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Concrete

The Sustainable Infrastructure Material for the 21st Century

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Concrete

The Sustainable Infrastructure Material for the 21st Century

A Keynote Paper Presented by
EDWARD G. NAWY

at the Honorary Forum, Dialogue with Leaders in the Design and Construction of Transportation Facilities

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Foreword

The Design and Construction Group of the Transportation Research Board sponsors an honorary forum, Dialogue with Leaders in the Design and Construction of Transportation Facilities, at TRB Annual Meetings to acknowledge distinguished nationally recognized experts who have demonstrated career-length participation in the work of the Transportation Research Board and a record of significant contribution to the transportation research community. Honorees present a dynamic overview within their technical area of expertise and their vision of the future.

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Concrete
The Sustainable Infrastructure Material for the 21st Century

EDWARD G. NAWY
Rutgers University

Revolutionary evolutions relating to novel materials of construction and modifications, and improvements in the behavior of traditional materials, have been taking place throughout the 20th century and into the 21st century. These evolutions have been considerably facilitated by increased knowledge of the atomic and molecular structure of materials, studies of long-term failures, development of more powerful instrumentation and monitoring techniques, decrease in cost-effectiveness of traditional materials, and the need for stronger and better performing materials suitable for larger structures, longer spans, more ductility, and extended durability. The 21st century, and we are in its first decade, is expected to be the century of high-strength, high-performance durable concrete—particularly in the world's infrastructure of roads, buildings, and bridges.

New cements, techniques, and composites have already achieved very high strengths, some as high as 300 MPa (45,000 psi). Massive projects already employ new and advanced construction techniques including those with traditional, lower strengths. This trend will continue in all phases of infrastructure constructability and rehabilitation. In short, the last few decades of the 20th century can be described as the decades of concrete admixtures and composite innovation. The 21st century will be the millennium of high-strength, high-performance concrete. More than 600 million tons of concrete are consumed annually in the United States, and in excess of 1.5 billion tons worldwide. Urbanization and improvements in both developed and developing countries will increase this demand.

These same developments also bring more industrialization and mineral byproduct wastes. For example, the world's production of fly ash was over half a trillion tons in 1989. Now, it exceeds one and a half trillion tons. However, some of these environmentally unfriendly by-products can be used in new concrete, but with better control. The versatility of concrete and its high-performance derivatives will satisfy many future needs. The present century can become the golden age of environmentally friendly, supplementary cementing materials for high-performance concrete.

SIGNIFICANT AREAS OF DEVELOPMENT

The following is a brief outline of some highlights of the research innovation that occurred in the 20th century which led to some of the major advancements that we see today. The first that comes to mind is the Duff Abrams original work with his water-to-cement ratio principle in 1918 as a means of proportioning concrete mixtures. This principle sustained itself all these years so that now we use the water–cementitious ratio as the criterion for the production of durable concrete mixtures.

Another development of significance is the work on polymer and latex concrete that introduced qualities hitherto unparalleled for use in highway and transportation systems. Original work at Rutgers University, and at the University of Texas at Austin by David Fowler and associates in the 1960s and 1970s and work of other investigators in Japan and elsewhere deserve mention. Starting with polymer-impregnated concrete and proceeding into polymer-modified concrete for overlays and deck structures in bridges, to marine environment. Figure 1 due to Sternberg, 1973, for impregnated concrete shows the enormous gain in strength at that time from 3.6 ksi for control specimens to17.4 ksi for the polymer concrete. Yet polymer-impregnated concrete was scarcely used due to the difficulty of field application. Figure 2 due to Nawy et al, 1977, presents the relationship between the percentage of mixing water replaced by polymer versus compressive strength for different ratios of total liquid-to-cement content (L/C). It shows the significant increase in strength gained by increased replacement of water by the resin in the polymer-modified concrete mixture leading to compressive strength of about 15,000 psi for L/C ratio of 0.6 and 93 percent replacement of water by polymer.

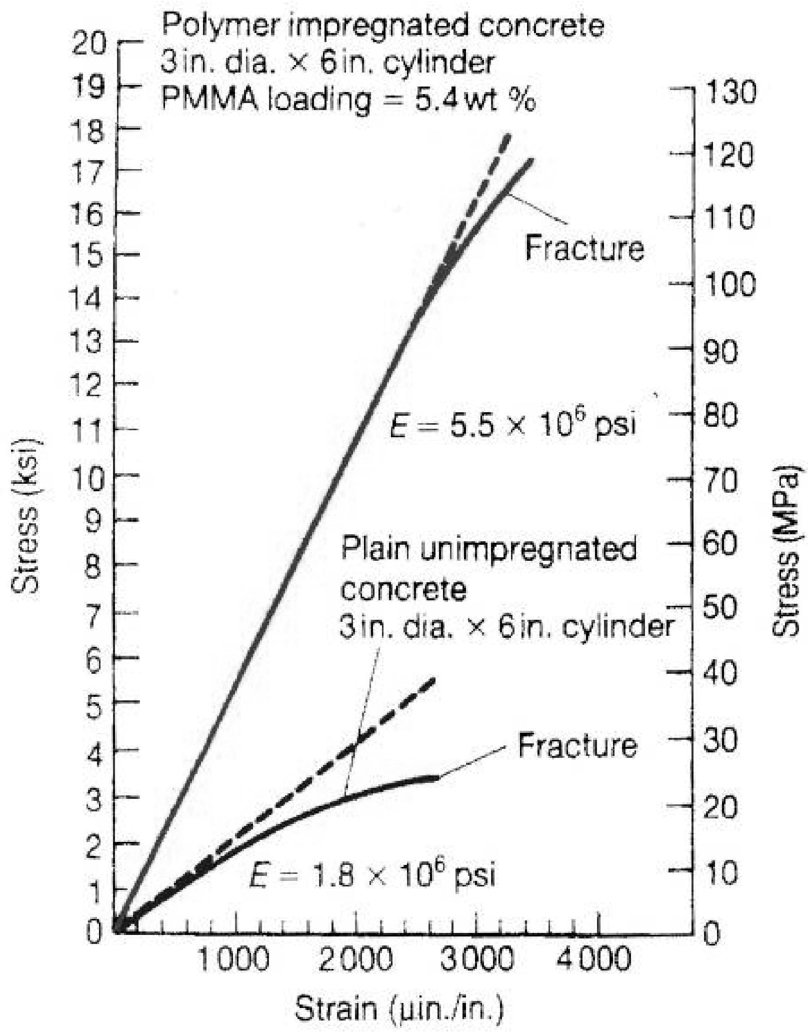

FIGURE 1 Polymer-impregnated concrete stress-strain relationship (*1*, Paper Ref. 9.3, Shah and Rangan, 1971).

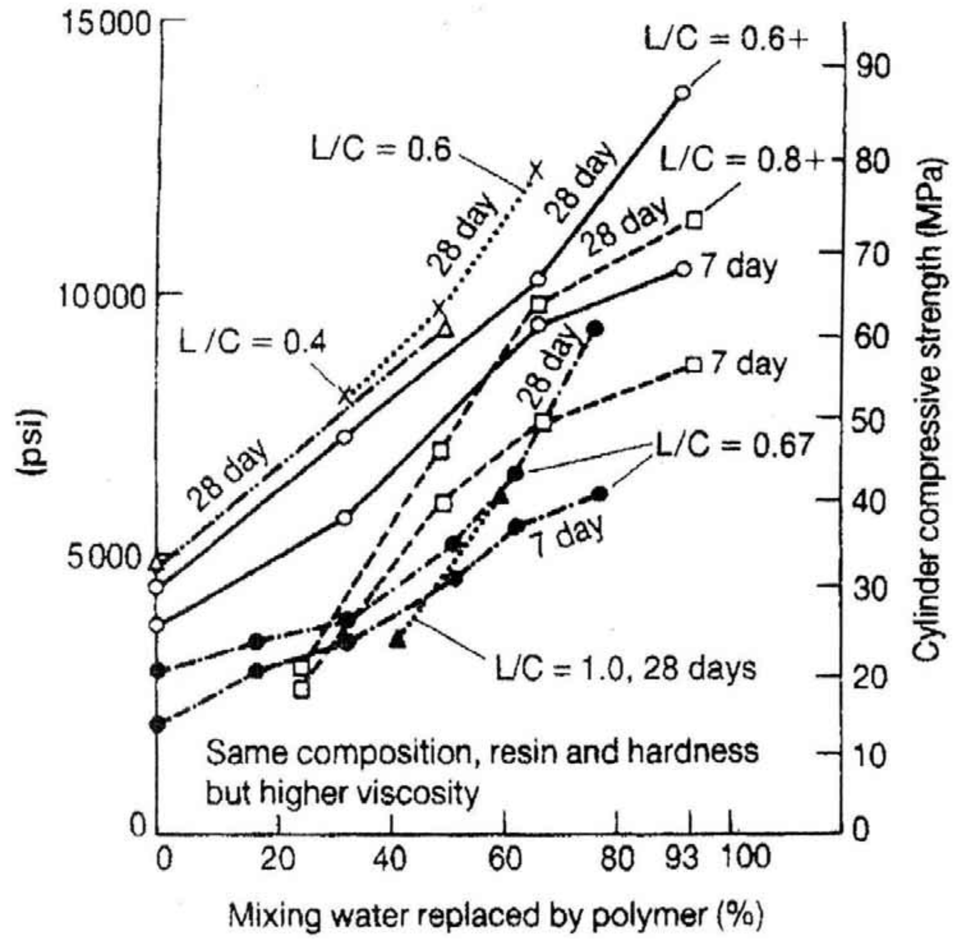

FIGURE 2 Compressive strength versus percentage mixing water replaced by polymer in polymer-modified concrete (*1*, Paper Ref. 3.38, Nawy et al., 1977).

Original work by Michael Sprinkel on latex-modified concrete (LMC) for overlays in the early 1980s at the Virginia Transportation Research Council is to be acknowledged as one of the significant developments of the time. To minimize lane closure due to bridge deck deterioration, the Virginia Department of Transportation (VDOT) constructed in 1985 its first LMC overlay using Type III cement so that traffic could be placed on the overlay after only 24 hours of curing, using the mixture proportions shown in the following Table 1. The success of the tests generated extended use, so that by 1997, VDOT constructed its first LMC overlay using rapid-set cement so that traffic could be placed on the overlays in three hours. Due to continuing research and development efforts, LMC overlays have been improved over the years to meet the needs of the transportation industry.

TABLE 1 Typical Mixtures for LMC Overlays (lb/yd^3) (*12*)

Mixture	LMC	LMC-HE	LMC-VE	LMC-K
Type cement	I/II	III	Rapid Set	K
Cement	658	815	658	658
Fine aggregate	1571	1402	1600	1544
Coarse aggregate	1234	1142	1168	1208
Latex (52% water)	205	218	205	205
Water	137	164	137	137

In another development, use of nonmetallic fibers, particularly fiberglass elements, bundled into continuous reinforcing elements had been considered in the 1950s for prestressing reinforcement at Princeton University on a limited basis. Bundled and resin-impregnated glass fibers forming deformed bars as main reinforcement in structural elements were prepared and investigated for the first time in the United States at Rutgers as main reinforcement in structural elements. This research work published in the ASCE Structural Division Journal in the 1960s demonstrated the feasibility of replacing steel reinforcing bars with what is termed now as glass fiber-reinforced plastics. Figures 3 and 4 of that work show the very high strength at 150 ksi (1200 MPa) that can be achieved for main reinforcement at ultimate load depending on whether the glass filaments are bundled or twisted.

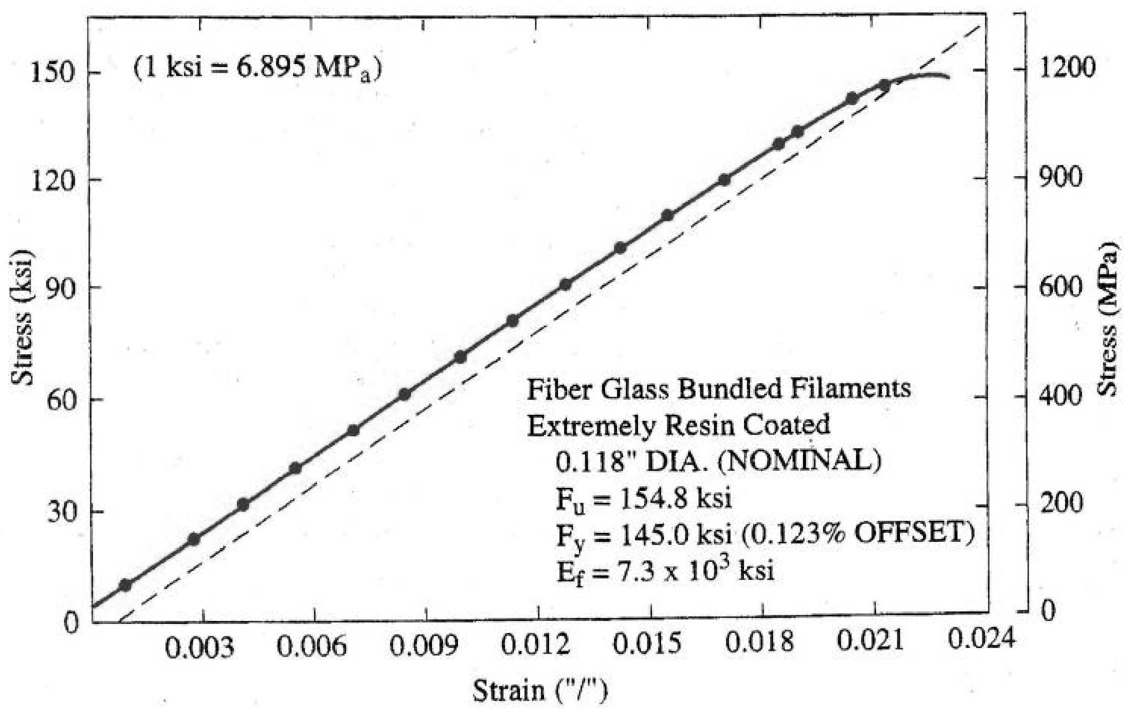

FIGURE 3 Typical stress-strain relationship of fiberglass plastic bar reinforcement for polymer-coated fibers (*1*, Paper Refs. 9.5, 9.6, Nawy et al., 1971).

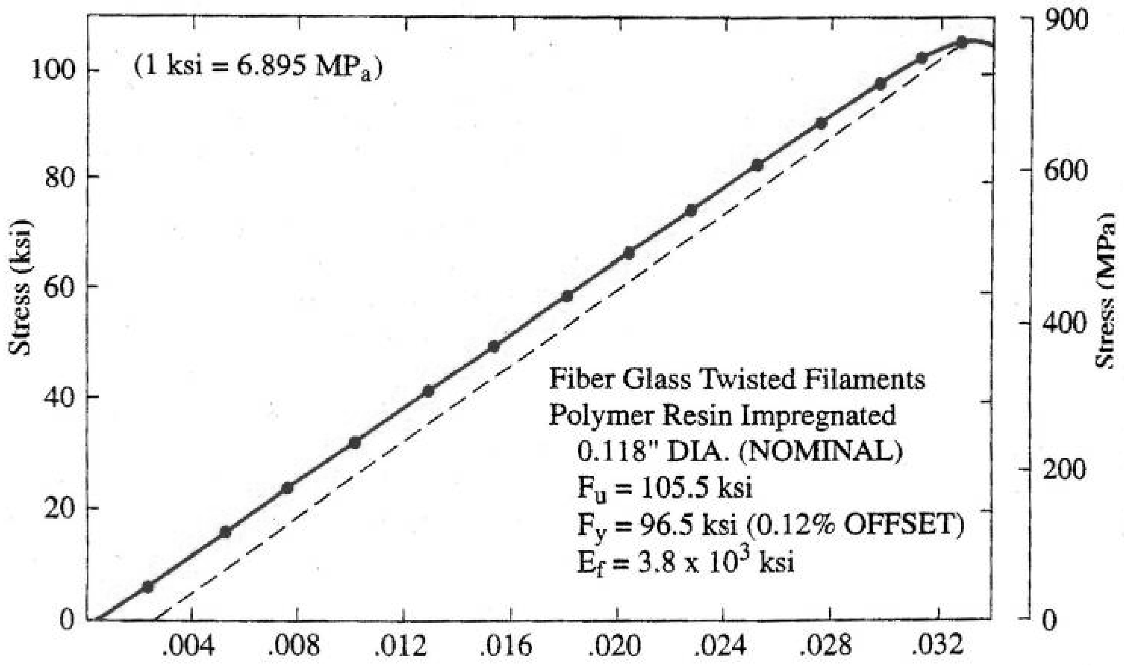

FIGURE 4 Typical stress-strain relationship of fiberglass plastic bar reinforcement for polymer-impregnated twisted filaments (*1*, Paper Refs. 9.5, 9.6, Nawy et al., 1971, 1977).

In the late 1970s and early 1980s increased interest developed in the use of such fiber-reinforced plastic bars with work by Shah, Mindess and Young, Swamy and Nanni. ACI Committee 544 Report of 1991 on the state of the art is an excellent compendium on this subject. Parallel with that, extensive research by Romualdi and Batson as early as the 1960s on use of random fibers in the concrete mixture has contributed to the improved crack control qualities of concrete that we see today. It should be stated that fibers have been used to reinforce brittle materials from time immemorial, dating back to the Egyptian and Babylonian eras, if not earlier. Straws were used to reinforce sun-baked bricks and mud-hut walls, horsehair was used to reinforce plaster, and asbestos fibers have been used to reinforce mortars. Romualdi and Batson in their organized and pioneering research have put into scientific perspective the effective use of such fibers in a standardized manner so as to achieve maximum durability and reasonable crack control. A typical proportioning mixture for fiber-reinforced normal weight concrete is shown in the following Table 2 from ACI 544 Report, while Table 3 that follows is for a typical fly ash fibrous concrete mixture.

The critical parameters on the effect of the fiber in the concrete mixture is a function of the length, the spacing, and the volume fraction of the fibers. Extensive work by many investigators in the United States and overseas resulted in several expressions for the length factor, the space factor, and the volume fraction that have to be chosen for good cracking and durability performance, both for steel fibers and organic fibers for the production of fiber-reinforced concrete. The following are typical plots of these factors taken from my book *High-Performance Concrete*, 2nd Ed., published by John Wiley, 2001.

TABLE 2 Typical Proportions for Normal-Weight Fiber-Reinforced Concrete (*7*)

Cement	550–950 lb/yd^3
W/C ratio	0.4–0.6
Percent of sand to aggregate	50–100%
Maximum aggregate	3/8 in.
Air content	6–9%
Fiber content	0.5–2.5 vol. % of mixture
Steel	1% = 132 lb/yd
Glass	1% = 42 lb/yd^3
Nylon	1% = 19 lb/yd^3

TABLE 3 Typical Fly Ash Fibrous Concrete Mixture (*7*)

Cement	490 lb/yd^3
Fly ash	225 lb/yd^3
W/C ratio	0.54
Percent of sand to aggregate	50%
Maximum size coarse aggregate	3/8 in.
Steel fiber content (0.010 ∞ 0.022 ∞ 1.0 in.)	1.5 vol. %
Air-entraining agent	Manufacturer’s recommendation
Water-reducing agent	Manufacturer’s recommendation
Slump	5–6 in.

Figure 5 from Shah’s work shows the relative toughness and strength versus fiber volume ratio. Figure 6 from Romualdi and Batson’s work shows the effect of fiber spacing on tensile cracking stress in fibrous concrete for different percentages. Figure 7 shows the effect of fiber spacing on the strength ratio of the first cracking load of fibrous concrete to the control plain concrete. Figure 8 from the work by Hsu gives the influence of volume fraction of steel fibers on the stress-strain behavior of 13,000-psi concrete, while Figure 9 from the work by Naaman shows the influence of the aspect ratio of steel fibers on the compressive strength of the concrete relating the axial strain to the compressive strength.

Another aspect of continuing development is the significant innovations in the proportioning of mixtures for easy construct ability, reduced permeability, durability, and environmental friendliness. Among many, a distinct example that needs to be included in this discussion is the self consolidating concrete (SCC), developed originally in 1988 at Tokyo University, Japan, around the turn of the century. It is gaining popularity in the United States, particularly that its behavior is essentially similar to that of normal concrete, with the exception of its lower modulus due to the use of high percentages of finer aggregate, finer cementitious materials and other inert powders. Long-term deformation performance of the SCC in structural elements is yet to be determined with time. It has high viscosity, with essentially free flow without segregation, leading to more consistency and increased durability of the concrete.

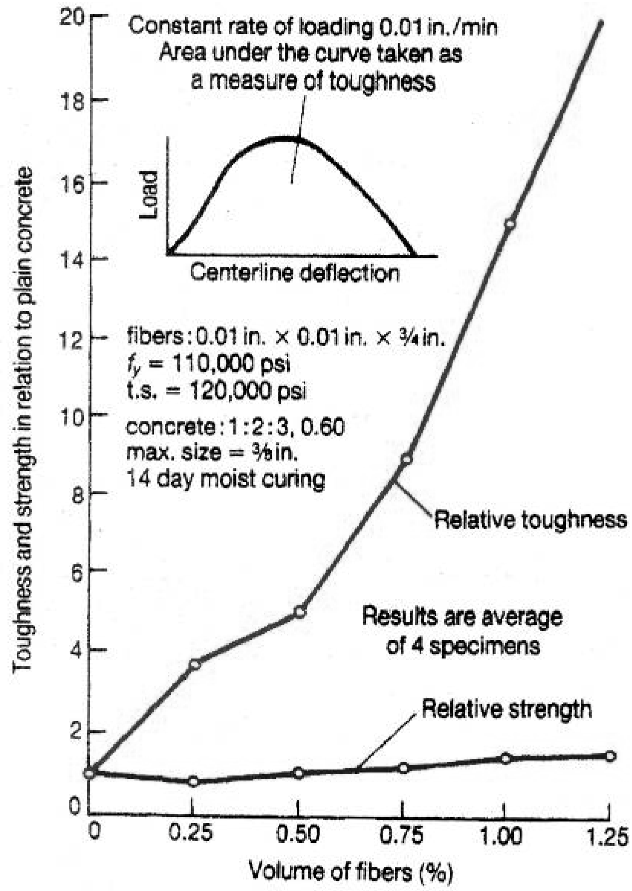

FIGURE 5 Relative toughness strength versus fiber volume ratio (*1*, Paper Ref. 9.3, Shah and Rangan, 1971).

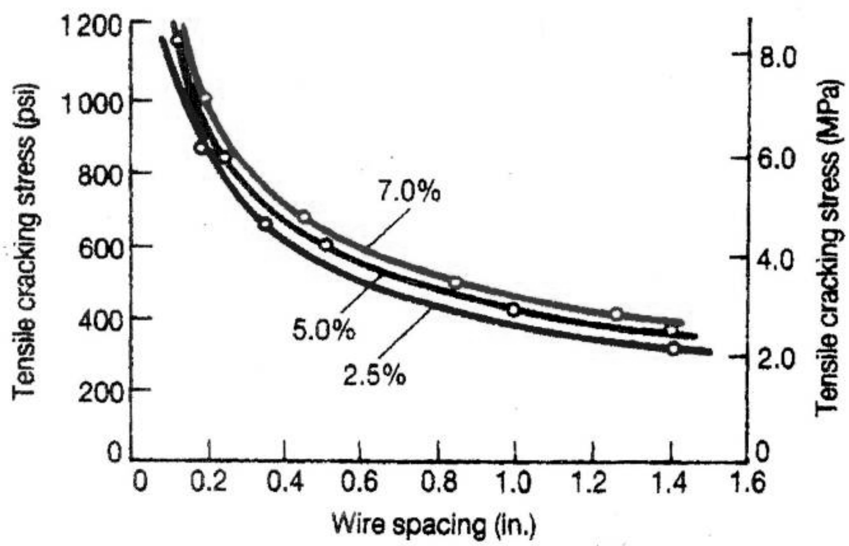

FIGURE 6 Effect of steel fiber spacing on the tensile cracking stress in fibrous concrete for ρ = 2.5, 5.9, 1n3 7.5% (*1*, Paper Ref. 9.1, Romualdi and Batson, 1963).

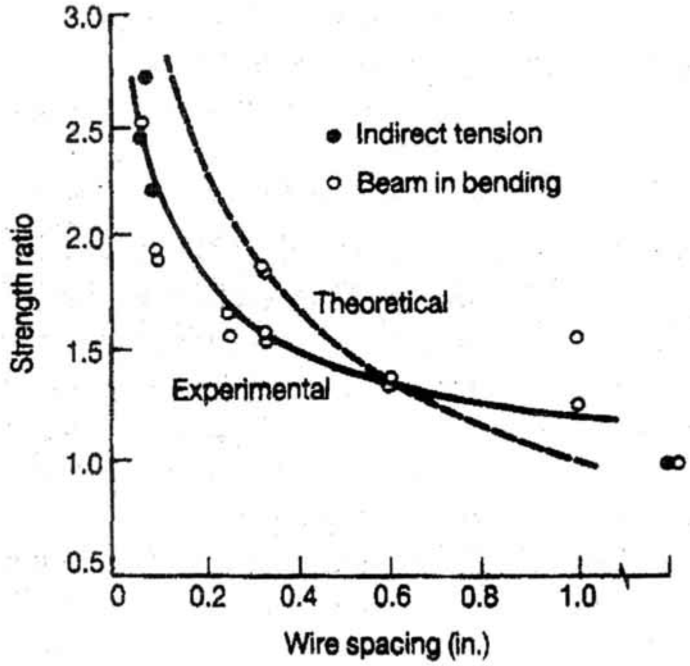

FIGURE 7 Effect of fiber spacing on strength ratio of first cracking load of fibrous concrete to strength of plain concrete (*1*, Paper Ref. 9.2, Romualdi and Mandel, 1964).

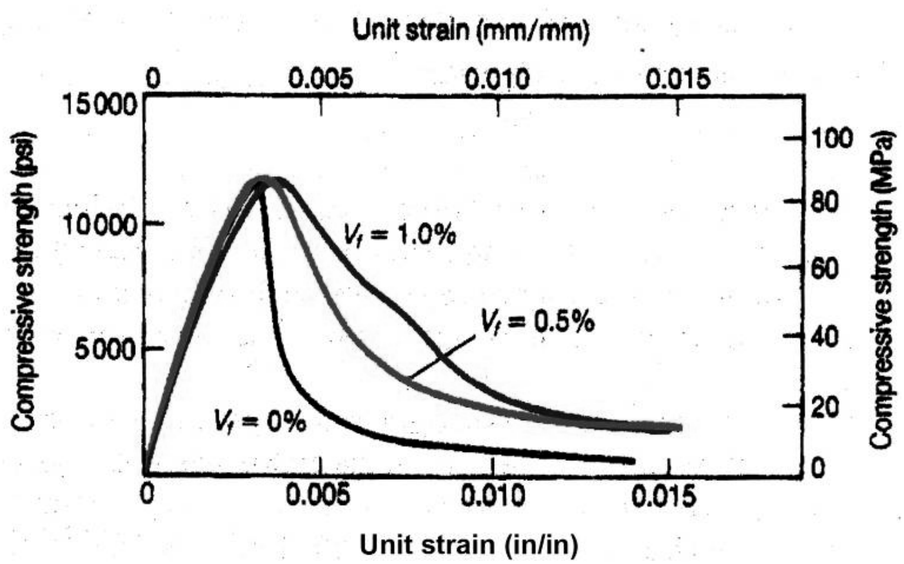

FIGURE 8 Influence of volume fraction of steel fibers on stress-strain behavior of 13,000-psi concrete (*1*, Paper Ref. 9.16, L. H. Hsu and T. C. T. Hsu, 1994).

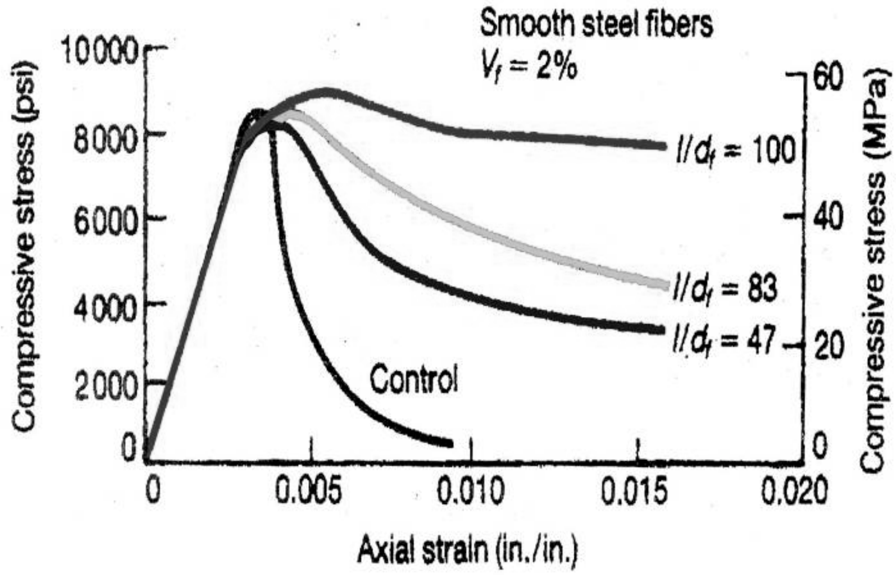

FIGURE 9 Influence of aspect ratio of steel fibers on stress-strain behavior of fiber reinforced concrete in compression (*1*, Paper Ref. 9.17, Fanella and Naaman, 1985).

REHABILITATION OF DETERIORATING AND DAMAGED INFRASTRUCTURE COMPONENTS

As a result of environmental deterioration or natural catastrophes such as earthquakes or fire, rehabilitation rather than replacement of the infrastructure elements such as bridge deck concrete beams and slabs using fiber reinforced plastics (FRP) has been a necessity. Nanni's extensive work followed by many other investigators since the 1980s and continuing deserve to be highlighted. This area has received prominence since the start of the research in the use of carbon-reinforced sheets, initially in Japan and thereafter extensively in the United States. Using carbon sheets appropriately mounted on the faces of structural elements that need to be strengthened can boost the ultimate capacity of these structural elements. Experimental tests by Nanni et al. on a bridge deck as seen in the following plots are an example. Figure 10 demonstrates the extensive reduction in the bridge midspan strain through the use of carbon fiber–reinforced plastic sheets as well as near surface mounted rods (NSM), while Figure 11 shows the reduction of deflection in comparison with the control specimens.

DESIGN AND REHABILITATION

Deterioration of the infrastructure mandates much replacement or rehabilitation while the increasing needs of a larger and more developed world population must be satisfied. As propounded by Shilstone, the body of knowledge accumulated in the latter part of the 20th century can also be used to develop major improvements in mixture proportioning and choice of components. Hundreds of thousands of tests of various types have been conducted on cylinders, cubes, uniaxial and multi-axial loading, and on all combinations of structural components.

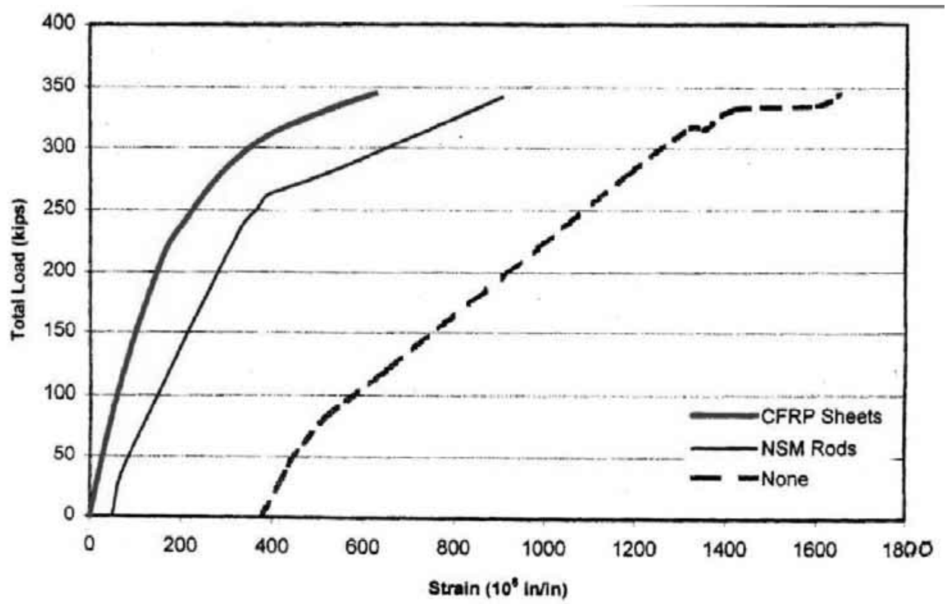

FIGURE 10 Bridge midspan strain versus load at the 350-kip level using CFRP and NSM reinforcement (*1*, Paper Ref. 9.39, Nanni et al., 1999).

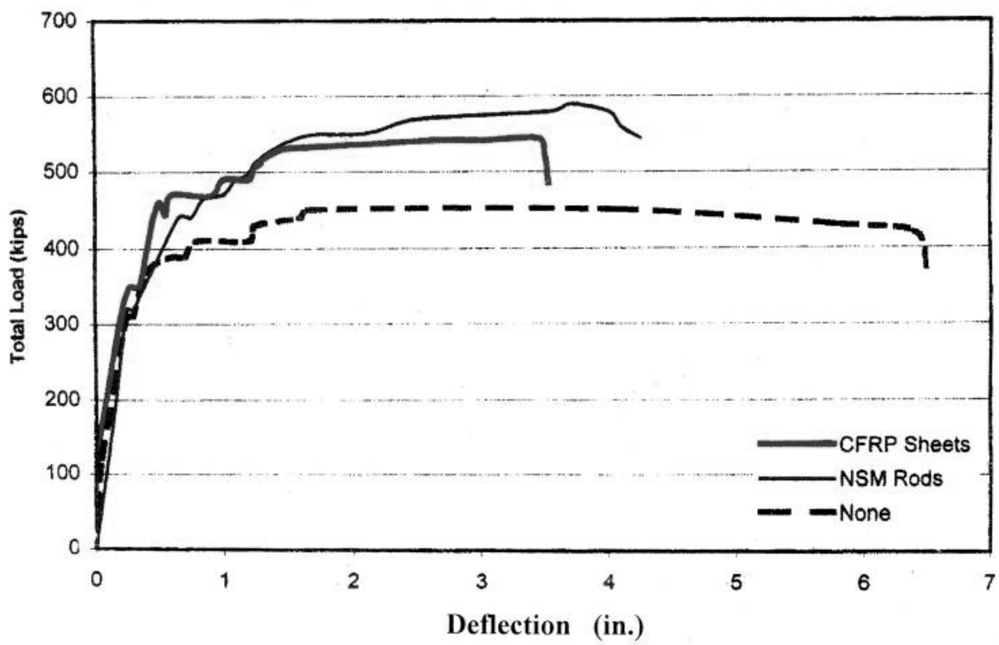

FIGURE 11 Load-deflection relationship for the three test bridge segments using CFRP, NSM rods reinforcement (*1*, Paper Ref. 9.39, Nanni et al., 1999).

Reasons have to be found through analysis of the existing voluminous data as to why certain old structural systems built early in the 20th century still perform admirably while other more recent have been failing. The lessons that will be learned will aid in preventing similar behavior in the future.

There is a sizeable backlog of decaying infrastructure in the United States. Repair and replacement of airports, bridges, mass transit, water supply, sanitary treatment plants, affordable housing, and other facilities is essential—often at emergency levels. High-performance concrete and efficient computer-generated complex solutions in structural design can provide cost-effective systems with long service life. While some design codes may be adequate, higher strengths will lead to more slender and lighter members with different behavioral characteristics. Their use can only be safely justified by continuous research into design aspects such as shear, torsion, stiffness, cracking, deflection, and stability.

Consider buckling. Even for long span bridges and tall columns, buckling stability is rarely a consideration with the relatively "massive" concrete proportions necessitated by today's traditional strengths, 5,000 to 8,000 psi (35 to 55 MPa), concrete covers, and the sizes and geometry of reinforcing steel. However, stability will become important, for example, for very thin webs, compression flanges, and slender columns. With the less ductile behavior of concrete that higher strength entails, it may be critical, necessitating more ductile concrete elements. Also, with thin sections, construction innovations come into play. There are no standards at present to address many of these parameters.

Slender concrete elements that naturally result from higher strengths offer less space for traditional reinforcement. While new materials such as glass, aramid, and carbon fibers offer hope, they lack sufficiently high moduli of elasticity to perform as passive (non-prestressed) reinforcement. Steel reinforcement seems to continue its dominance and special stainless steels are used more and more, while alternative reinforcing materials are continuously being sought. Nevertheless, the anticipated use of concrete strengths of 30,000 to 40,000 psi (295 to 275 MPa) and reinforcement with a yield in excess of 85,000 psi (590 MPa) will require new or modified codes and design procedures.

RECENT DEVELOPMENTS

To account for all these infrastructure demands, innovations and new research developments are inevitable. Several developments in the past decade and in the last few years have added to the viability of concrete as the sustainable material of the 21st century. The following developments can be chosen as the major impactors on the present decade and beyond.

Creep and Shrinkage Control Models

Creep, or lateral material flow, is the increase in strain with time due to sustained load. Initial deformation due to load is the elastic strain, while the additional strain or time-dependent deformation due to the same sustained load is the creep strain. Drying shrinkage, on the other hand, is the decrease in volume of the concrete element when it loses moisture due to evaporation. Since every infrastructure element under load will suffer this long-term deformation that has to be accounted for in a durable system, I have chosen this aspect as one of the major topics for consideration.

If we look at the three-dimensional Figure 12 and its two-dimensional counterpart, Figure 13, we can see that the non-linear relationship in the creep and shrinkage behavior makes it difficult to come up with an exact model of prediction. And that has been the challenge for researchers from the 1920s onwards, and that is why there are so many models of prediction: Ross (1935), Roll, Branson, ACI 209, CEB-FIP, Bazant, Gardner, and others. Because of the incomplete reversibility of both creep and shrinkage strains we can observe cracking, sagging of elements, and progressive deterioration as the strain continues to increase with time. The present ACI 318 Code expressions due to Branson are still the acceptable general purpose expressions for the prediction of creep and shrinkage as embodied in the ACI 209 model, and the designer can use other methods such as the CEB-FIP, Bazant's, or Gardner's for refined predictions. Recent work by Nassif at Rutgers, shown in Figure 14, indicates that the ACI 209 model seems to be a best fit for creep prediction in high-strength, high-performance concrete. Further universal agreement on the best model would immensely contribute to major improvement in the long-term durability performance of the transportation infrastructures constructed today and in the balance of the 21st century.

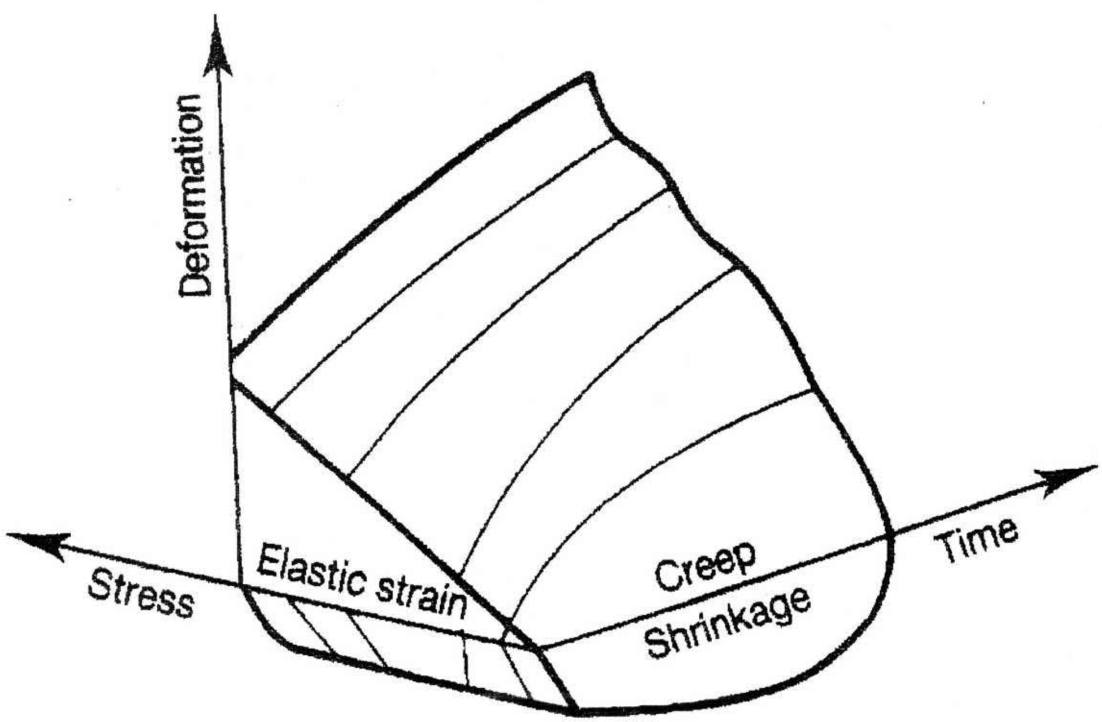

FIGURE 12 Three-dimensional model of time-dependent structural behavior of concrete (*1*, Book Ref. 6.1, Nawy, 1985, 2005).

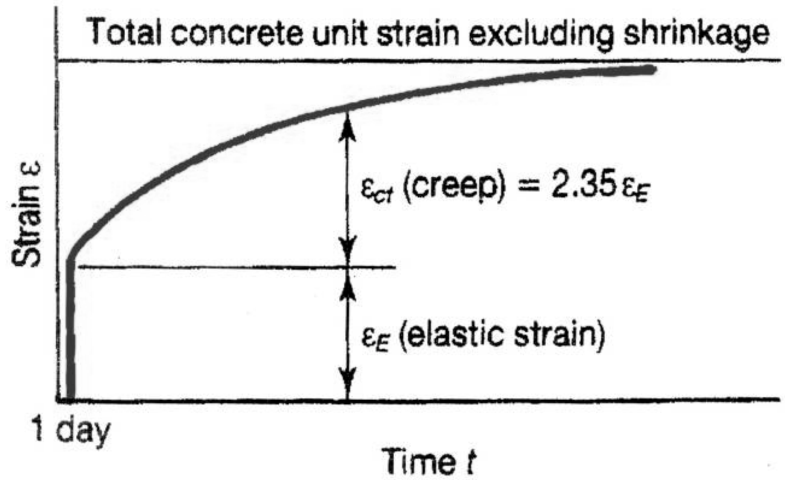

FIGURE 13 Load-creep versus time curve (*1*, Book Ref. 6.1, Nawy, 1985, 2005).

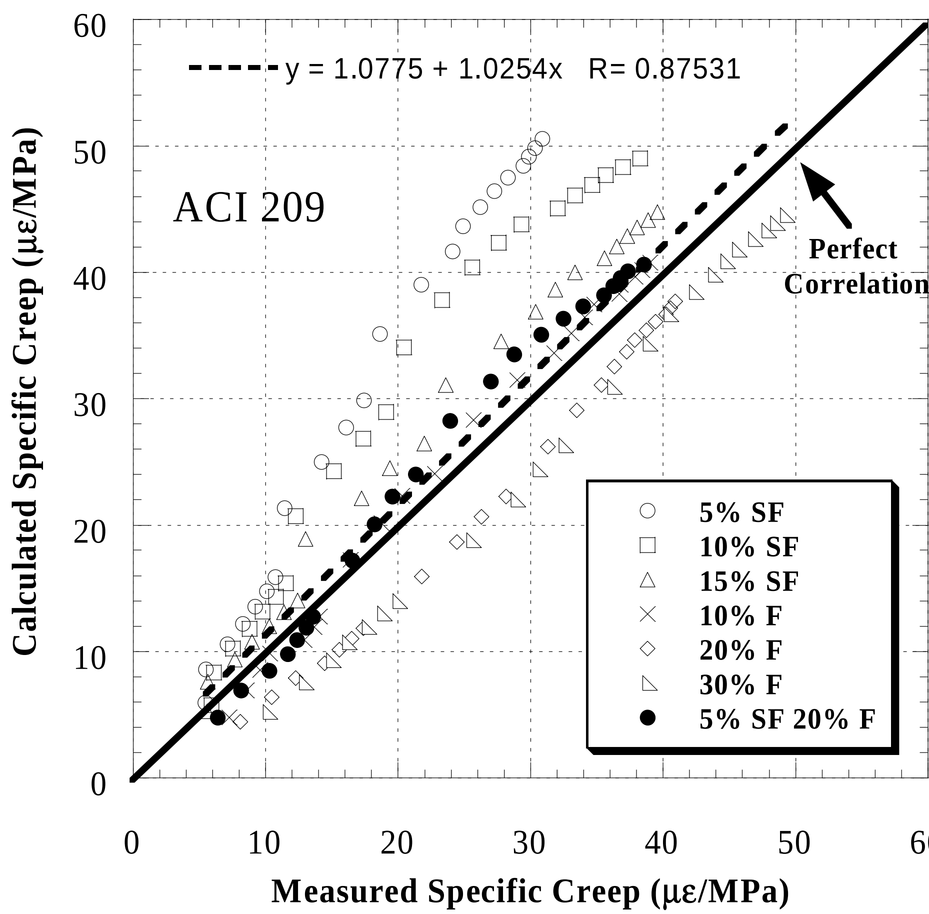

FIGURE 14 Comparison of measured and calculated specific creep for ACI 209 model.
(Source: Nassif, H., et al., ACI SP 228-89, Vol. II, 2005.)

Geopolymer Concrete

Ordinary portland cement concrete, irrespective of strength, will continue to be the dominant material in construction. However, the by-products in the production of cement, such as fly ash, the amount of high energy expended, the resulting release annually of substantial carbon dioxide to the atmosphere to the extent of 1.5 billion tons of carbon dioxide, encourages the development of more environmentally friendly concrete. The filler in lieu of cement can be through the development of inorganic alumina-silicate polymer, termed as Geopolymer, synthesized from materials of geological origin or by-product materials such as fly ash that are rich in silicon and aluminum. Research by Rangan and his team at Curtain University in Australia has demonstrated the viability of this option, particularly for fly ash–based geopolymer concrete, replacing cement with fly ash–based polymer at ambient temperatures as well as at higher temperatures up to 70°C.

The results were demonstrated through tests of beams and columns made of geopolymer concrete and reinforced with the usual steel reinforcement. These tests have demonstrated compliance of the performance to the ACI 318 and the Australian Codes in terms of strength and deflection. Figure 15 shows the water–polymer ratio versus compressive strength up to 70 MPa, while Figures 16 and 17 show the testing setup of the beams and columns that were tested to failure in Rangan's research. The test results demonstrated that the load capacity of the tested beams and columns have a good correlation with the values calculated in accordance with the ACI 318 Code.

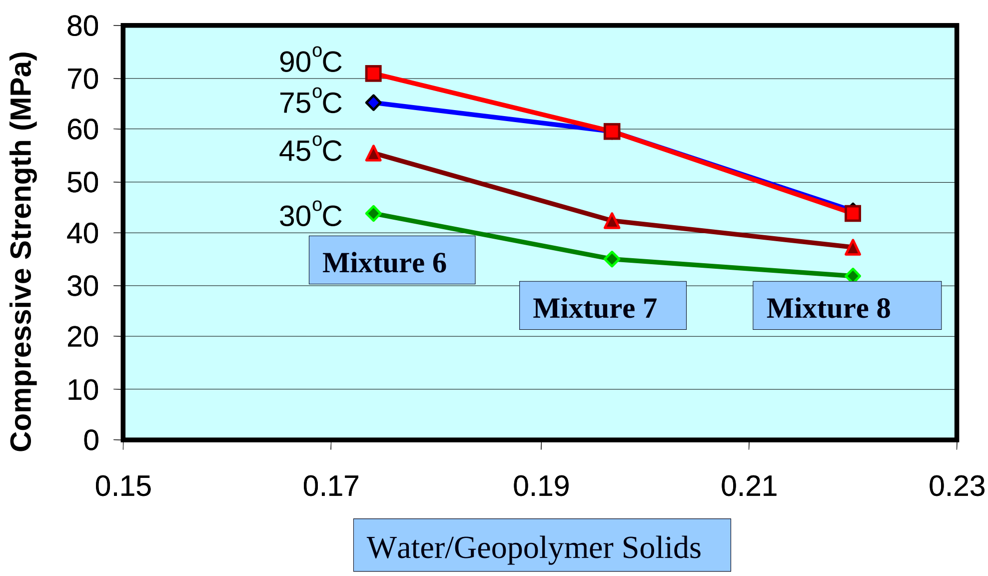

FIGURE 15 Water–geopolymer ratio versus compressive strength (MPa).
(Source: Rangan, B. V., et al., ACI SP 228-38, Vol. I, 2005.)

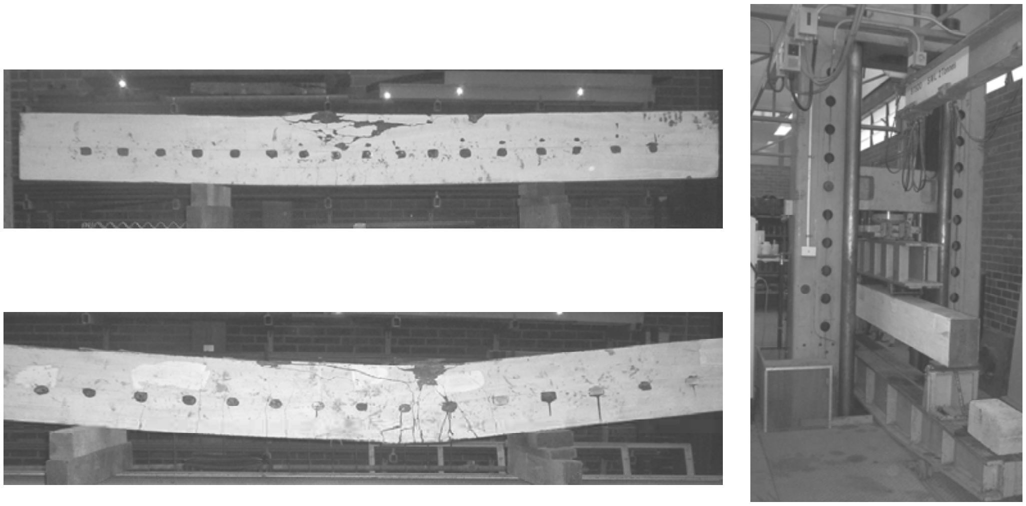

FIGURE 16 Testing setup of reinforced geopolymer concrete beams.
(Source: Rangan, B. V., et al., Proceedings International Workshop, Perth, Australia, September 2005.)

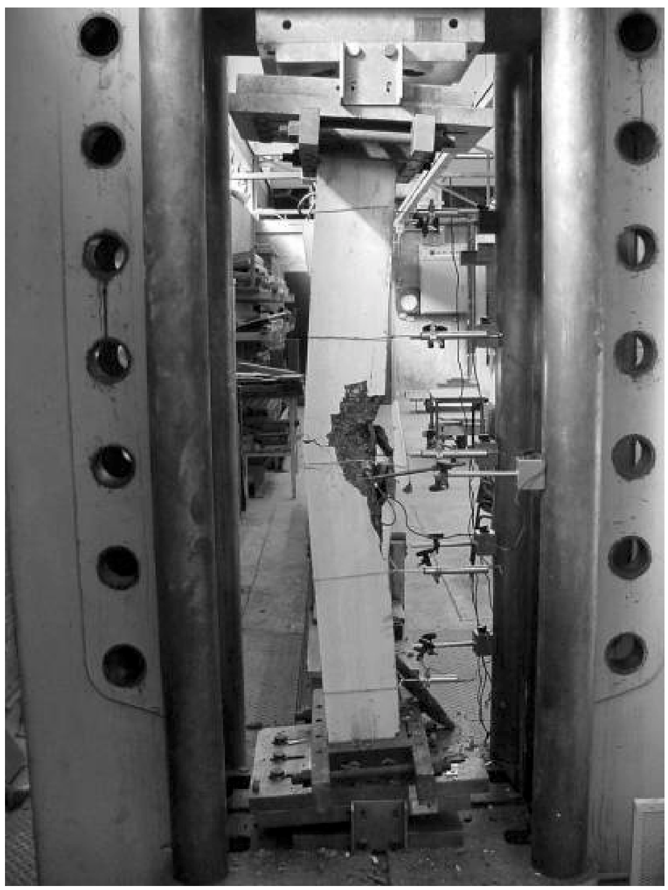

FIGURE 17 Testing setup of reinforced geopolymer concrete columns.
(Source: Rangan, B. V., et al., Proceedings International Workshop, Perth, Australia, September 2005.)

Flexible Engineered Cementitious Concrete

An extremely ductile concrete made with engineered cement composite resulting from extensive research by Victor C. Li of the University of Michigan is the most recent development for major sustainability of the infrastructure in terms of durability, strength, and cost reduction. Originally started in Japan, several bridges, including a cable-stayed bridge, have been built there and tests by Li on large-scale models have verified the strength and ductility unique performance of this concrete. Engineered cementitious concrete (ECC) is totally different from fiber-reinforced concrete (FRC) in that the fibers in the mixture are engineered to structurally behave totally different from the FRC through significant reduction of their bond to the mortar. One test on a 1-inch-thick slab of concrete using engineered cement composites showed that the slab can bend under extreme loads without fracturing, essentially behaving similar to a metal plate under extreme loads. Figure 18 shows the metal-like ductile behavior of the ECC and the negligible crack with at ultimate (85 micro mm). A typical mix for this polyvinyl alcohol fiber-reinforced engineered cementitious composite is as shown in the following Table 4.

Figure 19 shows the Mihara cable-stayed Bridge in Hokkaido, Japan, completed and opened to traffic in 2005, having an ECC deck layer thickness of 1-1/2 in. (38 mm).

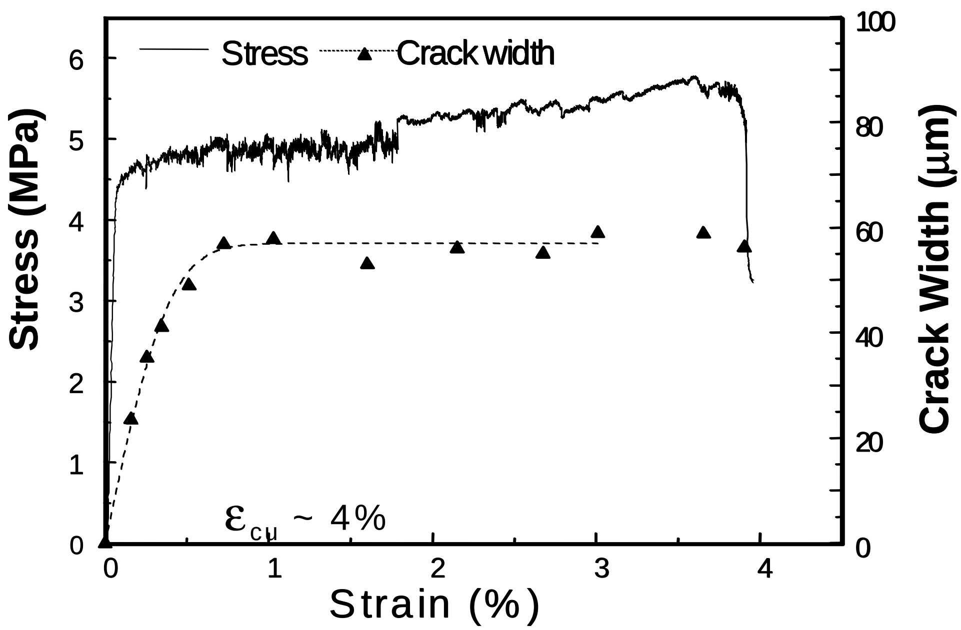

FIGURE 18 Stress-strain relationship of engineered composite concrete under uniaxial tension. (Courtesy of V. C. Li, University of Michigan, 2005.)

TABLE 4 Mixture Proportions of PVA-ECC (kg/m^3)

Cement	Sand	Class F Fly Ash	Water	Superplasticizer	PVA Fiber
583	467	700	298	19	26

Courtesy of V. C. Li, University of Michigan

Cable Stayed Bridge
Hokkaido, Japan
Completed: Oct., 2004
Open to traffic: April, 2005
Length: 1000 m, span: 340 m
Deck area: 20,000 sq. m.;
ECC layer thickness: 38 mm

Composite ECC-Steel Deck
ECC used for stiffening deck & decrease stress in deck steel
FRP shear key applied
Weight reduction 40%
Cost reduction: 50%
Expected service life: 100 yrs

FIGURE 19 Mihara cable-stayed bridge, Hokkaido, Japan, with deck superstructure constructed from composite ECC-steel, opened 2004 for traffic.
(Courtesy of V. C. Li, University of Michigan, 2005)

Hybrid GFRP-Reinforcement for Bridges and Other Structural Systems

As stated previously, fiber-reinforced plastics are being used increasingly in transportation structures in bridge decks and column encasement in earth quake retrofit construction. Hybrid glass fiber-reinforced plastic bars (GFRP) are receiving popular attention, particularly in bridge decks. Figure 20 from the work of Antonio Nanni of the University of Missouri at Rolla shows essentially negligible deflection at service load-up to the ultimate and the reserve deflection control capacity is almost at twice the theoretical ultimate load. Figure 21 shows the deck of the hybrid GFRP-reinforced bridge deck at the city of Bettendorf, Iowa, as an example. Figure 22 (both courtesy of Nanni) shows the use of this reinforcing system in beams in the superstructure of a typical parking garage. In short, such innovations can eliminate the problems of durability and reinforcement corrosion that often plaque bridge structures and garages.

Self-Consolidating Concrete

Self-consolidating concrete is a self-compacting concrete that has high viscosity but can flow without segregation. Hence, lower energy, minimized labor costs, increased material consistency, and improved ductility are all achieved because of the simplicity in its self-consolidation process.

SCC was originally developed at the University of Tokyo in 1988 and gained acceptance thereafter in the United States because of these qualities and ease in construction. It has been found to be particularly suitable in the transportation infrastructure and used in several states including Virginia and Kansas in prestressed concrete bridge girders, in New Jersey in noise barrier walls , and in South Carolina drilled shafts. Table 5 gives a mixture proportioning example for SCC that produced a slump of in excess of 24 in. (635 mm), yet possessing a compressive strength in the range of 8,000 psi (55 MPa).

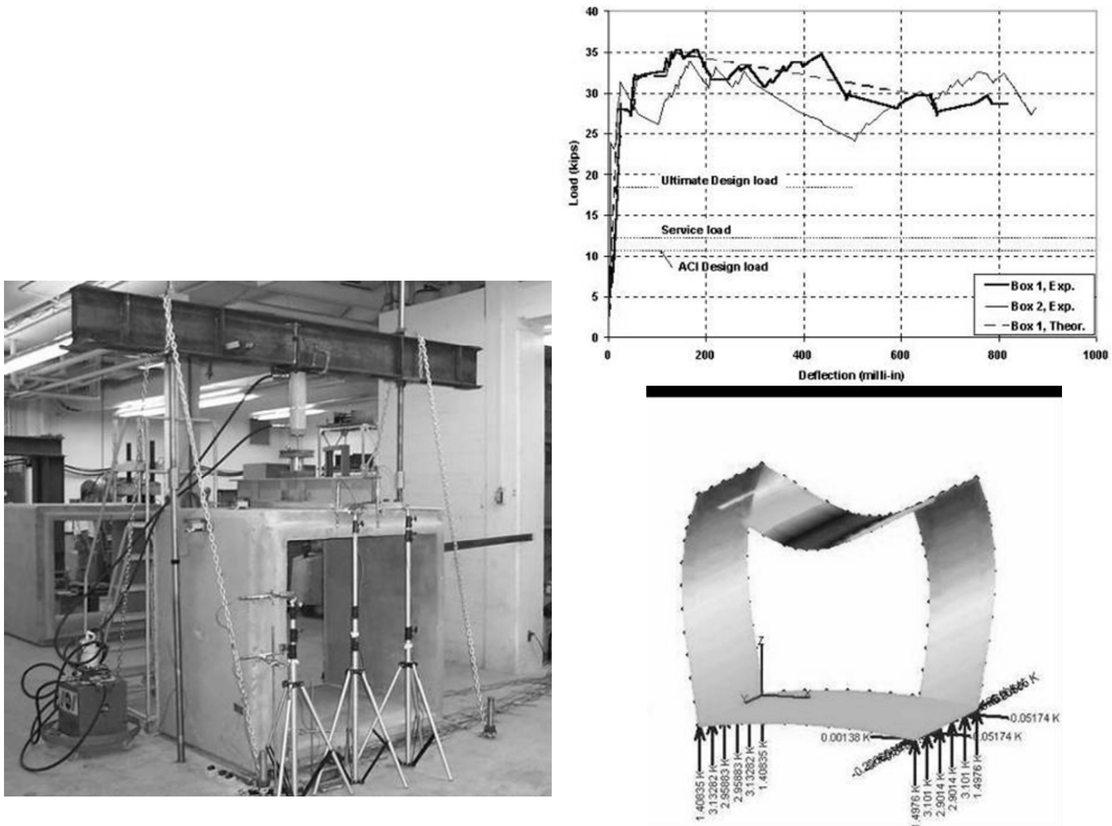

FIGURE 20 Deflection-load relationship of hybrid GFRP concrete box culvert analysis and laboratory testing. (Courtesy of A. Nanni, University of Missouri, Rolla, 2005.)

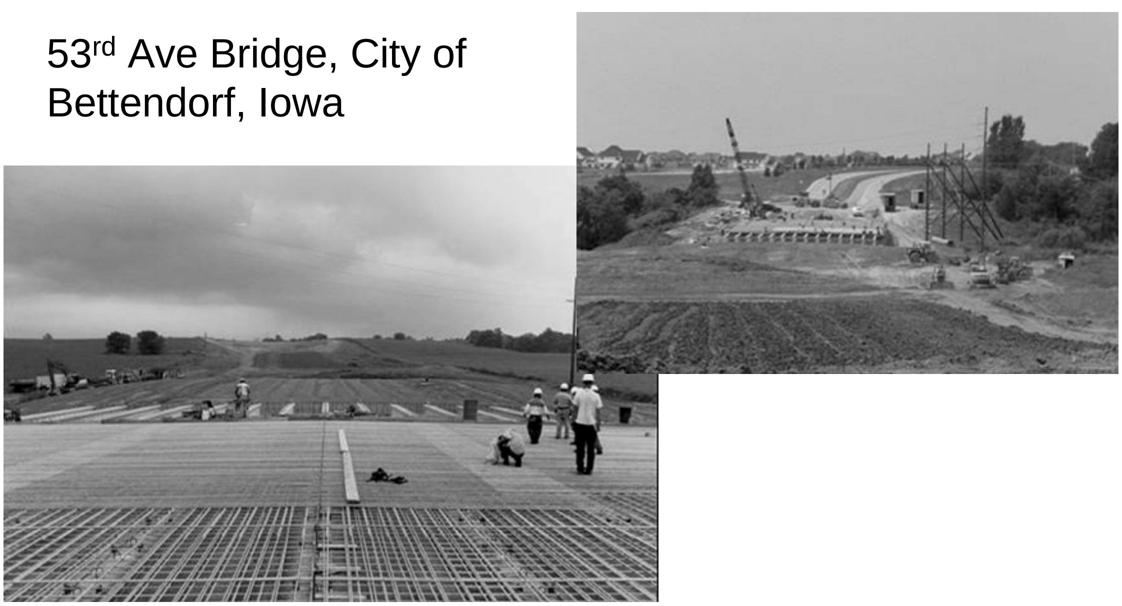

FIGURE 21 Hybrid GFRP-reinforced concrete bridge deck, Bettendorf, Iowa, 2005. (Courtesy of A. Nanni, University of Missouri, Rolla, 2005.)

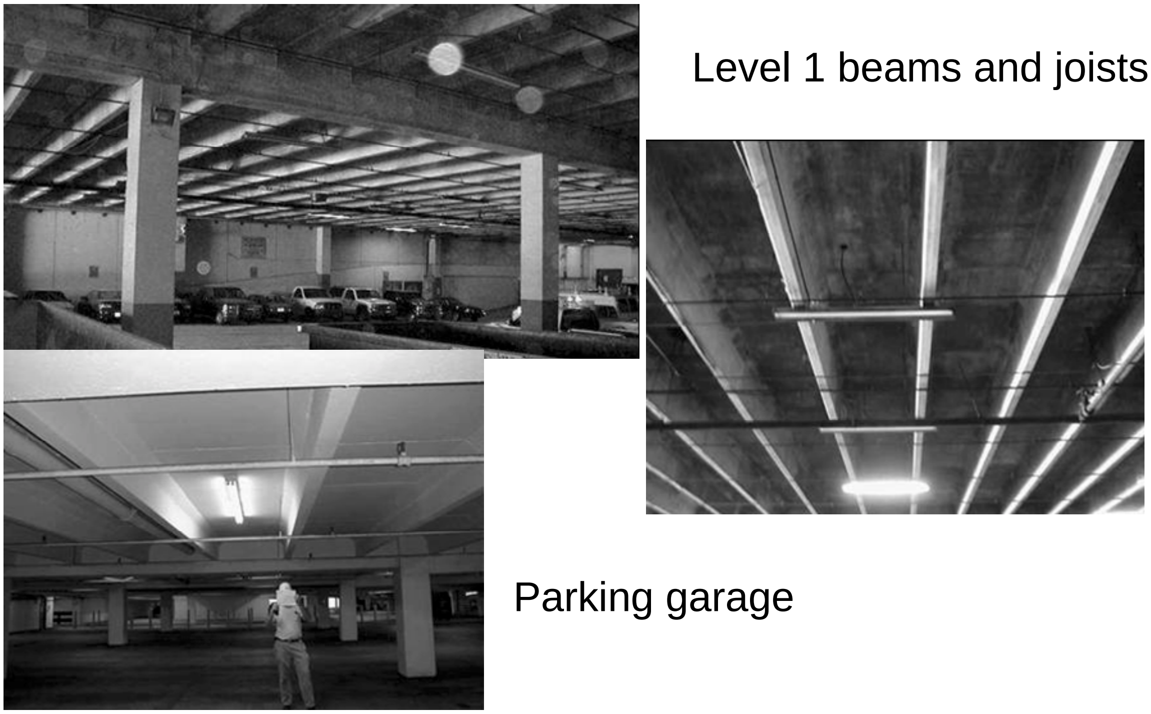

FIGURE 22 Upgrade of a retail building to house a telecom hotel using hybrid GFRP-reinforced concrete in beams and joists. (Courtesy of A. Nanni, University of Missouri, Rolla, 2005.)

TABLE 5 Mixture Proportions for SCC (*10*)

	PC	**SF** 5%	**F** 20%	**CA**	**FA**	**Water**	**w/cm**
kg/m^3	386	26	103	817	885	201	0.39
HRWR (ml)			**AEA (ml)**		**Slump(mm) +**		**Air(%)**
4620			51		635		5.0

+ Average spread
* Saksawang, N., and H. Nassif. Evaluation of Mechanical Properties of Self-Consolidating Normal and High-Performance Concrete. Presented at 85th Annual Meeting of the Transportation Research Board, Washington, D.C., January 24, 2006.

In summarizing these recent developments and others that have materialized in the present century, this expanded knowledge will lead to concrete structures, be they bridges, high-rise buildings, or floating cities, that are far more immune to dangerous conditions including seismic occurrences and hurricanes. They offer greater safety and less costly sustained repairs. Advances will be made in the use of both internal and external post-tensioning systems and details to facilitate resilient structures with zero permeability.

Similarly, improved design of connections will lead to widespread use of high-strength precast members for buildings and bridges in both seismic and non-seismic regions resulting in the universal standardization of factory-produced concrete components because of all these developments. Structural research into the efficient use of new materials, particularly new reinforcing materials and compositions, development, and design, will be the hallmark of the 21st century.

But other considerations have of necessity to accompany these major research developments for successful and efficient implementation. The following four considerations have to be highlighted because they go hand in hand with the requirement for a sustainable world infrastructure development and maintenance. They are constructability, long-term durability, education and training, and monitoring and cost evaluation.

CONSTRUCTABILITY CONSIDERATIONS

Many long-span concrete bridges have already been built using traditional materials and technology. Advances continue with methods such as precast segmental construction. Lighter members facilitated by high-strength concrete and new reinforcing and prestressing techniques and materials will not only enable very long-span systems but will also permit wider application of lightweight concrete in the production of lighter precast components to many routine structures. Quality-controlled, factory production is perfectly suited to higher-strength concrete components. Increased concrete strength and precise batching, mixing, and curing of new materials and admixtures require good quality control and quality assurance. Advances in computerized production and control systems will provide excellent quality and precise geometric tolerances. In addition, lighter members will lower transportation and erection costs. Artificial reinforcement fibers will find wider application to prestressed members and cable-stayed systems.

Longer spans, lighter members, and faster construction due to advanced erection techniques will permit fewer or smaller foundations with less environmental impact and reduced cost.

LONG-TERM DURABILITY

Significant improvements in durability through the use of materials such as granulated blast-furnace slag, fly ash, silica fume, densified cements, and other future-developed products will provide, through reduced permeability to unfriendly matter, longer life with lower maintenance costs. Instrumentation and monitoring of structural performance for corrosion deflection and cracking will continue to be more widely used, thus will lead to improved and intelligent materials and methods with predictable, long life.

EDUCATION AND TRAINING

High-performance, high-strength concrete involves many ingredients and requires proper proportioning, mixing, and handling to attain the desired benefits. Mixture proportioning is a complicated process requiring knowledge of the interaction of cements, natural pozzolans, slag, fly ash, silica fume, air-entraining admixtures, high-range water-reducing admixtures, and for the desired workability, strength, and finish. The correct choice and use of these materials will require designers and constructors trained in the knowledge, choice, applications, production techniques, site sampling, and laboratory testing. This will require new and expanded curricula at universities and other educational institutions. Such training both at the undergraduate and graduate levels will inevitably lead to more specialization in areas such as material science, corrosion engineering, and methods of concrete production and site control. In addition, new and continuously evolving standards, specifications, guidelines, and certification processes will be needed to implement this technology. Emphasis will be increased on environmentally friendly concrete structures requiring less binding materials so as to reduce heat of hydration and more saving in production energy.

Equally important is the knowledge and training of the field inspector. Such training will require correct interpretation of laboratory test data, effect of the loading rate on the test results, and the errors induced by testing machine loading pattern. In order to have personnel able, conversant, and proficient as concrete technologists, prescribed training and certification of field personnel is mandatory if the emerging technology in high-strength concrete is to be successfully transferred to full and cost-effective application. The challenge will be to produce high-performance concrete with the least binder content.

MONITORING AND COST EVALUATION

Longevity of systems to 75 to 100 years of life has become an increasingly important factor, and long-term cost-benefit analyses, accounting for all the costs throughout the life history, will become a yardstick for alternative designs and materials. For example, the American Segmental Bridge Institute has already committed to attaining life spans over one hundred years. Remote, real-time, and long-term instrumentation monitoring and feedback records will enable engineers to evaluate performance and maintenance leading to development of refined and realistic cost evaluations. Entire facilities, especially megaprojects, will be evaluated by proven methods, calibrated against scientifically established results and performance.

EXPECTATIONS AND CONCLUSIONS

High-performance durable concrete will dominate the new and rehabilitated infrastructure in this century. It will contain pozzolanic materials, new admixtures, and new cements and fillers. Fiber-reinforced concrete and artificial, high-strength fibers and prestressing will find wider application. Advanced, precast production and erection systems will be widely adopted along with computerized production and monitoring. Projects will be routinely instrumented to provide reliable feedback and information to design and maintenance entities. Engineering education will have to adapt to this highly sophisticated materials technology era by inclusion of adequate instruction to equip the graduating engineers with knowledge of the behavior of concrete constituents. New education, training, codes, standards, guidelines, and certification processes will be needed at all levels of the industry. Long-term cost-benefit analyses will have to become routine for choice of best solutions.

The inherent nature of major infrastructure projects will place increasing demands on this century's engineers, requiring more environmental awareness, public participation, meetings, and design convocations. It will be a challenging time. The engineer and the technologist will have to be an entrepreneur, a scientist, an architect, an artist, a draftsman, a constructor, a materials technologist, an economist, an environmentalist, a communicator, and an orator.

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