Concrete Technology for Sustainable Development

by P. Kumar Mehta

With growing industrialization and urbanization, there is a corresponding growth in world demand for clean air and water, waste disposal, safe and rapid transport of people and goods, residential and industrial buildings, and sources of energy. While humans have used many kinds of construction materials since antiquity, portland cement concrete has clearly emerged as the material of choice for modern infrastructure needs in the 20th century. It is not surprising, therefore, that the concrete industry today is the largest consumer of natural resources such as water, sand, gravel, and crushed rock. According to one estimate, the concrete industry is currently consuming natural aggregates at the rate of approximately 8 billion tonnes every year. The manufacture of portland cement, which is the commonly used binder for modern concrete mixtures, also requires large amounts of natural materials, as described as follows.

The world consumption of portland cement has risen from less than 2 million tonnes in 1880 to 1.3 billion tonnes in 1996. Besides other raw materials, each tonne of portland cement requires approximately 1.5 tonnes of limestone and considerable amounts of both fossil fuel and electrical energy. Also, it is well-known that the production of each tonne of portland cement clinker is accompanied by the release of approximately 1 tonne of carbon dioxide, which is one of the gases primarily responsible for global warming. About 7% of the world's carbon dioxide emission is attributable to the portland cement industry.[1] According to the recently concluded Kyoto Protocol to the United Nations Framework Convention on Climate Change, many countries have accepted legally binding commitments to reduce the emission rates of gases contributing to global warming by the year 2010.

Evidently, there is a rapidly growing public concern that we can no longer continue to ignore the issues of environmental pollution problems on the one hand, and the unrestricted depletion of natural resources on the other. A satisfactory resolution of this concern is essential. If these issues remain unresolved, they present a clear threat to our standard of living and, more importantly, to the entire fabric of life support systems on which our planet is dependent. We find ourselves approaching a milestone in human history with the advent of the new millennium. As we enter this new century, we might be wise to look back and reflect upon lessons that can be learned from the past, and construct a vision for the future. To advance the goal of sustainable development, obviously a judicious balance will have to be struck between the two equally important needs of society, namely, the infrastructure to support an acceptable standard of living for most of the world's inhabitants, and the protection of our environment. As the most important player in infrastructural development and a major consumer of limited natural resources, the concrete industry has an obligation to incorporate environmentally sound technologies.

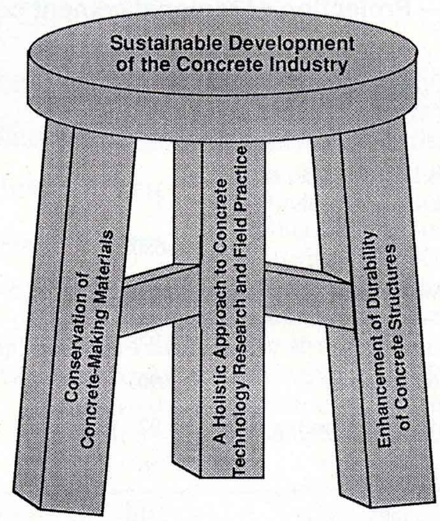


Fig. 1 — Foundation of an environmentally friendly technology for sustainable development of the concrete industry.

In this article, essential elements are identified that, in the author's opinion, are crucial to lay the foundation upon which the structure of an environment-friendly concrete technology can be built. The three essential elements of the foundation are: conservation of concrete-making materials, enhancement of durability of concrete structures, and a paradigm shift from reductionistic to a holistic approach in concrete technology research and education. This concept is illustrated in Fig.1.

For the purpose of discussion, the three elements in Fig. 1 are shown as independent of each other. In reality, they are interrelated and interdependent. For example, the enhancement of concrete durability also conserves natural resources and the holistic approach discussed as follows is necessary to address these elements.

The opinions expressed in this article are not necessarily those of the American Concrete Institute. Reader comment is invited.

Highlighting the problem

Driven by demographic pressures and fueled by technology, the earth's ecosystems are in crisis. To support more and more people and to provide better living conditions for most, the engines of the industry convert raw materials into consumer products at an ever-increasing rate. Environmental pollution as a byproduct of industrial activity is not a new problem. However, the environmental crisis we now confront is quantitatively and qualitatively different from anything faced before, simply because so many people have been inflicting damage to the world's ecosystem during the present century that the system as a whole — not simply its various parts — may be in danger. According to Gordon and Sampat in the 1999 World Watch Institute Report, an extraterrestrial observer might logically conclude that the conversion of raw materials into waste is the real purpose of human activity on the planet Earth.

Table 1 — Projection of regional cement consumption, million tonnes*

Area	Year		
	1994	2000	2005
Europe, including countries of former Soviet Union	313	393	432
Asia	680	853	1000
Middle East	65	79	82
Africa	63	71	77
North America	90	118	142
South and Central America	92	118	142
Miscellaneous	7	9	10
Total	1310	1625	1835

* Adapted from: *World Cement*, V. 27, No. 5. May 1996.

Another issue of considerable importance for the future is the large disparity in the standard of living in different parts of the world. We are divided into two worlds existing side by side, and both are intent upon exploiting the earth's natural resources. The first world enjoys a high standard of living and consists of the people in North America, Western Europe, and Japan, who comprise about 10% of the world's population but account for about 70% of the total energy consumption. These economies are driven by consumerism and generate considerable waste and pollution on a per capita basis. The people in Asia (except Japan), Africa, and South America, numbering almost five billion, form the second world. For a variety of reasons, including high rates of population growth, these latter countries are less industrially developed and have a much lower standard of living.

Judging from the number of ongoing large infrastructure projects in Western Europe, North America, and Japan, it is obvious that the industrially-advanced world is not slowing down its use of the earth's limited natural resources. At the same time, the world of less developed countries has greatly accelerated the pace of industrialization in pursuit of a better life for the poor masses. It is not difficult to imagine the end result of this process: the continuation of high rates of consumption of natural resources on the one hand, and correspondingly high rates of environmental pollution on the other. Clearly, a global environmental disaster is inevitable unless both the industrially-rich and the industrially-poor worlds share equally in the responsibility to find and adopt technologies for sustainable development.

Defining sustainable development

The 1992 Earth Summit in Rio de Janeiro defined sustainable development as economic activity that is in harmony with the earth's ecosystem. In an ideal world, the best way to ensure sustainable development would be to practice a barter system with the earth's bounty in which humans take as little as possible of the good things and return as little as possible of the bad things. While we may never live up to this golden rule, we can at least try to aim for it in all our economic and industrial undertakings.

Although the glass, paper, plastics, and steel industries have been successfully recycling some of their byproducts back into the manufacturing of new products, this is not possible in the case of every industry. For instance, metallurgical furnaces produce large quantities of slag, and coal-firing power plants produce huge volumes of coal ash. These byproducts cannot be recycled back into the industries which produced them. However, we would be following the spirit of the golden rule if we were able to use the byproducts of one industry as raw materials for some other industries, instead of disposing them in landfills and ponds. This recycling or "industrial ecology" is already increasingly being practiced by the cement and concrete industries. Much more, however, needs to be done.

Concrete technology for sustainable development

We have identified a foundation comprising at least three elements that are necessary to support the structure of an environment-friendly concrete technology for sustainable development (Fig. 1). These elements are discussed individually as follows.

Conservation of concrete-making materials

Aggregates, cement, and water are the primary components of concrete. It is possible to conserve large amounts of each of these resources by the adoption of environment-friendly technologies described in recent publications. For instance, the published literature contains numerous case histories of successful substitution of natural aggregate with crushed concrete from demolition and construction sites. Recycled water from ready-mixed concrete plants has been satisfactorily used as a substitute for fresh mixing water for concrete. Detailed coverage of this topic is not intended in this article. However, on the matter of portland cement conservation, which is of vital importance, the author would like to cite two paragraphs from an earlier paper as follows.[2]

The goal of sustainable development for the cement and concrete industries can be reached if we make a serious effort toward complete utilization of the cementitious and pozzolanic byproducts produced by power plants and metallurgical industries. According to Manz,[3] in 1992, 500 million tonnes of coal ash were produced and only 32 million tonnes were used as a pozzolan by the cement and concrete industries, which is approximately 7% of the total available ash. The current annual production of coal ash is estimated to be approximately 650 million tonnes, of which at least 70%, or 450 million tonnes, is fly ash or fine ash that is generally suitable for use as a pozzolan.

The worldwide yearly rate of consumption of fly ash today by the cement and concrete industries is estimated to be about 35 million tonnes, which is dismally low. Another byproduct that is useful for cement substitution is iron blast furnace slag. Although the world production of this slag is approximately 100 million tonnes per year, its utilization rate as a cement substitute is still low because, in many countries, only a small portion of the slag is processed into the cementitious form.

> "The goal of sustainable development for the cement and concrete industries can be reached if we make a serious effort toward complete utilization of the cementitious and pozzolanic byproducts produced by thermal power plants and metallurgical industries."

The author[2] was surprised to make an interesting discovery that relatively huge amounts of disposable coal ash and iron blast furnace slag happen to be available in precisely those countries that would require large amounts of cement in the future. For instance, China and India together produce about 200 million tonnes of coal ash every year. Russia and European countries, mainly Poland, the former Czechoslovakia, Romania, Germany, Spain, and the United Kingdom produce approximately 250 million tonnes of coal ash per year. Also, at least 50 million tonnes of the total yearly production of 100 million tonnes of blast furnace slag comes from China, India, and Europe. At the same time, note that nearly 440 million tonnes of the total projected increase in the cement consumption by the year 2005 is expected from these countries (Table 1). It should be immediately obvious that, if we can find ways to use all or most of the available coal ash and iron blast furnace slag, either in the form of blended portland cement or as mineral admixtures in concrete, we would be able to meet the projected cement demand in the year 2005 without any increase in the present capacity of portland cement clinker production. A sustainable development of the cement and concrete industries, as defined previously, can thus be assured. Considering the additional ecological benefits described as follows, it is hard to imagine a better solution to the problem.

Nearly 90% of the coal ash and metallurgical slag produced today end up either in low-value applications such as landfills and road bases, or simply disposed of by ponding and stockpiling. Disposal in this manner is not only wasteful but also harmful to human health because these materials contribute to land, air, and groundwater pollution. These byproduct materials generally contain toxic metals. The concrete industry provides a preferred vehicle for their use/disposal because most of the harmful metals can be immobilized and safely incorporated into the hydration products of cement. In fact, owing to its large size, the concrete industry is probably the ideal home for safe and economical disposal of millions of tonnes of byproducts. Based on a study by Schiessl and Hohberg,[4] Fig. 2 shows the excellent environmental compatibility of a mortar made with a cement-fly ash mixture. In a realistic leaching test (tank test), the authors reported that only 0.09 mg/kg zinc and 0.15 mg/kg chromium were leached from a cement-fly ash mortar when the total amounts of the metals added to the mortar were 185 mg/kg and 53 mg/kg, respectively. When scaled up to large concrete members that have much smaller surface-to-volume ratios, these numbers would be insignificant.

Given the overwhelming advantages that are possible from large-scale cement replacement by pozzolanic and cementitious byproducts, is it really possible to accelerate their use in the cement and concrete industries, as advocated here? In the earlier paper by the author,[2] the major obstacles preventing high rates of utilization of industrial byproducts in concrete, suggestions for overcoming these obstacles, and case histories of high-volume fly ash use are discussed in detail. Field applications of high-quality structural concrete, with up to 60% cement replacement by ASTM Class F or Class C fly ash, are reported by Malhotra,[1] and Langley and Leaman.[5] Examples of roller-compacted concrete dams

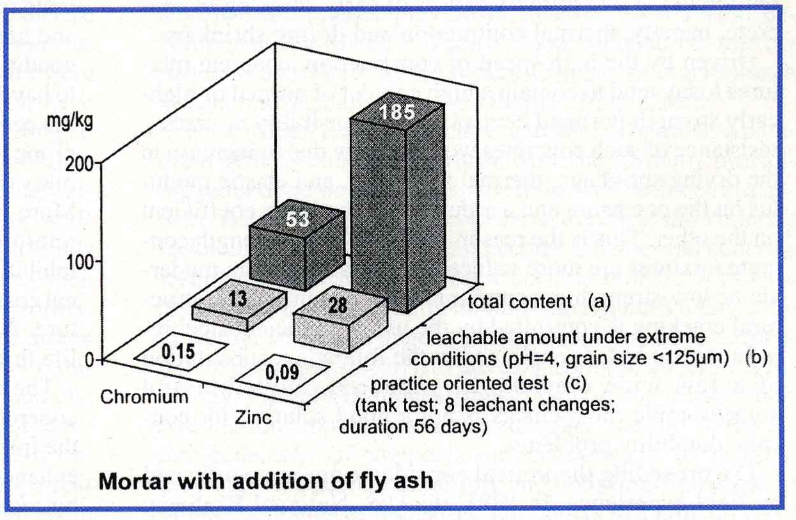


Fig. 2 — Investigation of a specimen from a mortar with the addition of fly ash; comparison of different leaching methods.[4]

and concrete pavements for highways with 70 to 80% cement replacement of fly ash, even nonstandard fly ash, are cited by the author in an earlier paper.[6]

Enhancement of durability of concrete structures

As stated above, the earth's natural resources are conserved when the service life of a manufactured product is prolonged. Recently, numerous materials and methods have been developed for enhancement of durability of concrete structures. Due to the high cost of materials and complex technologies involved, they have found limited applications. Ordinary concrete is the material of choice for construction because it is a relatively inexpensive product of simple technology. The challenge, therefore, lies in making the ordinary concrete a highly durable, high-performance building material for future structures.

It is generally known that the major causes of deterioration of reinforced concrete structures are the corrosion of reinforcing steel, exposure to cycles of freezing and thawing, alkali-silica reaction, and sulfate attack. From a review of case histories of concrete degradation, the author[7] developed a holistic approach encompassing the major causes of concrete deterioration. This approach is based on field experience showing that, with every one of these four causes of concrete deterioration, a high degree of water saturation is a prerequisite to the mechanisms responsible for expansion and cracking of concrete. Therefore, the watertightness of concrete, which is its first line of defense against a hostile environment, must somehow become breached before the material is seriously damaged. Data indicate that, compared to other properties, the integrity or soundness of concrete, i.e., the freedom from cracking, is closely related to concrete durability. A comprehensive report by Burrows[8] has conclusively shown that modern concrete construction practice does not pay adequate attention to the two primary causes of early cracking in concrete, namely, thermal contraction and drying shrinkage.

> "...relatively huge amounts of disposable coal ash and iron blast furnace slag happen to be available in precisely those countries that would require large amounts of cement in the future."

Driven by the high speed of construction, concrete mixtures today tend to contain a high content of normal or high-early strength portland cement. The extensibility or crack resistance of such concretes would be low due to increase in the drying shrinkage, thermal shrinkage, and elastic modulus on the one hand, and a reduction in the creep coefficient on the other. This is the reason that high-early-strength concrete mixtures are more vulnerable to cracking than moderate or low-strength concrete mixtures. Traditionally, structural cracking is controlled by the use of sufficient steel reinforcement but, as explained in the following, substitution of a few wide cracks with numerous invisible and unmeasurable microcracks is not a good solution for concrete durability problems.

The preceding theoretical considerations are confirmed by field experience. In 1995, the U.S. National Highway Cooperative Research Program conducted a survey of recently built concrete bridge decks. Noting that more than 100,000 bridge decks showed transverse cracks even before a structure was one month old, Rogalla et al.[9] drew the following conclusions:

• A combination of thermal shrinkage and drying shrinkage caused most of the cracks, not traffic loads or vibration during the hardening of the concrete.

• Generally, decks are made of high-strength concrete. These concretes have a high elastic modulus at an early age. Therefore, they develop high stresses for a given temperature change or amount of drying shrinkage, and most importantly, the concrete creeps little to relieve these stresses.

• High-strength concretes typically contain more cement. Therefore, they shrink more and produce higher temperatures during early hydration. Modern cements are apt to cause cracking because they are finer and contain higher sulfate and alkali contents.

In short, according to the holistic approach to concrete deterioration, a well-constituted and properly consolidated and cured concrete will remain essentially watertight as long as the pores and cracks present in the interior do not form an interconnected network of pathways leading to the surface. Structural loads, as well as weathering effects such as exposure to cycles of heating-cooling and wetting-drying, facilitate the propagation of microcracks that normally pre-exist in the transition zone between the cement mortar and coarse aggregate in concrete. This happens during the first stage of the structure-environment interaction. Once the watertightness of concrete has been lost, it can become saturated and harmful ions also can move into the interior. This marks the beginning of the second stage of the structure-environment interaction during which the deterioration of concrete takes place through successive cycles of expansion, cracking, loss of mass, and increase in permeability.

When thermal cracking and durability are of primary concern, experience shows that the most cost-effective solution is the replacement of a part of the portland cement in a concrete mixture with fly ash or slag, while meeting the setting and hardening requirements of the job under given ambient conditions. Concrete mixtures containing fly ash or slag tend to have stronger transition zone (the interfacial zone between the cement paste and particles of coarse aggregate), are less prone to microcracking, and have improved structural durability through prolonged watertightness during service life. More expensive solutions to enhance the service life of a reinforced concrete structure include the use of corrosion-inhibiting admixtures, epoxy-coated reinforcing steel, external coatings for concrete, and cathodic protection of the structure. Also, there is limited data on the extension of service life through adoption of these methods.

The foregoing comments on enhancement of durability of concrete structures are applicable to new construction. In the interest of cost economy and conservation of resources, enhancement of service life of existing concrete structures by repair and rehabilitation should not be ignored. Due to the tremendous growth of the concrete repair industry in recent years, it is not possible to cover the subject in this article. Nevertheless, it may be noted that superplasticized shotcrete containing fly ash and silica fume, external coatings for concrete, and cathodic protection of structures are increasingly being considered for the enhancement of service life of existing concrete structures exposed to severe environmental conditions.

Holistic approach to concrete technology research and education

Among the experienced researchers in the area of concrete durability, there is now an increasing appreciation of the value of a holistic approach to concrete technology research and field practice. As discussed in the following, the prevailing reductionistic approach is, in fact, responsible for many wasteful practices in concrete technology today. According to this approach, all aspects of a complex system can be fully understood and controlled by reducing it to parts and by considering only one part at a time. As a result, specifications and test methods for concrete durability have failed to consider that durability is not an intrinsic property dependent on concrete-making materials and mixture proportions alone. It is a holistic (pertaining to the whole structure) performance criterion that is determined by several other factors, including environmental exposure conditions, structural design, and concrete processing technology.

"...sustainable development has emerged as the key issue for the next century."

On the basis of his wide experience with concrete deterioration due to alkali-silica reaction (ASR), Idorn[10] has put together a very interesting account of the rise and fall of six decades of concrete technology research that, in his opinion, has become gradually infected with reductionistic philosophy and laboratory empiricism. According to Idorn, approximately 40 test methods have been developed during the course of research on ASR, but none of them, including ASTM C 289 and C 227, can establish whether a reactive aggregate will cause harmful or harmless reaction if used in field concrete. In spite of the fact that a harmless reaction has predominated in field practice, the adoption of a no-risk ASR policy in the U.S. has led to rejection of high-alkali cements and many deposits of aggregates that were found to be reactive in laboratory testing. On the other hand, smaller countries like Denmark and Iceland, where low-alkali cements were not available and reactive aggregates were plentiful, have successfully pursued a low-risk ASR policy according to which a pozzolanic admixture (viz., calcined clay or silica fume) was incorporated into concrete containing a high-alkali cement and reactive aggregates. The low-risk ASR policy is clearly holistic because it discourages materials waste and promotes the use of industrial byproducts such as silica fume and fly ash to enhance concrete durability.

Similarly, in a lucid review of alkali-aggregate attack in concrete, Swamy[11] stated, "to attack and cause damage, all three members of the triad must be present, namely, sufficient alkali in the concrete, critical amount of the reactive aggregate, and sufficient moisture." He also observed that, in a moist environment, the swelling pressure of ASR gel is unlikely to create structural distress in a well-designed reinforced concrete member. The economic and ecological implications of Swamy's conclusions are apparent. For example, it is not necessary to reject high-alkali raw materials for cement making, or reactive aggregates for making concrete mixtures, provided the concrete structure remains dry during its service life, and it is properly reinforced. This is a good illustration of a holistic approach to durability that considers climatic conditions and structural design in addition to concrete-making materials, mixture proportions, and processing methods.

A highly controversial topic in concrete technology today is the damage caused by the DEF (delayed ettringite formation) phenomenon. Using the holistic approach, Collepardi[12] has concluded that a high risk of damage due to the DEF would occur only if all three of the following conditions are present: late sulfate release, microcracks in concrete, and exposure to water. Again, the economic and ecological implications of this conclusion are profound. For example, for the production of portland clinker, it is not necessary to stop the use of secondary fuels such as old automobile tires and petroleum coke, which usually contain a high sulfur content. From economic and ecological standpoints, a preferable solution is to reduce the chances of excessive cracking and microcracking, and of subsequent water penetration during the service life of concrete made with a portland cement containing higher than normal sulfate content.

It may be noted that a holistic approach should not be confused with a systems approach, which is commonly practiced in the resolution of complex problems. An integrated approach considering both structural design and structural durability aspects is a good example of a systems approach. However, it is not comprehensive enough to be called holistic. The holistic approach has its roots in the idea that the whole exists before the parts. For instance, the holistic approach would consider society as a whole, and the concrete industry as a part of the whole. Therefore, in addition to providing a low-cost building material, the concrete industry must assume responsibility for other societal needs, for example, conservation of the earth's natural resources and safe disposal of polluting wastes produced by other industries, as discussed previously. In short, if sustainable development is a wheel, and conservation of concrete-making materials and durability are spokes, then the holistic approach to concrete technology is the kingpin of the wheel.

The difficult question is: how can we accomplish a paradigm shift to a holistic approach from the currently prevailing reductionistic practices in the industry? To develop a holistic field practice for the concrete industry, the concrete technology research must first become holistic, and concrete technological research will not become holistic without a major transformation in the mind set that guides today's engineering education in general, and concrete science education in particular. Clearly, to develop a holistic concrete technology, the reform process must begin at the universities. Are the universities providing adequate training to the future generation of engineers and technologists for tackling the issues of concrete durability and pollution-free disposal of large amounts of industrial byproducts in a holistic way?

Judging from the number of courses in concrete technology and engineering education curricula worldwide, the situation seems appalling. For instance, a 1995 survey of civil engineering schools in North America showed that most undergraduates receive only insignificant exposure to cement concrete topics offered as part of a required course on all engineering materials. Less than one-half of the responding institutions offered a full-semester, optional course in concrete technology. Hardly any such courses are offered at the graduate level, and only a few students undertake experimental research on concrete. Obviously, the concrete technology education requires a complete restructuring before it is able to address the pressing needs of society.

Actually, this lack of a holistic approach is a much more serious issue encompassing the entire field of general education today. In a recently published book, Wilson[13] writes: "Most of the issues that vex humanity daily — ethnic conflicts, arms escalation, overpopulation, abortion, environment, endemic poverty, to cite some most persistently before us — cannot be solved without integrating knowledge from the natural sciences with that of the social sciences and humanities. Only fluency across these boundaries will provide a clear view of the world as it really is. . . . A balanced perspective cannot be acquired by studying disciplines in pieces but rather through pursuit of consilience among them."

What is consilience? Consilience is defined as unification of knowledge by linking together facts and insights across disciplines to create a common ground for action. Wilson[13] cites an example to illustrate his point. An adapted version

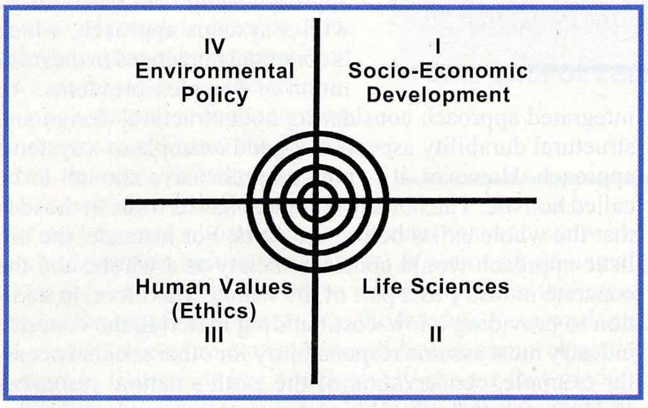


Fig. 3 — Consilience illustrated.[13]

of Wilson's example is shown in Fig. 3. Two intersecting lines are drawn, forming a cross; one quadrant is labeled socioeconomic development, the next life sciences, the next ethics, and the last as environmental policy. According to Wilson, we intuitively think that these four domains are closely connected so that rational inquiry in one informs reasoning in the other three, yet each domain stands apart in the contemporary mind, with its own practitioners, language, modes of analysis, and standards of validation. The result is confusion. Now, if a series of concentric circles is drawn around the point of intersection, it is the ring closest to the intersection (where most real-world problems exist) in which fundamental analysis is most needed, yet virtually no maps exist to guide us. Only in the imagination can we travel clockwise from the recognition of infrastructural needs for socioeconomic development of society to the selection of solutions based on the biological sciences, to ethical issues involved in the pursuit of global social justice, and then to development of a sound environmental policy.

Because governments everywhere are at a loss in identifying the best policies for utilization of natural resources, this demonstrates that sustainable development is not yet a science; it is still a primitive art whose economic, social, and psychological benefits remain wholly unexplored. Wilson[13] says that the time has come to achieve this tour in reality. According to him, how wisely policy is chosen will depend on the ease with which the educated public, not just the intellectuals and political leaders, can think around these and similar circuits, starting at any point and moving in any direction. This evidently requires a holistic approach in public education.

A simplified model for the evolution of technology for sustainable development is shown in Fig. 4. The three circles, with only a little overlapping between them, represent the state-of-the-art. Significant growth of the area occupied by TSD (technology for sustainable development) will occur when there is considerable overlapping between the circles. Of the three circles, efforts are already underway to integrate the socioeconomic-development technologies with a unified scientific base that includes both physical and life sciences. It is the circle representing ethics or human values that needs more attention, because technology, unless tempered with human values, can lead the human race to disastrous consequences.

Conclusion

We do not have to wait for environmental disasters to teach us how to achieve sustainable development. Surely we should be able to envision and then reshape our living on this planet in a way that offers long-term well-being instead of endangering the survival of future generations.

A new century and a new millennium are imminent. This is an appropriate time to consider the future needs of society and how they might affect the concrete industry. Among the forces shaping tomorrow's world are unprecedented population growth, increasing industrialization and urbanization, and threats to the environment from uncontrolled pollution. In short, sustainable development has emerged as the key issue for the next century.

The problem is that sustainable development is still an art whose economic, social, and psychological benefits have yet to be fully explored. A complete restructuring of the public education will be needed in the future to usher in an era of

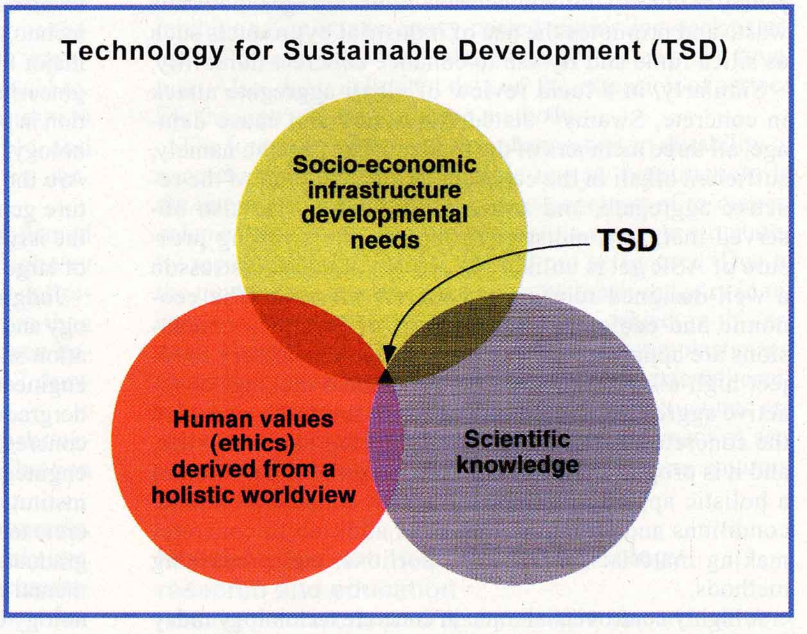


Fig. 4 — Diagrammatic illustration showing the components that must be integrated to evolve technology for sustainable development.

sustainable development. Meanwhile, as the concrete industry is the most important player in meeting the infrastructural needs of our industrializing society, and is therefore the largest consumer of natural resources, we can begin the process of sustainable development through adoption of materials conservation technologies, durability enhancement methods, and pursuit of holistic research and education in concrete technology.

References

1. Malhotra, V. M., "Making Concrete Greener with Fly Ash," *Concrete International,* V. 21, No. 5, May 1999, pp. 61-66.

2. Mehta, P. K., "Role of Pozzolanic and Cementitious Materials in Sustainable Development of the Concrete Industry," *Fly Ash, Slag, Silica Fume and Other Natural Pozzolans*, SP-178, V.M. Malhotra, ed., American Concrete Institute, Farmington Hills, Mich., 1998, pp. 1-20.

3. Manz, O. E., "Worldwide Production of Coal Ash and Utilization in Concrete and Other Products," *Fuel*, V. 76, No. 8, 1997, pp. 691-696.

4. Schiessl, P., and Hohberg, I., "Environmental Compatibility of Cement-Based Building Materials," *Proceedings of the Mario Collepardi Symposium on Advances in Concrete Technology*, 1997, pp. 27-48.

5. Langley, W. S., and Leamen, G. H., "Practical Uses of High-Volume Fly Ash in Concrete Utilizing a Low-Calcium Fly Ash," *Fly Ash, Slag, Silica Fume and Other Natural Pozzolans*, SP-178, V.M. Malhotra, ed., American Concrete Institute, Farmington Hills, Mich., 1998, pp. 545-574.

6. Mehta, P. K., "Advancements in Concrete Technology," *Concrete International*, V. 21, No. 6, June 1999, pp. 69-76.

7. Mehta, P. K., "Durability — Critical Issues for the Future," *Concrete International*, V. 19, No. 7, July 1997, pp. 69-76.

8. Burrows, R.W., "The Visible and Invisible Cracking of Concrete," *Monograph* No. 11, American Concrete Institute, Farmington Hills, Mich., 1999, 78 pp.

9. Rogalla, E. A.; Kraus, P. D.; and McDonald, D. B., "Reducing Transverse Cracking in New Concrete Bridge Decks," *Concrete Construction*, V. 40, 1995, pp. 735-738.

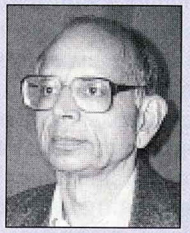
10. Idorn, G. M., *Concrete Progress from Antiquity to the Third Millennium*, Thomas Telford Publishing, London, UK, 1997, 395 pp.

11. Swamy, R. N., "Alkali-Aggregate Reaction: The Bogeyman of Concrete," *Concrete Technology: Past, Present, and Future*, SP-144, P.K. Mehta, ed., American Concrete Institute, Farmington Hills, Mich., 1994, pp. 105-140.

12. Collepardi, M., "A Holistic Approach to Concrete Damage Induced by Delayed Ettringite Formation," *Proceedings of the Mario Collepardi Symposium on Advances in Concrete Technology,* 1997, pp. 373-396.

13. Wilson, E. O., *Consilience, the Unity of Knowledge*, Alfred Knopf Inc., 1998, 325 pp.

Received and reviewed under Institute publication policies.



P. Kumar Mehta is Professor Emeritus of Civil Engineering, University of California, Berkeley, Calif., recently retired after 30 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.