority research needs are in ***bold italics***

Selected repair and rehabilitation research topics are shown in broad classifications as follows.

A. New Repair Materials

New materials and material technologies are a *high-priority* for repair and rehabilitation. These materials technologies should be environmentally friendly to the greatest extent possible. Historically, the repair industry has introduced its share of promising new materials technologies, and new ones are likely to emerge. The challenges are getting these new technologies into practice and maintaining research at a meaningful level in a field where new developments are slow to show a commercial (profit) return.

Heat-Resistant Pavements – Heat-resistant pavement research is needed, particularly for upgrading military runways and taxiways to enable them to withstand expected temperatures from future aircraft of up to 1,750 F. As existing airfields were designed to withstand about 350 F, upgrading is much more of a challenge than designing new ones. Further, blast effects from next generation gas turbine engines complicate the problem, and there is also a need for compatible repair materials that withstand volume change. The science that will arise from these solutions will have wide-ranging benefits across the concrete construction industry.

Existing Steel Reinforcement – Research is needed for determining the remaining life of existing steel reinforcement in the conditions in which they are placed. Prediction models also need to be developed that will accurately determine remaining life. Models are suggested for black, zinc-coated, epoxy-coated, and stainless steels. Electrochemical protection for black steel is an important subset.

Non-Metallic Reinforcement – Research is needed in the use of fiber-reinforced plastic or carbon fiber as a primary reinforcement for repaired structures. In addition, there is a need for fireproofing research of FRP (see section on Constituent Materials). Because nonmetallic reinforcements have come on the scene more recently than traditional steels, this research has been hampered by the lack of standard test methods, specifications, and design guides. There is a pressing need for attention to these issues before non-metallics can achieve full potential as materials to repair failed traditional reinforcements.

Self-Repairing Concrete – Research is needed to develop self-repairing concrete. There are also needs for compatible, self-repairing repair materials, materials with user-controlled setting, and new automatic systems for strengthening materials, all of which can be easily placed and finished.

Sulfate-Resistant Concrete – Concrete attacked by exposure to alkali-sulfate soils or water-containing alkali-sulfates is a long-standing problem. Alkaline sulfate soils and ground waters are particularly prevalent in the western part of the United States. Though repair methodologies for concretes affected this way are well known, research is needed to develop improved sulfate-resistant concretes.

High-Performance Fiber-Reinforced Concrete – Growing interest in developing new cement-based fiber-reinforced composites for repair and renovation has led to increased areas needing research.

B. Assessment Tools and Modeling/Measurement Technologies

Proper assessment is crucial to efficient and comprehensive repair and rehabilitation of concrete. This includes measuring, modeling, characterizing, monitoring, and analyzing.

Development of effective means to measure stress in concrete and steel by improved nondestructive techniques (see Design and Structure) is a *high-priority*. Another *high-priority* research need is to improve the long-term monitoring of structures, from inexpensive, uncomplicated, field-expedient means to high-technology applications, such as the use of satellite monitoring.

New and emerging technological advances that may lead to improved techniques for evaluation of concrete condition include nonlinear elastic wave spectroscopy for interrogation of damage, staining methods for characterizing deterioration mechanisms, laser-induced breakdown spectroscopy, high-intensity neutron diffractometry for characterizing concrete in the bulk state, and superconducting quantum interference.

Assessment Tools – Research is needed to develop the use of laser technology as an assessment tool. This requires additional research into nondestructive laser techniques for characterizing concrete and detecting structure, plus the use of very high-powered lasers in invasive techniques that actually change structure.

Model Development – Every new technology changes the system model in which it is used, creating, in effect, new systems. In the repair arena, new technologies affect old systems, often differently than if applied to new construction. Therefore, model development for the repair industry is significantly different than for the same technology in most other applications. Application-specific models must be developed for the repair industry. Some areas needing investigation include: life-cycle modeling for new and repaired structures; expert-system modeling, tools, and models for improved analysis of repair methods and materials; and meso-to-macro scale statistical performance characterization methodologies.

Measurement Techniques – There is a research need to advance the technologies of measurement and monitoring of existing concrete structures, particularly with respect to detecting corrosion rates and activity. Additional analytical research needs include half-cell measurement techniques; X-ray fluorescence spectroscopy (XRF) for analyzing concrete composition (XRF is a recognized, accurate method of measuring the atomic composition of materials by irradiation with high-energy photons such as X-rays or gamma rays and observing X-ray fluorescence); improved forensic analysis methods; and acoustic, nondestructive methods to analyze cracking, curing, and strength.

C. Repair Field Process Technologies

Perhaps the most important area of research in the repair, rehabilitation, and retrofit arena involves field process technologies. Diagnostic and repair techniques that work in the laboratory quite often do not scale up to the field for the most basic of reasons, including restricted access to the repair area, general site conditions, power requirements, safety considerations, and nonavailability of skilled technicians. Understanding a repair and/or having an advanced remedy available are of little use if a repair cannot be physically and economically achieved in the field.

Research is warranted to overcome those site problems and to produce field-expedient repair technologies in these areas:

Laser and Robotic Techniques – Lasers can be used for non-impact removal of concrete, but scaling their use to field applications is problematic. The development of laser or other non-impact removal techniques is needed for the repair industry. Lasers for plasma jet deposition of repair materials are also needed. Research is needed to enable robotic repair of structures.

Reconstituted/Recycled Concrete – Research is needed for rapid and cost-effective reconstitution of concrete. It is environmentally important to recycle demolished concrete (see Concrete Materials), particularly on the job site. "Old" concrete that can be removed and processed back into the repair on the spot eliminates disposal and transportation processing that could have negative environmental impact.

Mitigation of Alkali-Silica Reaction (ASR) – Alkali-silica reaction (ASR), which occurs when silica in aggregates and aqueous alkali-hydroxide solutions in concrete (formed from the cement and water) react with water to form a gel-like mass, is a common problem in portland cement concrete bridges and pavements. Portland cement concrete is normally highly durable, yet ASR can cause concrete structures and pavements to crack and eventually lose serviceability. ASR was first identified sixty years ago, but recognizing and preventing ASR is still a daunting task. Research to mitigate existing ASR conditions in structures is a *high-priority* need.

Corrosion Protection Technologies – More corrosion-protection solutions exist in the laboratory than the field. Research is needed to develop practical, field-expedient, corrosion-protection technologies. The use of corrosion-cancellation technologies, such as magnetic field generation for reducing corrosion, is a *high-priority* for the industry. Another *high-priority* is to develop low-maintenance, long-life repair of concrete that provides corrosion protection for the embedded steel. The science and use of corrosion-inhibiting admixtures needs to keep pace with changing performance requirements.

Exhibit 10 - Research Pathways for Repair and Rehabilitation

(High-priority research pathways are in ***bold italics***)

Repair and Rehabilitation	Short-Term R&D Activities (0 - 3 Years)	Mid-Term R&D Activities (4 - 18 Years)	Long-Term R&D Activities (19 - 28 Years)
New Repair Materials	· ***New repair materials and applications technologies*** · Zinc-coated and epoxy-coated steel reinforcement to repair or replace existing steel · Stainless steel as new reinforcement · Hardening rehabilitation for survivability	· Heat-resistant pavements · Non-metallic reinforcement (polymer-reinforced concrete) · Adhesives to improve bond between repair layers and substrate · New fiber-reinforced cement-based composites · Admixture research to stay abreast of changing performance requirements	· ***Self-repairing (damage-insensitive) concrete*** · Repair of sulfate damage with sulfate-resistant concrete
Assessment Tools and Modeling/Measurement Technologies	· ***Nondestructive testing for stress in existing structures*** · Costing model for non-corrosive steel reinforcement systems vs. non-metallic, alternative reinforcement systems · Use of laser as assessment tool	· Low-maintenance, long-life repair techniques for concrete · Remaining life determination of existing reinforcement	· ***Long-term monitoring of structures***
Field Process Technologies	· ***Mitigation of alkali-silica reactivity in existing structures*** · ***Corrosion-canceling technologies*** · Applications for reconstituted and recycled concrete · Field mitigation means for existing ASR damage	· Non-impact removal techniques	· ***Low-maintenance, long-life repair of concrete for corrosion protection of embedded steel*** · Robotic and laser non-impact repair technologies · Corrosion cancellation and avoidance technologies

VII. ADDITIONAL CHALLENGES

The concrete industry recognizes that there are challenges that the industry must face in addition to those stated in this roadmap. The following have been factored into the industry's strategic plan and relate to the research needs classified in this document.

Human Resources – The concrete industry must continue to attract highly skilled people to work in all areas of concrete technology, particularly research, education, design, manufacturing, construction, and rehabilitation. Attracting future talent to the concrete workforce will require early indoctrination at the primary and secondary school levels not only about the principles and uses of concrete, but about the professional / vocational desirability of construction-related careers. This challenge will be served by innovative approaches to improved image marketing.

Education and Training – Developing methods to educate the large number of small and diverse companies for which the concrete construction industry is known is a formidable challenge. Comprehensive certification programs are part of the solution. These can become integrated into all areas of "concrete" and will ensure high standards of design, quality, and workmanship from laboratory to job site. Continuing education and training of workers is absolutely essential to keeping pace with innovations. For specifiers, training is needed to ensure acceptance of new technology and new standards. For practitioners, bringing new technologies and practices on-line requires a versatile and intelligent workforce that can quickly adapt to change. Superior education and training will close the gaps between knowledge developed, knowledge specified, and knowledge applied.

Data Collection – The concrete industry must have accessible, accurate data about research, design, placement, and performance of the materials and systems of concrete construction. This requires accurate data, better access to it, and reliable feedback from the breadth of the industry. Comprehensive and well-distributed mapping of accurate performance parameters will facilitate decision-making, reduce duplicated research, and add leverage to research underway.

Permitting and Regulation – The nation's entrenched system for development of standards and codes severely limits timely implementation of important new technologies and designs. Innovative methodologies that expedite certification can help the concrete industry meet society's needs in time to make a difference in the quality of life. Improvements that would speed up the industry's comprehensive peer review system without detriment to quality are needed to accelerate standardization of eagerly awaited technologies.

Public Perception – The American public is generally unaware of the benefits of concrete as a construction material. Educating the public about new industry innovations is vital to maintaining concrete's position as the primary construction material of choice in the 21st century and to attracting young people to rewarding careers in the concrete industry.

Basic Science – There is a continuing need for basic research in materials and chemical sciences as they relate to concrete. Unfortunately, because of industry fragmentation and the commodity nature of concrete products, there is little incentive for the industry to invest in basic research. In these circumstances and in view of the vital importance of concrete to the nation's infrastructure, it would seem to be appropriate for government agencies to play a leading role in facilitating and performing basic research. This would be analogous to the support the government provides for research in the medical and agricultural fields. As it is, funding for concrete research by the federal government has diminished greatly in the last twenty years.

Almost all of the basic research that remains in government is carried out at the National Institute of Standards and Technology (NIST) or supported by National Science Foundation (NSF) through grants to university researchers. Furthermore, with the low level of research and development activity within the industry, it is difficult to couple the results of basic research to industrial practice. This makes it particularly important that the government's basic concrete research agenda be aligned with the needs of the industry.

Teaming Methods – Teaming methods used in the concrete industry often fail to facilitate optimal product development and thereby harm the industry's image. This is due in part to pointless competition on the part of organizations that need to be working with each other. Generally poor coordination and communication across the industry are the causes. Better development and acceptance of improved contracting methods will encourage greater collaboration of talent and thereby facilitate greater communication, coordination, and cooperation at all levels. The result will be fully integrated, more cost-effective systems available to the public. To bring together materials producers, designers, and contractors, fundamental changes, particularly with codes and enforcement agencies, will be required to produce realistic codes that allow important advancements of new technologies and materials to get to market. It will also require convincing owners about the advantages of integrated cooperation. New and innovative contracting methods can be developed that foster integrated systems for design and construction without stifling fair and legitimate competition.

VIII. ACHIEVING OUR GOALS

The successful completion of the research activities called for in the systematic path proscribed by *Roadmap 2030* will bring to pass the broad, strategic goals of *Vision 2030*. The relationship of the research needs outlined in this document to the *Vision*'s goals is charted in Exhibit 11.

Many of the research needs discussed address multiple goals. Though representative, the list is complete neither in present time nor in the future, as new needs and promising technologies to meet them will arise over the thirty years covered by this living document.

Exhibit 11 - Relationship of Concrete Industry Research Needs to *Vision 2030* Goals

Vision Goal	Research Needs	Impact
Process Improvements	· Process improvements in manufacturing for the production of cement · Develop innovations in robotics and automation · Develop durability, design, and structural assessment models · Develop predictive capabilities for performance that allow improved durability by tailoring of mixture design for specific uses and specific environments · Develop and apply innovative sensing and measuring technologies · Develop tests to assess or predict strength, rheology, maturation, and performance · Develop new aggregate types and sources · Improve placement and forming · Develop predictive models to compliment or replace existing quality control procedures	· 50% of new homes made of structural concrete · 50% reduction in labor costs · 10% reduction in material costs · 20% reduction in construction time
Product Performance	· Eliminate corrosion or corrosion effects · Develop new performance-based materials · Develop smart materials · Enhance specifications for fire-retardant concrete · Develop earthquake- and blast-resistant systems · Develop biogenic, sulfuric-acid-corrosion-resistant concrete · Enable concrete for any environment · Design intelligent control systems that virtually eliminate job site rejection · Eliminate cracking in concrete products and structures · Improve ductility and increase strength of reinforcement · Develop self-repairing concrete · Eliminate alkali limits · Develop practical permanent concrete form systems · Promote the development and use of performance life prediction models and resources	· Become the undisputed primary material of construction by 2030 · Eliminate material rejection at the job site by 60% · Reduce replacement work by $1 billion per year · Reduce concrete repairs in buildings by 25%
Energy Efficiency	· Reduce transportation energy use · Reduce concrete density or increase concrete strength to decrease the weight of transported material · Increase the range and application of composites to help achieve lighter-weight concrete · Boost thermal efficiency by cement kilns by electric power generation from kiln and cooler waste gasses	· 20-25% reduction in transportation energy usage from current levels · 20% reduction in cement plant power demand
Environmental Performance	· Improve recycling and reuse processes and technologies · Identify and develop reuses for alkaline water · Perform detailed life-cycle assessments	· 50% reduction in net waste from current levels · Increase concrete recycling by 500% · Achieve 5% recycling of plastic concrete · Achieve 60% reduction in alkaline water

Technology Transfer	· Achieve widespread acceptance of performance-based materials and systems · Achieve widespread acceptance of testing means · Develop user-friendly performance specifications for cementitious materials · Develop a completely integrated, interoperable, knowledge system covering all of concrete technology	· Average time of technology acceptance reduced to two years
Institutional Improvements	· Establish standards acceptance procedures for accelerating new technologies into practice · Develop intelligent, integrated, interoperable knowledge systems · Develop general application guidelines for self-consolidating concrete	· Concrete industry is vertically integrated, with recognizable leadership and accountability
Education and Employment	· Develop curricula for teaching the design and use of concrete · Attract skilled workers through increased emphasis on education · Strengthen certification and/or performance-based contracting activities	· Workers certified at all stages of production process in newest technologies · Industry attracts top graduates and achieves high employee retention
Industry Image	· Develop benchmarking to establish current performance	· Concrete is widely recognized as an effective, sustainable building material by the general public

IX. RESEARCH PATHWAYS

Exhibits 12-15 outline the research pathways for Design and Structural Systems; Constituent Materials; Concrete Production, Delivery, and Placement; and Repair and Rehabilitation. Please note that these exhibits are also shown in their respective sections.

Exhibit 12 - Research Pathways for Design & Structural Systems

(High-priority research pathways are in ***bold italics)***

Design & Structural Systems	Short-Term R&D Activities (0 - 3 Years)	Mid-Term R&D Activities (4 - 18 Years)	Long-Term R&D Activities (19 - 28 Years)
Stuctural Concrete	· ***System survivability (different than durability or sustainability)*** · Environmental and chemical factors such as freeze/thaw, chlorides, and sulfates · Layout and specification of reinforcement · Ratio determination of concrete to reinforcement volumes · Size/configuration of reinforced concrete elements	· Type and size of connections between structural elements · Relative direction, speed, location, and cycling of external loading or internal forces · Chemical and mechanical bonds between concrete, reinforcement, and connectors · Location and classification of cracks	· Time-dependent changes due to relaxation, creep, and shrinkage · Interaction of elements within structural system
Reinforced Concrete	· ***Design methodologies for reinforcement and fibrous concrete*** → · Nonmetallic reinforcement → · Coated and corrosion-free steel reinforcement · Enhanced design procedures for shear reinforcement	· Improved ductility of structural systems and high-performance concrete · Corrosion- and reinforcement-free bridge deck systems · Total precast bridge deck system · Permanent cementitious form systems · Electrically-conductive concrete	
Modeling and Measurement	· Durability models that predict interaction of stresses and environmental factors—all applications → · Service life design models—all applications	· Monitoring and embedded sensors—all applications · Smart materials that monitor, predict, and adjust (see Constituent Materials)	
High-Performance Concrete	· HPC mixture optimization software → · Placing, finishing, and curing technologies	· Field-expedient, accurate testing of HPC · Advanced testing methods for HPC · HPC designs for residential housing	· Manufacturing processes for fiber-reinforced HPC components
Technology Transfer	· ***Comprehensive plan for accelerating technology transfer times from 15 to 2 years*** · Greater use of appraisal services by standards and codes bodies		
Fire-, Blast-, and Earthquake-Resistant Concrete	· ***Survivability research***	· ***Rational (smart) systems for design of fire-, blast-, and heat resistant alternative reinforced structures*** · Fire-resistant, high-strength concrete (see New Materials)	
Crosscutting Innovations		· Research that considers concrete as part of a multi-material constructed system	· Adaptation of improved forming technologies used by other industries · Adaptation of industrial sensing/testing devices used by other industries (see Test Methods and Sensors)

Exhibit 13 - Research Pathways for Constituent Materials

(High-priority research pathways are in ***bold italics***)

Constituent Materials	Short-Term R&D Activities (0 - 3 Years)	Mid-Term R&D Activities (4 - 18 Years)	Long-Term R&D Activities (19 - 28 Years)
New Materials	· ***Noncorroding steel reinforcement*** · Fiber-reinforced composites · Rebar and welded wire reinforcement, four categories: (a) stainless steel, (b) zinc-coated, galvanized and epoxy-coated, (c) epoxy-coated, and (d) combination zinc-and epoxy-coated · ***New materials to reduce shrinkage and cracking*** · ***Reduction of alkali-silica reactions in concrete*** · Methods for accurate characterization of aggregate shape and size · Self-consolidating, self-leveling concrete · Alternative fuels used in production of constituent materials · Optimized use of cementitious materials · Advanced concrete mixtures to reduce dependence on reinforcement · Moisture-insensitive mastics · Controlling vapor migration in slabs · Guidelines for concrete to be used in impervious overlays · Supercritical carbon dioxide research for rapid strength	· Materials for active and passive corrosion prevention · Performance-based standards · New aggregate sources and types, including compatible lightweight aggregates · New admixtures and cementitious materials · Sulfate- and alkali-silica-resistant concrete · Smart materials	· ***Families of innovatively manufactured concrete with predictable performance*** · Corrosion-inhibiting admixtures · Acid-, fire-, and heat-resistance cementitious composites · New materials from novel waste streams · Advanced mixtures to promote internal curing and prevent shrinking and cracking
Measurement and Prediction	· Models for predicting the performance of zinc-coated, epoxy-coated, combination zinc- and epoxy-coated, and stainless steel reinforced concrete structures · Joint concrete and steel industry research to minimize corrosion of reinforcing steel · Prediction model for exposed structures with >2" cover over black steel rebar and welded wire reinforcement	· Tests for alternative reinforcement materials · Measurement and prediction of self-desiccation in concrete	· ***Prediction methods and models for permeability, cracking, durability, and performance (including environmental interactions)*** · ***Tools and data for quantifying benefits of using alternative materials*** · Multiscale modeling to connect microstructure with engineerging properties · Predictive models to augment or replace QC tests
Reuse and Recycling	· ***Reuse of high-alkali wastewater*** · Aggregate recycling · Incorporation of waste and by-product materials from other industries · Reuse of cementitous materials, cement kiln dust, and other waste products		

Exhibit 14 - Research Pathways for Concrete Production, Delivery, and Placement

(High-priority research pathways are in ***bold italics***)

	Short-Term Impact by 2005 (0 - 3 Years)	Mid-Term Impact by 2020 (4 - 18 Years)	Long-Term Impact by 2030 (19 - 28 Years)
Information and Control	· ***Improved control over non-specified (general application) concrete*** →	· Techniques to optimize, predict, and verify concrete performance · Modeling and measurement systems to predict and control properties →	· ***Intelligent, integrated, interoperable knowledge systems***
Production, Delivery, and Placement Enhancements	· Prevention of slab delamination → · Improved surface modification and finishability of high-performance concrete → · DEF as relates to accelerated curing →	· ***On-line batching control*** → · Advanced precast, prestressed concrete technique · Advanced forming technologies, such as extrusion · Controlling curing · Lightweight components for residential construction	· ***Increased applications for robotics and automation***
Test Methods and Sensors	· ***Non-destructive test methods—all applications*** →	· ***Procedures and technologies for ensuring performance requirements are met*** · Procedures and technologies for tests in the curing process · Tests and models to predict cracking and strength development immediately after settling · Tests for fundamental rheology properties · ***Improved sensing technologies, including portability*** · Improved on-site monitoring of concrete during early age · Time-lapse migration imaging · Computer-based systems to monitor properties during delivery · Continuous test for rheology and air in plastic concrete	
Energy and Environment	·Recycling of concrete	· ***Reduction of transportation energy use*** · ***Life-cycle model for carbon dioxide*** · Carbon dioxide utilization · Waste heat power recovery from kiln and cooler exhaust gasses as an additional power source → · ***Aggregate and alkaline water reuse (see Constituent Materials)*** · ***Increased use of waste streams from crosscutting technologies from other industries via the use of validated, integrated models to optimize concrete information*** · "Cradle-to-grave" assessment · Admixtures to eliminate steam cleaning/curing of precast · Frost-resistant, non air-entrained concrete · Greater thermal efficiency in cement manufacturing process	· Carbon dioxide reduction

Exhibit 15 - Research Pathways for Repair and Rehabilitation

(High-priority research pathways are in ***bold italics***)

Repair and Rehabilitation	Short-Term R&D Activities (0 - 3 Years)	Mid-Term R&D Activities (4 - 18 Years)	Long-Term R&D Activities (19 - 28 Years)
New Repair Materials	· ***New repair materials and applications technologies*** · Zinc-coated and epoxy-coated steel reinforcement to repair or replace existing steel · Stainless steel as new reinforcement · Hardening rehabilitation for survivability	· Heat-resistant pavements · Non-metallic reinforcement (polymer-reinforced concrete) · Adhesives to improve bond between repair layers and substrate · New fiber-reinforced cement-based composites · Admixture research to stay abreast of changing performance requirements	· ***Self-repairing (damage-insensitive) concrete*** · Repair of sulfate damage with sulfate-resistant concrete
Assessment Tools and Modeling/Measurement Technologies	· ***Nondestructive testing for stress in existing structures*** · Costing model for non-corrosive steel reinforcement systems vs. non-metallic, alternative reinforcement systems · Use of laser as assessment tool	· Low-maintenance, long-life repair techniques for concrete · Remaining life determination of existing reinforcement	· ***Long-term monitoring of structures***
Field Process Technologies	· ***Mitigation of alkali-silica reactivity in existing structures*** · ***Corrosion-canceling technologies*** · Applications for reconstituted and recycled concrete · Field mitigation means for existing ASR damage	· Non-impact removal techniques	· ***Low-maintenance, long-life repair of concrete for corrosion protection of embedded steel*** · Robotic and laser non-impact repair technologies · Corrosion cancellation and avoidance technologies