Advancements in Concrete Technology

by P. Kumar Mehta

Portland cement concrete has clearly emerged as the material of choice for the construction of a large number and variety of structures in the world today. This is attributed mainly to low cost of materials and construction for concrete structures as well as low cost of maintenance. Therefore, it is not surprising that many advancements in concrete technology have occurred as a result of two driving forces, namely the speed of construction and the durability of concrete.

During the period 1940-1970, the availability of high early strength portland cements enabled the use of high water content in concrete mixtures that were easy to handle. This approach, however, led to serious problems with durability of structures, especially those subjected to severe environmental exposures.[1]

Among the recent advancements, most noteworthy is the development of superplasticized concrete mixtures which give very high fluidity at relatively low water contents. The hardened concrete due to its low porosity is generally characterized by high strength and high durability. Macro-defect-free cements and chemically bonded ceramics are examples of alternative technological approaches to obtain low-porosity, high-strength products. For the specific purpose of enhancement of service life of reinforced concrete structures exposed to corrosive environments, the use of corrosion-inhibiting admixtures, epoxy-coated reinforced steel, and cathodic protection are among the better known technological advancements.

In addition to construction speeds and durability, there is now a third driving force, namely the environmental friendliness of industrial materials, which is becoming increasingly important in technology assessment for the future. In this article, a critical evaluation of various technologies is attempted using the following three criteria:

- cost of materials and construction,
- durability, and
- environmental friendliness.

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It is not intended to present a comprehensive review of all the recent advancements in concrete technology. Only selective developments of the last 30 years, that are judged to be significant by the author, are briefly reviewed.

Superplasticizing admixtures

Seventeen years ago, Malhotra made the following statement:

"There have been very few major developments in concrete technology in recent years. The concept of air entrainment in the 1940s was one; it revolutionized concrete technology in North America. It is believed that the development of superplasticizers is another major breakthrough which will have a significant effect on the production and use of concrete in years to come."[2]

Malhotra's prediction has proven to be correct. This is supported by the development and use of a growing family of superplasticized, high-performance concrete products, such as superplasticized high-strength concrete, superplasticized high-durability concrete, superplasticized high-volume fly ash and high-volume slag concretes, superplasticized self-compacting concrete, superplasticized anti-washout underwater concrete, and superplasticized fiber reinforced concrete. Collepardi[3] and, more recently, Malhotra[4] and Nagataki[5] have published excellent reviews on the development of various technologies incorporating the use of superplasticizing admixtures.

Superplasticizers, also known as high-range water-reducing admixtures, are highly efficient water reducers. In late 1960s, products based on naphthalene sulfonates were developed in Japan, and concurrently the melamine sulfonate products were introduced in West Germany. The anionic long-chain molecules of the admixture become adsorbed on the surface of the cement particles which are effectively dispersed in water through electrical repulsion.

According to Nagataki, the first applications of superplasticized concrete in Japan were for the production of high-strength precast concrete piles which could resist cracking during the pile driving process.[5] During 1970s, the girder and beams of several road and railway bridges in Japan were fabricated with 50 to 80 MPa (7300 to 12,000 psi) superplasticized concrete mixtures having low to moderate slump. In West Germany, where the initial objective was to develop anti-washout underwater concrete, superplasticizers were used to improve the fluidity of stiff mixtures without altering the water-to-cementitious material ratio (*w/cm*). As it is possible to realize both the objectives simultaneously, now superplasticizing admixtures are used throughout the world for the purpose of obtaining high strength, high fluidity, and high durability.

Superplasticized concrete mixtures containing naphthalene or melamine sulfonates often suffered from rapid slump loss. The problem can be resolved by the introduction of an additional dosage of the superplasticizer at the job site; however, this method is cumbersome and costly. In 1986, slump-retaining or "long-life" superplasticizers were developed in Japan. According to Yonezawa, a typical "long-life" superplasticizer contains a water-insoluble compound comprising carboxylic acid salts, amide, and carboxylic anhydride.[6] The alkaline solution resulting from the hydration of portland cement gradually hydrolyses the superplasticizer, releasing a water-soluble dispersant which helps to maintain the initial slump for a long time. Tanaka et al. have described the development of polycarboxylate-based superplasticizers containing a cross-linked polymer which imparts high fluidity, long-term slump retention, and high resistance to segregation.[7] Long-life superplasticizers based on naphthalene or melamine sulfonate polymers are also commercially available now.

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High-strength concrete and mortars

High-strength concrete (> 40 MPa [> 6000 psi] compressive strength) was first used in reinforced concrete frame buildings with 30 or more stories. In tall buildings, the size of columns in the lower one-third part of the building is quite large when conventional concrete is used. Besides savings in the materials cost, construction engineers have found that the choice of reinforced concrete frame instead of steel frame in high-rise buildings permits additional savings resulting from higher construction speeds.[8] Beginning with 50 MPa (7300 psi) concrete columns for the Lake Point Tower in Chicago, constructed in 1965, many tall buildings containing high-strength concrete elements have been built in North America and elsewhere. The 79-story Water Tower Place in Chicago contains 60 MPa (8700 psi) concrete columns. The Scotia Plaza Building in Toronto and the Two Union Square Building in Seattle have columns with 90 and 120 MPa (13,000 psi to 17,400 psi) strength concrete, respectively.

To obtain high strength, the *w/cm* of the concrete mixture is usually held below 0.4 with the help of a superplasticizing admixture. Due to the low *w/cm*, an important characteristic of high-strength concrete is its low permeability, which is the key to long-term durability in aggressive environments. Consequently, far more high-strength concrete has been used for applications where durability rather than strength was the primary consideration. Marine concrete structures — long-span bridges, undersea tunnels, and offshore oil platforms — are examples of such applications.

High fluidity without segregation is yet another factor contributing to the growth of the superplasticized, high-strength concrete industry. The workability of superplasticized concrete mixtures can generally be improved by the use of pozzolanic or cementitious admixtures, such as silica fume, fly ash, rice husk ash, and ground granulated blast furnace slag. Ease in pumping and easy-to-form concrete mixtures can reduce construction cost significantly in large projects; high-rise buildings and offshore structures, for example. This is especially the case when heavily reinforced and prestressed concrete elements containing narrowly-spaced reinforcement are fabricated.

Roy and Silsbee have reviewed the development of a new family of high-strength cement-based products which do not depend on the use of superplasticizers.[9] Chemically-bonded ceramics (CBC), are mortars with little or no coarse aggregate, a very high cement content, and a very low *w/cm*. They are densified under high pressure and then thermally cured to obtain very high strength. The products, typically consisting of 50 percent anhydrous phases, exhibit properties approximating those of fired ceramics. The so-called MDF (macro-defect-free) cement products are made with a cement paste containing up to 7 percent by mass of a water-soluble plasticizing agent, such as hydroxypropyl-methyl cellulose, polyacrylamide, or hydrolyzed polyvinyl acetate. The paste is subjected to high shear mixing, and the products are molded under pressure and finally heat cured at temperatures up to 80 C (176 F). Compressive strengths on the order of 150 MPa (22,000 psi) are obtained with portland cements, and up to 300 MPa (44,000 psi) with calcium aluminate cements. Studies have shown that moisture has an adverse effect on the mechanical properties of MDF cement products. Products densified with small particles (DSP) contain 20 to 25 percent silica fume particles which are densely packed in a superplasticized portland cement paste (0.12 to 0.22 *w/cm*). Compressive strengths of up to 270 MPa (39,000 psi) and Young's moduli up to 80 GPa (12,000 ksi) were achieved through mechanical compaction.[9] On account of their brittleness, the use of CBC, MDF, and DSP is limited to non-structural applications.

The high-ductility requirement for structural use of high-strength, cement-based products can be achieved by the incorporation of steel microfibers. Reactive power concrete (RPC) products developed by Richard and Cheyrezy[10] are actually superplasticized cement mortars typically comprising 1000 kg/m^3 (1700 lb/yd^3) portland cement, 900 to 1000 kg/m^3 (1500 to 1700 lb/yd^3) fine sand and pulverized quartz, 230 kg/m^3 (390 lb/yd^3) silica fume, 150 to 180 kg/m^3 (250 to 300 lb/yd^3) water, and up to 630 kg/m^3 (1100 lb/yd^3) microfibers. Mechanically pressed samples, heat treated at 400 C (752 F) showed up to 680 MPa (99,000 psi) compressive strength, 100 MPa (15,000 psi) flexural strength, and 75 GPa (11,000 ksi) Young's modulus. It is too early to predict the future of RPC. In spite of the very high initial cost and a complex processing technology, the material may have a niche in the construction industry, especially for applications in highly corrosive environments. The presence of a large volume of microfibers enhances the crack-resisting ability of the material, thereby preserving its watertightness.

High-performance concrete

The term high-performance concrete (HPC) was first used by Mehta and Aïtcin for concrete mixtures possessing three characteristics, namely high workability, high strength, and high durability.[11] Thus, a primary distinction between high-strength concrete and high-performance concrete was the mandatory requirement of high durability in the case of HPC. As high durability under severe environmental conditions cannot be achieved unless a structure remains free from cracks during its service life, the concrete mixture ought to be designed for high dimensional stability. Therefore, to reduce cracking from thermal and drying shrinkage strains it is necessary to limit the cement paste content of the concrete mixture.

Mehta and Aïtcin proposed a method of proportioning HPC mixtures, which limits the total cement paste content to one-third by volume of concrete.[11] This method also permits a partial substitution of portland cement by a pozzolanic or cementitious admixture. Aïtcin has recently reviewed the art and science of high-performance concrete.[12] The author foresees increasing use of ternary cement blends containing slag, fly ash, silica fume, metakaolin, rice husk ash, and limestone powder to take advantage of the synergetic effect in the improvement of properties of both fresh and hardened concrete in addition to making HPC more economical.

In 1993, a subcommittee of the American Concrete Institute's Technical Activities Committee proposed a new definition of HPC as "a concrete meeting special performance requirements that may involve enhancement of placement and compaction without segregation, early-age strength, toughness, volume stability or service life in a severe environment." According to this definition, durability is not mandatory for high performance. This has encouraged the development of concrete mixtures which qualify to be classified as HPC but may not be durable under severe environmental conditions.

For example, for use in highway structures, Goodspeed et al.[13] proposed several HPC mixtures typically made with a high early strength cement, and cement contents of the order of 400 kg/m^3 (670 lb/yd^3) or more. Therefore, unless special measures are taken, such concrete mixtures would be vulnerable to cracking from thermal, autogenous, and drying shrinkage stresses.[14] Clearly, one can jeopardize the service life of a concrete structure if driven by the construction timetables alone. In structural design, therefore it is advisable to consider the life-cycle cost rather than the initial cost of the structure. Also, there is a need to re-examine the issue of whether or not concrete mixtures of questionable long-term durability should be marketed as high-performance products.

HPC technology is being successfully used for the construction of numerous off-shore structures and long-span bridges throughout the world.[15] Langley et al. describe several types of HPC mixtures used in the construction of structural elements for the 12.9 km (8.0 mi) long, Northumberland Strait Bridge in Canada.[16] The concrete mixture for the main girders, pier shafts, and pier bases contained 450 kg/m^3 (760 lb/yd^3) of a blended silica-fume cement, 153 L/m^3 (260 lb/yd^3) water, 160 mL/m^3 (4 oz/yd^3) air-entraining agent, and 3 L/m^3 (75 oz/yd^3) superplasticizer. Typically, fresh concrete mixtures showed 200 mm (8 in.) slump and contained 6.1 percent air. The compressive strengths of hardened concrete samples at 1, 3, and 28 days were 35, 52, and 82 MPa (5100, 7500, and 12,000 psi), respectively. For approach pier foundations and other mass concrete elements, the HPC contained a mixture of 307 kg/m^3 (518 lb/yd^3) silica-fume blended cement and 133 kg/m^3 (224 lb/yd^3) fly ash. At a similar water content (159 mL/m^3 [270 lb/yd^3]) but a considerably reduced dosage of air-entraining agent (88 mL/m^3 [2 oz/yd^3]) and superplasticizer (1.05 L/m^3 [27 oz/yd^3]), the fresh concrete mixture gave 185 mm (7 in.) slump and 7 percent air content. The compressive strengths of hardened concrete at 1, 3, 28, and 90 days were 10, 20, 50, and 76 MPa (1450, 2900, 7300, and 11,000 psi) respectively. Both concrete mixtures showed extremely low permeability, as measured by the CANMET Water Permeability Test and the AASHTO T 277 Rapid Chloride Permeability Test. With HPC structures, Langley et al place a great emphasis on site laboratory testing and quality assurance.[16]

Another development in the HPC field is in high-performance lightweight concrete (HPLC). Relative to steel, the structural efficiency of normal concrete is quite low when judged from strength/weight ratio. This ratio is considerably enhanced in the case of superplasticized, high-strength concrete mixtures, and can be further enhanced by full or partial replacement of normal-weight aggregate with microporous, lightweight aggregate particles. Depending on the aggregate quality, high-performance lightweight concrete (HPLC) with a density of 2000 kg/m^3 (3400 lb/yd^3) and compressive strengths in the 70 to 80 MPa (10,000 to 12,000 psi) range has been commercially produced for use in structural members. According to Bremner and Holm, HPLC has been used in off-shore platforms, both fixed and floating, in Australia, Canada, Japan, Norway, and the United States.[17] Furthermore, according to the authors, due to the high interfacial bond strength between the cement paste and aggregate, HPLC remains virtually impermeable to fluids and is therefore highly durable in aggressive environments.

The superior adhesive quality of superplasticized concrete made with cement blends containing 10 to 15 percent or even a higher content of silica fume makes them well suited for repair and rehabilitation of concrete structures by the wet-mix shotcreting process. This is another area of growing HPC applications. Morgan has reviewed new developments in shotcreting with several examples of shotcrete repair of infrastructure in North America.[18]

Self-compacting concrete

Shortage of skilled labor and savings in construction time were the primary reasons behind the development and increasing use of self-compacting concrete in Japan. The composition, properties, and applications of self-compacting, superplasticized concrete mixtures are described in several recently published Japanese papers.[19-23] Note that some authors prefer to use the term, "self-levelling concrete," instead of self-compacting concrete.

According to Nagataki, the successful development of superplasticized, anti-washout, underwater concrete mixtures in West Germany during the 1970s provided the impetus for the subsequent development of self-compacting, high-fluidity concrete in Japan in 1980s.[5] In both cases, high fluidity and segregation resistance were obtained by the simultaneous use of a superplasticizing admixture and a viscosity-increasing admixture. Note that cellulose and acrylic water-soluble polymers are widely used as main components of viscosity-increasing admixtures. The viscosity of self-compacting concrete mixtures is greatly influenced by their powder content. A high content of cement can cause thermal cracking in some structures. Therefore, it is a common practice to use substantial amounts! of mineral admixtures, such as fly ash, ground granulated blast-furnace slag, or limestone powder. Nagataki reported that 290,000 m^3 (380,000 yd^3) of a self-compacting concrete mixture, containing 150 kg/m^3 (250 lb/yd^3) limestone powder and a superplasticizing admixture, were used for the construction of the two anchorage bodies of the Akashi-Kaikyo Bridge system in Japan. The anchorage consisted of densely-arranged reinforcement and cable frame congested with steel. In another application, high-fluidity concrete with extremely low *w/cm* was used for bottom-up concreting of a concrete-filled steel column without compaction.[6]

In France, the ready-mixed concrete industry is using self-compacting concrete as a noise-free product that can be used around the clock in urban areas. Due to noise reduction, labor savings, and longer life of steel molds, the precast concrete products industry is also investigating the use of the material.

Technologies for prolonging service life

Corrosion of reinforcing steel is implicated in a majority of deteriorating concrete structures. In addition to HPC described previously, there are several recently developed technologies that are being pursued to address this problem, namely the use of corrosion-inhibiting admixtures, epoxy-coated steel reinforcement, cathodic protection, and application of protective coatings on the concrete surface. These are briefly reviewed:

Corrosion-inhibiting admixtures: Berke and Weil presented a comprehensive review of corrosion-inhibiting admixtures in concrete.[24] Gaidis and Rosenberg showed that the addition of 2 percent calcium nitrite by mass raised the threshold chloride concentration to levels that were high enough to inhibit the corrosion of steel.[25] The anodic inhibitors, such as calcium nitrite, function by minimizing the anodic reaction promoted by the chloride ions. This is the reason that the amount of nitrite ions present relative to the amount of chloride ions in the vicinity of the steel surface determines whether or not corrosion protection will be achieved. It was proposed that protection from corrosion is obtained if the chloride/nitrite ratio does not exceed 1.5.[25] Nmai et al. believe this to be a serious limitation of anodic inhibitors including calcium nitrite.[26] The authors investigated an amino-ester which offers protection by forming a protective film at the steel surface in addition to reducing the ingress of chloride ions into the concrete cover. In a preliminary investigation on pre-cracked concrete beams ponded with 6 percent NaCl solution, the amino-ester containing admixture, at a dosage of 5 L/m^3 (130 oz/yd^3) of concrete, gave better protection against corrosion than the calcium nitrite inhibitor at a dosage of 20 L/m^3 (520 oz/yd^3). It seems more research is needed to clearly establish the limitations and long-term effectiveness of various corrosion-inhibiting admixtures.

Epoxy-coated reinforcing steel: In the United States, epoxy-coated reinforcement (ECR) was used in bridge decks during the 1970s and in parking ramps during the 1980s. It is estimated that the United States has approximately 27,000 bridge decks with ECR, mostly located in regions where deicing chemicals are used. In some cases, for instance the Seven Mile Bridge in Key West, Fla., unsatisfactory performance of ECR concrete was reported. Problems with early ECR concrete structures were generally attributed to improper epoxy coatings, epoxy debonding, inadequate cover, or other construction errors. A 1993 survey of 18 to 20 year old ECR bridge decks in 14 states, where the structures were exposed to cycles of freezing and thawing, showed that little or no maintenance was needed since installation of the structures.[27] However, a 1996 survey of parking garages containing epoxy-coated reinforcement in concrete showed that only 60 percent of the respondents indicated performance to expectation.[27] According to the Concrete Reinforcing Steel Institute, industry users feel that the use of epoxy-coated steel in parking garages adds 10 to 15 years of protection before corrosion starts. Apparently, it is too early to answer the question whether or not the use of ECR offers long-term corrosion protection in a cost-effective manner.

Cathodic protection of reinforced concrete: Cathodic protection techniques involve the suppression of current flow in the galvanic cell either by external supply of current in the opposite direction or by using sacrificial anodes. The externally-applied current method is commonly used for corrosion protection in chloride-contaminated reinforced concrete structures. Researchers including Rasheduzzafar have reported the degradation of bond between steel and concrete probably due to a buildup of sodium and potassium ions which results in the softening of concrete at the steel-concrete interface.[28] The degradation of steel-concrete bond was found to increase with the increase in the impressed current density and chloride content of concrete.

Surface coatings: According to Swamy and Tanikawa, surface or barrier coatings when applied to the concrete surface to protect it from external attack have a long but checkered history of effectiveness.[29] This is due to the availability of a wide range of barrier coatings, and the fact that coatings of similar generic types may vary considerably in diffusion characteristics. The authors used a highly elastic acrylic rubber coating, which showed excellent engineering properties and a very low diffusion coefficient. The effectiveness of this coating to preserve concrete durability including the control of deleterious alkali-silica expansion in concrete was clearly demonstrated. More research is needed to establish the long-term performance and cost-effectiveness of surface coatings.

High volume fly ash and slag concretes

The current annual production of fly ash in the world is of the order of 450 million tonnes. Only about 25 million tonnes or 6 percent of the total available fly ash is being used as a pozzolan in blended portland cements or in concrete mixtures. The environmental friendliness of concrete can be considerably enhanced if the rate of fly ash utilization by the concrete industry is accelerated in the ash producing countries. Countries where large amounts of blast-furnace slag is available as a by-product can similarly benefit from the use of high volumes of granulated slag either as a concrete admixture or as an additive in the manufacture of portland slag cements. Examples of high volume fly ash and slag concretes are given here:

Structural concrete: Studies by Malhotra[30] with superplasticized concrete mixtures have shown that, when the *w/cm* is limited to 0.3 or less, up to 60 percent cement can be replaced with a Class F or Class C fly ash (ASTM C 618) to obtain excellent strength and durability characteristics. For instance, a test mixture containing 150 kg/m^3 (250 lb/yd^3) ASTM Type I cement, 200 kg/m^3 (340 lb/yd^3) ASTM Class F fly ash, 102 kg/m^3 (170 lb/yd^3) water, 1220 kg/m^3 (2100 lb/yd^3) coarse aggregate, 810 kg/m^3 (1400 lb/yd^3) fine aggregate, and 7 L/m^3 (190 oz/yd^3) superplasticizer gave 8, 55, and 80 MPa (1200, 8000, and 12,000 psi) compressive strengths at 1, 28, and 182 days, respectively. From extensive laboratory tests,[30,31] it was concluded that the Young's Modulus of elasticity, creep, drying shrinkage, and freezing and thawing characteristics of high volume fly ash (HVFA) concrete are comparable to normal portland cement concrete. It is noteworthy that high volume fly ash concretes showed exceptionally high resistance to water permeation and chloride-ion penetration. These findings are of considerable importance from the standpoint of durability of structures including control of corrosion of reinforcing steel in concrete exposed to chloride environments. Therefore, HVFA superplasticized concrete may turn out to be the best value-added use of fly ash in the construction industry.

> **"It is too early to predict the future of corrosion-inhibitors, epoxy coated reinforcing bars, surface coatings, and cathodic protection technology... their *high cost* and *low environmental friendliness* would clearly be a major disadvantage."**

Roller-compacted concrete dams: Since the 1980s, roller-compacted concrete (RCC) has been accepted worldwide as the most rapid and economical method for the construction of medium height dams. According to Dunstan, until the end of 1992 approximately 100 RCC dams had been built in 17 different countries.[32] The high paste type RCC mixtures typically contain 250 kg/m^3 (420 lb/yd^3) cementitious material of which 70 to 80 percent is a pozzolan. Fly ash has been used as a pozzolan in most RCC dams. The Upper Stillwater Dam in the United States required 1.24 million m^3 (1.61 million yd^3) of concrete containing 79 kg/m^3 (130 lb/yd^3) portland cement and 173 kg/m^3 (292 lb/yd^3) fly ash. In all, over 200,000 tonnes of low calcium fly ash from six different power plants was used. Large volumes of pozzolanic materials are needed for the Zungeru Dam in Japan which contains 5 million m^3 (6.5 million yd^3) RCC, and the 217 m (700 ft) high Longton Dam in China will contain 7.5 million m^3 (10 million yd^3) RCC. Further, according to Dunstan, even nonstandard fly ash is being successfully used as a component of RCC mixtures.[32] For instance, the RCC mixture for the construction of 95 m (310 ft) high Platanovryssi Dam in Greece contains 35 kg/m^3 (59 lb/yd^3) portland cement and 250 kg/m^3 (420 lb/yd^3) of a fly ash which has an unusually high calcium content (42 percent total CaO). The fly ash is generated from thermal power stations using lignite as fuel, and was pretreated (pulverized and hydrated) before use.

Concrete pavements for highways: According to Golden, approximately 70 percent of the low volume highways and local access roads in the United States require upgrading.[33] Considering the cost savings resulting from the replacement of cement with high volumes of fly ash, the Electric Power Research Institute (EPRI) funded several demonstration projects. In North Dakota, during the summers of 1988 and 1989, 20,000 m^3 (26,000 yd^3) of a 200 mm (8 in.) thick concrete pavement was constructed with "pozzocrete," which is a 0.43 *w/cm*, air-entrained concrete mixture containing 100 kg/m^3 (170 lb/yd^3) portland cement and 220 kg/m^3 (371 lb/yd^3) high calcium fly ash. Demonstration projects in Kansas have successfully used both low calcium and high calcium fly ashes in concrete pavement mixtures (10 to 20 percent fly ash by mass of concrete). An innovative feature of this project was the utilization of crushed concrete from the old pavement as a source of coarse aggregate in the concrete mixture for the new pavement.

Base courses and embankments: High volume fly ash and bottom ash applications in highway construction may include soil stabilization, pavement base courses, embankments, and road shoulders. According to Golden, in 1989 more than 350,000 tonnes of fly ash were used for the construction of a highway embankment in Pennsylvania.[33] In Georgia, cement treated fly ash mixtures have been used as base courses in highway test sections. In Michigan, high carbon fly ash is being used at the rate of 300,000 tonnes per year for the construction of base courses and road shoulders.

High volume slag cement: Approximately 100 million tonnes of blast furnace slag are produced every year in the world. Its utilization rate as a cementitious material is quite low because, in many countries, only a small portion of the slag is available in the granulated form which is cementitious. Although blended portland cements containing up to 65 percent granulated slag are permitted according to ASTM standard specifications, usually the slag content of commercial cements does not exceed 50 percent.

Recent work by Lang and Geiseler on a German blast furnace slag cement (405 m^2/kg [220 yd^2/lb] specific surface) containing 77.8 percent slag showed that excellent mechanical and durability characteristics were achieved in superplasticized concrete mixtures with 455 kg/m^3 (767 lb/yd^3) cement content and 0.28 *w/cm*.[34] The compressive strengths at ages 1, 2, 7, and 28 days were 13, 37, 58, and 91 MPa (1900, 5400, 8400, and 13,000 psi), respectively. The concrete showed good resistance to carbonation, penetration of organic liquids, freezing and thawing cycles (without air entrainment), and salt scaling.

Recycled concrete aggregate

For a variety of reasons, reuse of concrete waste by the construction industry is becoming increasingly important. This is reflected in several research papers from different countries which were presented at a special session on concrete for environmental enhancement at a recent international conference, “Concrete in the Service of Mankind,” held in Dundee, Scotland. In addition to environmental protection, conservation of natural aggregate resources, shortage of waste disposal land, and increasing cost of waste treatment prior to disposal are the principal factors responsible for growing interest in recycling concrete waste as aggregate.

According to Hendriks, presently the European Union countries produce 200 million tonnes of building and demolition waste every year, which is expected to double in 10 years.[35] In the Netherlands where waste recycling has become a growth industry since 1970s, 60 percent of the demolition waste is reused. Uchikawa and Hanehera estimated that 29 million tonnes, which is one-third of the 86 million tonnes of the construction waste produced in Japan in 1992, consisted of concrete rubble.[36] Twelve million tonnes was recycled as road-base aggregate; the rest was disposed. Saeki and Shimura reported the satisfactory performance of recycled concrete aggregate as a road-base material in cold regions.[37] In the United States, in 1983, deteriorated concrete from a 9 km (6 mi) long freeway pavement in Michigan was crushed, and the rubble was used as aggregate for concrete that was needed for the construction of the new pavement.[8]

The end-use of the aggregate recovered from concrete waste depends on its cleanness and soundness, which are controlled by the source of origin of the rubble and the processing technology. Aggregate recovered from surplus fresh concrete in precasting yards and ready-mixed concrete plants is generally clean and similar in properties to the virgin aggregate. Concrete rubble from demolition of road pavements and hydraulic structures requires screening to remove the fines. Many laboratory and field studies have shown that the size fraction of the concrete rubble corresponding to coarse aggregate can be satisfactorily used as a substitute for natural aggregate. A comparison of properties of concrete from natural aggregate and the recycled concrete aggregate shows that the latter would give at least two-third of the compressive strength and the elastic modulus of natural aggregate.[8]

Demolition wastes from buildings are more difficult to handle. The concrete is usually contaminated with deleterious constituents, such as wood, metals, glass, gypsum, paper, plastics, and paint. In combination with selective demolition of building components, such wastes can be handled in a cost effective way by processing into a number of subflows, which can be recycled separately. Evidently, due to the processing cost, at times the recycled concrete aggregate from building rubble may be more expensive than natural aggregate. However, this situation will rapidly change as the natural sources of good aggregate become scarce and the alternative waste disposal costs are included in the economic analysis.

Cost-benefit analysis

There is not much published information on materials and

Table 1 — Suggested ratings for recent advancements in concrete technology

Identification of the technology	Complexity of the technology	Initial cost of materials and construction	Life-cycle cost	Environmental friendliness of the product	Future impact on the concrete industry
Macro-defect-free cement pastes and mortars	High	High	High	Poor	Negligible
Chemically-bonded ceramics	High	High	Unknown	Poor	Negligible
Reactive powder mortars	High	High	Unknown	Poor	Negligible
Superplasticized, concrete with or without silica fume	Moderate	Moderate	Low	Moderate	Moderate
Self-compacting concrete	Moderate	Moderate	Unknown	Moderate	Moderate
Superplasticized, high-volume fly ash concrete	Low	Low	Low	Excellent	High
Superplasticized, high-volume slag concrete	Low	Low	Low	Excellent	High
Corrosion-inhibitors	Moderate	High	Unknown	Poor	Unknown
Epoxy-coated reinforcement	High	High	High	Poor	Unknown
Surface coatings for concrete	High	High	High	Poor	Unknown
Cathodic protection of the structure*	High	High	High	Poor	Unknown

*This technology has proven to be effective for extending the service life of chloride-contaminated reinforced-concrete structures in moist environment. If the concrete can be completely dried, and kept dry during the remaining service life, it would be a less expensive alternative.

construction costs. Unpublished reports may provide some useful data; however, costs vary considerably from one country to another, and even within a country. Also, due to insufficient experience, there are no hard data on the cost-benefit analysis of technologies that have been recently developed for the enhancement of service life of reinforced concrete structures exposed to aggressive environmental conditions.

Gerwick made an attempt to examine the economic aspects of the concrete durability problem.[38] Comparing the relative cost of mitigating measures commonly recommended for controlling the deterioration of concrete due to the corrosion of steel reinforcement (as a percentage of the first cost of the concrete structure, based on 1994 prices in Western countries), the following conclusions can be drawn from Gerwick's data:

- The use of fly ash or slag as a partial replacement for portland cement involves no increase in cost. It may actually result in a lower cost;
- Lowering the *w/cm* with a superplasticizer increases the cost by 2 percent. The cost increase will be 5 percent if silica fume is also used;
- The use of a corrosion-inhibiting admixture or epoxy-coated reinforcement increases the cost by 8 percent; using both will increase the cost by 16 percent; and
- The use of external coatings for concrete or cathodic protection of the structure requires 20 to 30 percent cost augmentation.

Evaluation of recent advancements

Any exercise in technology assessment to judge the impact of recent technological advancements on the concrete industry as a whole will have to be subjective. The author has designed an arbitrary rating system to evaluate each advancement in the following categories: complexity of the technology, initial cost of materials and construction, life-cycle cost, environmental friendliness of the product, and future impact on the concrete industry as a whole. Relative grades of low, moderate, and high are assigned to each technology in all the five categories. From the tabulated results shown in Table 1, the following conclusions can be drawn:

1. Due to complex processing technologies, high cost, and low environmental friendliness of the products, it appears that macro-defect free cements, chemically-bonded ceramics, and reactive powder mortars will have a negligible impact on the concrete industry as a whole.
2. Superplasticized concrete mixtures with or without silica fume and self-compacting concretes will continue to have a niche in the concrete industry. Due to stickiness and high autogenous shrinkage, these concretes require special care in finishing and curing and, therefore, are expected to have only a moderate impact on the industry.
3. Due to simplicity of the technology, low initial cost, high durability, and high environmental friendliness of the product, superplasticized high volume fly ash or slag concrete is expected to have a high impact on the concrete industry. Considerable research and development is expected in the area of ternary blends containing portland cement, silica fume or rice-husk ash, and large volumes of fly ash or slag.
4. It is too early to predict the future of corrosion-inhibitors, epoxy coated reinforcing bars, surface coatings, and cathodic protection technology. When compared to high volume fly ash or slag concretes, their high cost and low environmental friendliness would clearly be a major disadvantage.

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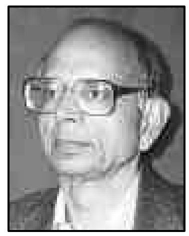

P. Kumar Mehta is Professor Emeritus of Civil Engineering, University of California, Berkeley, Calif., retiring recently after 36 years on the faculty there. A Fellow of ACI, he has authored numerous papers on the properties of concrete and cementitious building materials. At the recent convention in Chicago, Ill., he was presented with ACI's Construction Practice Award for a July 1997 article, published in *Concrete International*, on concrete durability issues for the 21st Century.