HOLISTIC DESIGN
KEY TO SUSTAINABILITY IN CONCRETE CONSTRUCTION

R. N. Swamy
University of Sheffield

Synopsis

There have been unparalleled advances during the latter half of the last century, to the scientific, engineering and social face of the world, but in that process, the world has also been plunged into several inter-related crises. In the context of the construction industry, these crises can be broadly classified in terms of environment, durability and sustainability. The crises have risen from a number of factors such as technological industrialization, population growth, world-wide urbanization, and uncontrolled pollution and creation of waste. There is now the real danger that the massive, indiscriminate and wasteful consumption of the world's material and energy resources may result in extensive global warming that is hard to reverse. The price for this environmental abuse is the rapid deterioration and destruction of the world's infrastructure, water shortages, environmental disasters, and material/structural deterioration by the forces of nature.

Every crisis experienced in the world has a direct impact on the construction industry, and since the construction industry is closely interlinked with energy, resources and environment, irredeemable environmental degradation can only be prevented by sustainable development of the industry which alone can give hope for a better world and better Quality of Life. This paper advocates a Holistic approach to design and construction integrating all aspects from conceptual design to completion and maintenance during service life.

Introduction

The world at the end of the 20th century that has just been left behind was very different to the world that its people inherited at the beginning of that century. The latter half of the last century saw unprecedented technological changes and innovations in science and engineering in the field of communications, medicine, transportation and information technology, and in the wide range and use of materials. The construction industry has been no exception to these changes when one looks at the exciting achievements in the design and construction of buildings, bridges, offshore structures, dams, and monuments, such as the Channel Tunnel and the Millennium Wheel.

2. There is no doubt that these dramatic changes to the scientific, engineering and industrial face of the world have brought about great social benefits in terms of wealth, good living and leisure, at least to those living in the industrialized nations of the world. But this process of the evolution of the industrial and information technology era has also, however, been followed, particularly during the last four to five decades, by unprecedented social changes, unpredictable upheavals in world economy, uncompromising social attitudes, and unacceptable pollution and damage to our natural environment. In global terms, the social and societal transformations that have occurred can be categorized in terms of technological revolutions, population growth, worldwide urbanization, and uncontrolled pollution and creation of waste. But perhaps overriding all these factors is **globalization** - not merely in terms of economics, technologies and human and community lives - but also with respect to climatic changes and weather conditions as typified by the El Ninos of this world.

Global urbanization - the ripple/domino effect

The infrastructure crisis

3. The unprecedented changes that have occurred in the world and society during the latter half of the last century have placed almost insatiable demands on the construction industry in terms of the world's material and energy resources. Continued population growth and evolutionary industrialization have resulted in an endless stream of global urbanization. It took the world population until the year 1804 to reach the first one billion; yet the increase from 5 to 6 billion has taken just 12 years. It is now estimated that the world's population will increase from 6 billion now to 8 billion by 2036 and 9.3 billion by 2050. More than 95% of this increase will take place in the developing parts of the world. Further, for the first time in human history, about 50% of the world live in and around cities rather than in rural areas. It is estimated that by the end of this year, there will be at least 20 mega cities with 10 million or more inhabitants, and there will be a hundred or more big cities with more than 1 million people, almost all again in the developing nations of the world. This explosion into an urban way of life will continue to demand enormous resources and supply of construction materials required to build the infrastructure - such as housing, transportation, education, power, water supply and sanitation utilities - the basic facilities needed to support life in these mega cities and big cities.

World energy demands

4. The impact of global urbanization and world industrialization is not merely on the demand for construction materials; a more insidious implication is on world energy demands, which again impinges finally on the construction industry. In the present context of the world, some 25% of the world's population live in the industrialized world, and they account for nearly 75% of the global energy consumption. This disproportionate consumption of energy and world resources can be better understood when one considers that whilst, on a world-wide basis, the average energy availability per individual is 2 kW years p.a. (defined as one unit), the average per capita consumption is about 11 units in N. America compared to 0.6 units in China and 0.43 units in South East Asia and Africa [1]! A large proportion of the world's energy budget is spent on the manufacture of materials such as cement, metals and plastics. On an approximate basis, materials consume some 20-25%

of the world's total energy budget. If it is now assumed that a doubling of the present population will entail an increase in the global energy consumption to only double the present level, then the demand for construction materials will place an impossible burden on the environment. Whether fossil fuel and/or wind, water, or nuclear energy will be capable of meeting these needs on a global basis is a different debatable issue, but bearing in mind that the dramatic increase in the demand for power has to be in the developing nations of the world, one can understand and appreciate the complex and vicious interaction in this global scenario of population growth, global urbanization, energy demand and material resources, all of which could contribute to irredeemable environmental degradation.

Global warming and infrastructure destruction

5. The massive and wasteful consumption of a disproportionate share of the earth's material and energy resources by the industrialized nations of the world has resulted in a massive increase in the emission of greenhouse gases. In 1960, CO_2 emission was about 10 billion tonnes. In 1995, this was about 23 billion tonnes excluding those from deforestation and fires. About 4% of the world population produces around 25% of the world's CO_2 emission! Some 60% reduction in CO_2 emission is required to stabilize the earth's eco system and climatic changes. The Kyoto agreement in 1997 was to reduce the CO_2 emission from the developed world by 5% by 2012! The Portland Cement industry accounts for some 5 to 7% of the total global emission of CO_2 [2].

6. The direct and unmistakable consequence of the emission of greenhouse gases is **Global Warming**. Global warming puts more energy into the climate system and increases global storminess resulting in increasing number and intensity of storms, rapid climatic changes, and larger, more frequent, more damaging, extreme and erratic weather events. El Ninos will now occur once in every 2.8 years instead of once in 5 years.

7. Climate will take about 30 years to catch up with the consequences of the extra greenhouse gases already in the atmosphere. Current world weather - rise in sea levels,

global warming, larger deserts, severe droughts, flash floods, and storms and hurricanes - is because of the emissions up to 1968/69. The scale of the environmental pollution in 1999 will be reflected in the climatic reactions in about 2030. The present century, and the first few decades of this century in particular, will therefore bring a catalogue of natural disasters arising from decades of man-made follies.

8. A taste of the frequency of natural disasters that are likely to occur, and of the scale and devastation that they are likely to bring can be obtained by a brief glimpse of the major environmental tragedies that have occurred during the last six months of last year.

March, 2000	-Heavy floods in Mozambique
April, 2000	-Cyclone Hudah in Madagascar.
May, 2000	-Severe drought in Eritrea, Ethiopia, Sudan, Horn of Africa, and Rajasthan in India.
June, 2000	-Storms and flash floods in north of England
	- 95 flood warnings issued by the Environment Agency
	- Catastrophic drought covering most of north and central China
July, 2000	- Heat wave up to 45°C (113°F) and forest fires in southern Europe.
	- Heat wave in Korea.
	- Typhoon Kai-Tak in the Philippines.
August, 2000	- Forest fires ravaging 11 states of western America.
to	- Forest fires in large parts of Spanish Catalonia.
September, 2000	- Fires and heat wave in southern Europe.
	- Drought in Masai land in Kenya.

- Hurricane Debby sweeping several Caribbean islands.
- Super typhoon Bilis in Taiwan.
- Hurricane and floods in Okinawa, Japan.
- Floods, land slides and mud slides in several states in India, Nepal, Bhutan, Bangladesh, Vietnam, Cambodia, the Philippines, China, Italy, Switzerland and the US.
- Floods, hurricanes, hail and snow in the UK.
- Mile-wide hole in North Pole ice.

Apart from the death and devastation that these climatic changes and natural disasters inflict, their greatest impact is on the destruction of the civil engineering infrastructure, and thus on the construction industry. The destruction of property and infrastructure caused by these environmental upheavals is estimated to cost several billions of pounds and it will take many decades to rehabilitate the damage and regenerate acceptable living conditions. In 1998, for example, which is generally considered calm in terms of weather, wind-related storms caused, in the US alone, damage worth $5.5 billion. It is reported that the cost of climate related disasters has doubled every decade from $50 billion in the 1960s when there were 16 disasters to nearly $400 billion in the past ten years, when there were 70 disasters. In the UK, it is estimated that it will cost £95 million a year for 50 years to keep the sea and rivers within existing flood defences.

9. Whilst the ravages brought to the engineering infrastructure of Honduras, Venezuela and, more recently, of Mozambique are still fresh and vivid in our minds, the spectre of droughts, failing rains and water shortages loom large in the background. The difference is that whilst the effects of hurricanes and cyclones are felt quickly and almost instantly, droughts are disasters on a slow fuse. It is estimated that more than half of Europe's freshwater habitat has been destroyed in the past 50 years. More than 85% of the UK lowland rivers and streams are no longer in their natural state mainly due to drainage for intensive farming and urban development. The more recent spectacles of drought and

famine in Ethiopia and Angola, the desiccation of vast areas in Rajasthan and Gujerat in India, and the arid cornland of the US mid-west are indications of the huge problems facing large sections of the human population. The provision of new water supplies and the process of recycling wastewater will be expensive. It is estimated that it will cost the UK as much as £5 billion over the next 30 years to make up for a 20% shortfall in fresh water supplies.

Concrete and the environment

10. How does concrete fit into this complex world scenario of the construction industry? The answers are simple but wide-ranging. Whatever be its limitations, concrete as a construction material is still rightly perceived and identified as the provider of a nation's infrastructure and indirectly, to its economic progress and stability, and indeed, to the quality of life. It is so easily and readily prepared and fabricated into all sorts of conceivable shapes and structural systems in the realms of infrastructure, habitation, transportation, work and play. Its great simplicity lies in that its constituents are most readily available anywhere in the world; the great beauty of concrete, and probably the major cause of its poor performance, on the other hand, is the fact that both the choice of the constituents, and the proportioning of its constituents are entirely in the hands of the engineer and the technologist. The most outstanding quality of the material is its inherent alkalinity, providing a passivating mechanism and a safe, non-corroding environment for the steel reinforcement embedded in it. Long experience and a good understanding of its material properties have confirmed this view, and shown us that concrete can be a reliable and durable construction material when it is built in sheltered conditions, or not exposed to aggressive environments or agents. Indeed, there is considerable evidence that even when exposed to moderately aggressive environments, concrete can be designed to give long trouble-free service life provided care and control are exercised at every stage of its production and fabrication, and this is followed by well-planned inspection and maintenance schemes.

Concrete - why then the tarnished image?

11. Inspite of this excellent known performance of concrete in normal environments, there are two aspects of the material that have tarnished its image. The first relates to the environmental impacts of cement and concrete, and the second, to the durability of the material.

Environmental impacts

12. Engineers cannot afford to ignore the impact of construction technology on our surroundings - and this applies to our environment at a regional, national and global scale. The construction industry has a direct and visible influence on world resources, energy consumption, and on carbon dioxide emissions. Compared to metals, glass and polymers, concrete has an excellent ecological profile. For a given engineering property such as strength, elastic modulus or durability, concrete production consumes least amount of materials and energy, produces the least amount of harmful byproducts, and causes the least damage to the environment. In spite of this, we have to accept that Portland Cement is both resource and energy - intensive. Every tonne of cement requires about 1.5 tonnes of raw material, and about 4000 to 7500 MJ of energy for production. The cost of energy to produce a tonne of cement is estimated to account for 40 - 45% of the total plant production cost. Much more importantly, every tonne of cement releases 1.0 to 1.2 tonnes of CO_2 into the environment by the time the material is put in place. In the world we live in, the use of resources and energy, and the degree of atmospheric pollution that it inflicts are most important.

Deterioration of concrete

13. It is now well established that the record of concrete as a material of everlasting durability has been greatly impaired, for no fault of its own, by the material and structural degradation that has, nevertheless, become common in many parts of the world (3-9). The

major reasons for this apparent fall from grace are numerous - partly out of the perceived (or sometimes planted) image of concrete as a material of enduring quality that needs no maintenance, and as a medium that will not deteriorate; and partly by the assumption that somehow the impermeability of concrete and protection of the embedded steel against external aggressive agencies will be automatically and adequately provided for by the cover thickness and the presumed quality of concrete. Experience has shown that neither can be assumed as a normal and natural consequence of the process of concrete fabrication.

14. The world-wide damage to concrete and concrete structures is best illustrated by the following data. In the UK, for example the total construction industry output in 1995 was about £52 billion, of which some 50% was spent on maintenance, repair and rehabilitation. The amount spent on repair and rehabilitation has risen from about £6.9 billion in 1981 to something in excess of £26.0 billion now. As a specific example, the Midlands link motorway around Birmingham cost £28 million to construct; between 1972-89, £45 million was spent on repairs, and it is now estimated that another £120 million will be required in the next 15 years [10]. The cost of corrosion to the UK economy is estimated at £15 billion per year. In Europe, structural damage repair every year is estimated to cost 1.4 billion euro. The more recent state of the nation report grades the quality of the UK's infrastructure from B (fair) to D+ (poor) with an overall grading of C (average) [11].

15. In the US, the 1998 ASCE Report on America's Infrastructure estimated a five-year total investment need of US $1.3 trillion, just to put back the roads, bridges, dams, drinking water and other infrastructure systems to good serviceable life. The average state of America's infrastructure was given a Grade D - Poor [12, 13]. As a specific example, some 40% of more than 500,000 highway bridges are rated as structurally deficient or functionally obsolete. Some $100 billion is the estimated requirement to eliminate current backlog of bridge deficiencies, and maintain repair levels.

16. It can be readily seen that there is a fundamental problem in the construction industry - with choice of materials, design, construction, maintenance, repair and rehabilitation.

What's wrong with modern Portland Cement?

Changes in the chemistry of cement

17. The experience that even when specific building code requirements of durability in terms of concrete cover and concrete quality are achieved in practice, there is an unacceptably high risk of premature corrosion deterioration of concrete structures exposed to aggressive salt-laden environments, directly points to the fact that Portland Cement concretes are not totally resistant to penetration by aggressive ions, even when the water-cementitious materials (w/cm) ratio is as low as 0.40 (14-19). The strong implication here is that with current design codes, premature deterioration due to steel corrosion is likely to continue. There is thus a need for a fundamental change in thinking about concrete and concrete quality made with Portland Cement (9, 18-21).

18. One of the major reasons for this much lower resistance of modern Portland Cement concrete to penetration by aggressive ions is the gradual but significant changes that have occurred in the chemical composition of Portland Cements during the last four to five decades (21,22). The two major changes in cement composition, and their implications on engineering and durability properties of the resulting concrete can be identified as:

i) A **significant increase in the C_3S/C_2S ratio from about 1.2 to 3.0** resulting in higher strengths at early ages with a lower proportion of strength developed after 28 days . From a design point of view, this implies that structural design strengths can be achieved with lower cement contents and higher water/cement ratios.

ii) A direct result of the changes in this chemical composition of Portland Cement is an **increase in the heat of hydration** evolved, and more importantly, in the **evolution of heat at early ages**. It is estimated that the average increase in peak temperature is about 17%, and this peak temperature is reached in less that half the time (22).

19. The high strength may appear to be attractive at first sight, but may give misleading ideas of durability. Although strength is clearly the result of the pore-filling capability of the hydration products, there is considerable evidence to show that there is no direct relationship between cement/concrete strength and impermeability, for example and hence durability, whatever be the nature of the concrete constituents (23).

Cracking and quality of concrete

20. The three major factors that encourage the transport of aggressive agents into concrete, and influence significantly its service behaviour, design life and safety are cracking, depth and quality of cover to steel, and the overall quality of the structural concrete. These three factors have an interactive and interdependent, almost synergistic, effect in controlling the intrusion into concrete of external aggressive agents such as water, air, chloride and sulphate ions (16, 18, 24). Chloride and sulphate ions, atmospheric carbonation, and the corrosive effects of the oxides of nitrogen and sulphur, are recognized to be the most potentially destructive agents affecting the performance and durability of concrete structures, whilst the depth of cover, concrete quality, and cracking are the most critical factors in determining the electrochemical stability of steel in concrete (16, 18, 24).

The ubiquity of exposure and environment

21. But perhaps the most devastating effect on the performance of concrete is brought about by aggressive, salt-laden climatic conditions - the daily unpredictable and seasonal fluctuations in temperature and Relative Humidity (RH) which create a host of damage

processes arising from cyclic thermal and moisture movements, thermal fatigue and freezing and thawing (25-30). The cumulative synergistic effects of rapid and high fluctuations of temperature and RH, thermal fatigue, air-entrained and water-borne chlorides and sulphates in moist environments, and other atmospheric pollutants can cause unexpected and premature damage to concrete structures which is often observed at a much earlier age, and to a much greater extent, than that predicted by current service life models. Aggressive environments thus provide the greatest challenge and test to the engineer to provide a quality of concrete that will ensure stability and long service.

22. One of the clear messages of the time-dependent combined interaction of loads, and adverse environmental, climatic and geomorphologic conditions is that their effects are cumulative, concomitant and synergistic. This creates a complex combination of many individual deterioration mechanisms, the exact role, effect and contribution of each of which to the totality of damage can not be realistically assessed. But the ultimate result is an unknown factor affecting the microstructure leading to increased permeability, decreased durability and consequent structural instability. Continually severe surroundings is thus one single external factor that can create an alarming degree of deterioration in a short time, and critically determine the stability and serviceability of concrete structures. It so happens that the environment is also the one single factor that is beyond human control.

Modified binders - the only way forward

23. Extensive research has now established, beyond a shadow of doubt, that the most direct, technically sound and economically attractive solution to the problems of reinforced concrete durability lies in the incorporation of finely divided siliceous materials in concrete. The fact that these replacement materials, or supplementary cementing materials as they are often known and described, such as pulverised fuel ash (PFA), ground granulated blast-furnace slag (slag), silica fume (SF), rice husk ash, natural pozzolans, and volcanic ash are all either pozzolanic or cementitious make them ideal companions to Portland Cement (PC).

Indeed, Portland Cement is the best chemical activator of these siliceous admixtures so that PFA, slag and/or SF and PC can form a life-long partnership of homogeneous interaction which can never end in divorce or unhealthy association and after-effects. But more importantly, the PC + FA/slag/SF partnership can result in high quality concrete with intrinsic ability for high durability with immense social benefits in terms of resources, energy and environment - the only way forward for sustainable development.

24. There are two fundamental reasons why this PC-siliceous materials partnership is essential for sustainable development in the cement and concrete industry.

Environmental aspects

25. Every tonne of cement clinker requires about 4000-7500 MJ total energy for production whilst slag requires only 700 to 1000 MJ/tonne, and PFA about 150 to 400 MJ/tonne. Replacing 65% of cement with slag having 15% moisture content, for example, will only require 0.5 tonnes of raw material and about 1500 MJ of energy. Each tonne of cement replaced will thus save at least 2500-6000 MJ of energy. Further, since every tonne of cement releases 1.0 to 1.2 tonnes of CO_2, for every one tonne reduction in clinker production, there is an almost equivalent reduction in CO_2 emissions. These direct impacts on economics and environment are strong, hard-to-refute arguments for using cement replacement materials in concrete construction (2).

Durability considerations

26. It is now well-established that the incorporation of industrial byproducts such as PFA, slag and silica fume in concrete can significantly enhance its basic properties in both the fresh and hardened states (31-34). Apart from enhancing the rheological properties and controlling bleeding of fresh concrete, these materials greatly improve the durability of concrete through control of high thermal gradients, pore refinement, depletion of cement alkalis, resistance to chloride and sulphate penetration and continued microstructural development through long-term hydration and pozzolanic reactions (18, 34-39). Further,

concrete can provide, through chemical binding, a safe haven for many of the toxic elements present in industrial wastes; and there are strong indications that these mineral admixtures can also reduce the severity of concrete deterioration problems arising from chemical phenomena such as alkali silica reaction, delayed ettringite formation and thaumasite formation (31-34, 38-40).

Sustainability - the ultimate challenge

27. A critical evaluation of the world scenario described above emphasizes the complex but close interrelationship between three seemingly unrelated but gigantic problems that confront the construction industry, namely

- the insatiable infrastructure needs of a rapidly growing and urbanizing world coupled with the desire for a better quality of life of nations suffering from a lack of availability and accessibility to world resources, global warming, and the consequent destruction of infrastructure through natural disasters.
- the need to achieve a balance between economic development and protection of environment
- the crises in the area of materials and durability.

28. Sustainability implies that the needs of the present generation are met without wasting, polluting or damaging/destroying the environment, and without compromising the ability of future generations to meet their needs. In the construction industry, sustainable development would involve, amongst others,

- design for durable and functional service life of structures for the duration of their specified design life.
- use of waste materials, reduction of waste and recycling of waste.
- construction to cause the least harm to our environment.

29. However, sustainable development will remain a simplistic, fanciful pipedream unless there is total commitment from all sectors of the industry. For example, some 70m tonnes (29%) of UK's controlled waste total is estimated to be from construction and demolition. Of this, only about 4% is recycled for high grade use, while the rest is used for low grade applications, or is unaccounted for [41]. This is not altogether surprising. Everybody seems to know that recycling makes environmental sense - so the fundamental question is, why don't we all recycle? If we take domestic waste, for example, around half is made up of recyclable materials such as paper, textiles, cans and plastic bottles. Yet in the UK, currently only about 8% of all household waste is recycled - far less than the 40% needed for sustainability! It will be readily seen that if society is finding it difficult to achieve sustainability in the domestic waste industry, the challenge facing the construction industry is far more complex and entrenched.

21st Century concrete construction

30. Bearing in mind the technical advantages of incorporating PFA, slag, SF and other industrial pozzolanic byproducts in concrete, and the fact that concrete with these materials provides the best economic and technological solution to waste handling and disposal in a way to cause the least harm to or environment, **PFA, slag, SF and similar materials thus need to be recognized not merely as partial replacements for PC, but as vital and essential constituents of concrete**. Indeed a stage has now been reached where the use of PC alone as the binder in the concrete system would need to be justified before such a material can be accepted for construction. Viewed in this way, the 21st century concrete will be seen as a provider for mankind with a construction material requiring the least consumption of energy and raw material resources, and reduced environmental pollution through reduced carbon dioxide emissions. Enhancement of the durability of infrastructure construction and stopping of the desecration of the environment - the essential basis for quality of life - should thus be the criteria for selection of material constituents for the 21st Century Concrete.

Example of High Rise Structures

31. High rise buildings provide a typical example for this approach to the 21st century concrete construction. They also represent the modern way of life, the inevitable consequence of global urbanization and changes in professional and social life all over the world.

32. High rise structures are highly sensitive to cumulative differential length changes of their vertical elements such as columns and shear walls. The effect of long-term shortening, differential movements and unequal stress levels in columns could create cracking of internal partitions, and of external cladding elements as well as additional shear forces and bending moments on the floor systems. The new material/structural interactive technology approach to such structures would include (42-46)

High volume PFA concrete for foundations

High strength PFA/slag normal weight concrete for columns at lower floors

High strength structural PFA lightweight aggregate concrete for columns at upper floors

Normal strength structural PFA lightweight aggregate concrete floor slabs

PFA fibre concrete to resist punching shear

Composite floor slabs: ferrocement as permanent formwork

In such a structure, there will be no concrete which does not contain PFA, slag and/or SF as essential constituents for concrete.

The present scenario

33. The present construction technology scenario thus poses two major challenges to the concrete technologist and design engineer.

- First, how do we preserve and maintain the durable service life of the current stock of structures? i.e., how do we protect, rehabilitate and strengthen deteriorating or otherwise structurally inadequate constructions?
- Secondly, how do we design and construct new structures that will have a specified durable service life and which will require a minimum of repair and retrofitting during that time?

34. It is clear that the only way to achieve these challenging goals is to develop and adopt a "**Global Holistic/Design Strategy**" that will integrate material properties with those factors that produce durable in-situ structural performance and preserve structural integrity. Such a "**Design Strategy**" will involve three distinct but inter-related and interactive approaches, namely.

- "**A Material Strategy**" to develop a high-durability concrete, i.e. "**High-Strength through Durability**" rather than High Durability through Strength.
- "**A Management Strategy**" to develop an efficient "**Protective System**" to protect concrete and steel from aggressive environmental attack.
- "**A Design Strategy**" to integrate material properties with structural performance that will ensure "**Material Stability and Structural Integrity**".

Criteria for durable service life

35. One of the intriguing and puzzling characteristics of concrete is its double-faced nature. Whilst being intrinsically protective to steel, it is also the same material that controls and permits the ingress of water, air, oxygen, chlorides, sulphates and other deleterious agents that damage concrete, and lead to the progressive destabilization of steel. Hence, the core property that controls the overall long-term stability of reinforced concrete has to be its "**impermeability**" and therefore its "**pore structure**" [18-24, 31-38]. Nevertheless, however "**impermeable**" the concrete is, and however "**well-protected**" it is from an aggressive environment, internal and external stresses will always crack the concrete as its tensile strain capacity is only of the order of 150 to 200 microstrain. Therefore, there cannot be a single

approach to ensure long-term concrete durability and structural integrity, particularly if concrete is exposed to severely aggressive environments. It has to be an "**Integrated Global Design Strategy**" that will involve four distinct steps.

Development of a Highly-Durable Concrete

Protection of Concrete

Use of protected Steel/Use of Stainless Steel or Non-metallic Reinforcement

Design for Structural Integrity.

Obviously not every exposure condition would need all these distinct stages to be incorporated in the global design strategy, but if durable service life is the focus of all construction activity, then close attention needs to be paid to all these aspects to some degree or other.

The ingredients for high durability concrete

36. Whatever the nature and severity of the environment, the key to high performance of a reinforced concrete structure lies in the development of a highly durable concrete matrix. Such a material has to satisfy the following basic requirements:

i) Very-low porosity through the development of a tight and refined pore structure of the cement paste.
ii) Very-low permeability of the concrete.
iii) High resistance to chemical attack.
iv) Low heat of hydration.
v) High early strength and continued strength development.
vi) Low water-binder ratio.
vii) High workability and control of slump loss.
viii) Low bleeding and plastic shrinkage.

37. This may appear to be an exorbitant and/or unreasonable list of demands and, for many normal situations, it may well be that not all these requirements need to be met for durable concrete performance. On the other hand, for severe climatic and exposure

conditions where cyclic environmental hot/wet/cold/dry conditions can continually erode the performance characteristics of concrete, many of these requirements need to be satisfied if durable service life is to be obtained from structural concrete.

38. Perhaps it is appropriate at this stage to consider what exactly we mean by **"High Durability Concrete"**. Obviously, what will perform well in frigid or torrid zones will not be suitable for temperate climatic conditions. There is also another factor that engineers cannot afford to ignore. Unfortunately, in real life, initial costs often dominate engineering decisions while obscuring performance-related costs. The author's definition has therefore to be as follows:

"A HIGH DURABILITY CONCRETE ELEMENT IS THAT WHICH IS DESIGNED TO GIVE OPTIMIZED PERFORMANCE CHARACTERISTICS FOR A GIVEN SET OF LOAD, USAGE AND EXPOSURE CONDITIONS CONSISTENT WITH THE REQUIREMENTS OF COST, SERVICE LIFE, SUSTAINABILITY AND DURABILITY".

39. Thus both in the concept and production of high durability concrete as well as in design, construction and maintenance one needs to adopt an **"INTEGRATED GLOBAL DESIGN STRATEGY"** that will ensure **"MATERIAL STABILITY AND STRUCTURAL INTEGRITY"** at every stage from conception to completion of the fabrication process of concrete, and thereafter, during its life. By implication, **"HIGH DURABILITY CONCRETE"** does not necessarily mean the use of expensive materials or complex process technologies unless, of course, they are warranted by the situation or the environment.

Design for sustainability

40. Designing concrete materials for durability, and incorporating PFA, slag, SF or similar natural or industrial pozzolans as vital and essential constituents of concrete is the

first, and indispensable, step towards achieving sustainable development of the cement and concrete industry. However, it would be flippant and facetious of engineers to believe that sustainable development in the construction industry can be achieved merely by utilizing siliceous industrial byproducts in concrete alone. Indeed one needs to look at concrete construction as a whole - **globally**, **holistically** - as an industry that can only thrive if the characteristics of the material are integrated with structural innovations and durable performance.

41. Sustainable growth in the construction industry can be achieved only if the materials that are created and used, and the structures that are designed and built are eco-friendly, cost-effective, ductile and give durable service performance over their specified design life. Above all, they should be such that their engineering capabilities are fully utilized and maximised in their service behaviour. Construction should thus be seen as a **Global and Holistic** activity involving all aspects from conceptual design to completion and maintenance - such an approach would integrate material selection, design, in-situ performance, monitoring, maintenance and reappraisal at critical stages in the designed service life of the structure. Such an approach would involve, amongst other things, the following [47-54].

New structures

Design for durable environmentally friendly concrete

42.
- Do not use PC alone as the cementitious matrix for concrete.
- If you do, justify the basis for such use.
- Specify and design concrete with recycled materials - LW Aggregates, PFA, slag, SF, etc.
- Manufacture cementitious materials for **DURABILITY** and not for **STRENGTH**.

Design for sustainable development

43.
- Design for cost-effective durable performance and service life.
- Design for **"Strength through Durability"** rather than **"Durability through Strength"**.
- Design for site waste minimization.
- Reduce waste, recycle waste.
- Design for least damage to environment.
- Innovate design: closer analysis of design loads: avoid overdesign.
- Design for specified design life based on cost-benefit analysis.
- Design for dismantling, and reuse, e.g. demountable car parks.
- Design for material stability and structural integrity.

Existing structures

44.
- Detailed diagnostic evaluation of the capabilities, weakness and deficiencies at the end of the specified/designed service life.
- Justify demolition.
- Rehabilitate, retrofit and regenerate.
- Protect concrete (and indeed all materials) from aggressive environments.
- Repair, strengthen structures: Plate bonding technology for beams and slabs, Fibre wrapping for columns, for example.

Structural management strategy

45.
- Inspect, Monitor, Remedy defects.
- Develop planned maintenance programme

Concluding Remarks

46. The latter half of the 20th century has seen unprecedented social and technological changes in the world in terms of population growth, engineering and industrial revolutions, world-wide urbanization and uncontrolled pollution and creation of waste. These unparalleled changes in the evolution of the industrialized, information technology era have created high demands not only for infrastructure regeneration and rehabilitation but also for a more equitable distribution of the use of the world's material and energy resources. The greatest impact of these global changes is on the construction industry, and because the construction industry is so much interlinked with energy, resources and environment, a sustainable development of the cement and concrete industry alone can avoid irredeemable environmental degradation and enable the maintenance and enhancement of the quality of life.

47. It is shown that three major factors - namely the energy intensiveness, CO_2 emissions and lack of durability - have contributed to the apparent tarnished image of cement and concrete materials. It so happens that the remedies for this undesirable state of affairs are not only simple but lie within the grasp of those involved in construction. **Use of Cement Replacement Materials, Design for Durability** and **Design for Sustainability** are the three essential pillars to achieve sustainable growth. However, sustainable development will remain a pipedream unless cementitious materials are manufactured for **Durability rather than for Strength** and cement replacement materials are seen as vital and essential constituents of concrete. Above all, construction should be seen as a **holistic activity**, integrating material characteristics and in-situ structural performance, leading to **material stability and structural integrity** for the loads, usage and exposure conditions for which the structure is designed.

References

1. Schlaich, J., World energy demand population explosion and pollution: could solar energy utilisation become a solution?, *The Structural Engineer*, **69**, no. 10, 21 May 1991, 189-192.
2. Malhotra, V. M., Role of supplementary cementing materials in reducing greenhouse gas emissions, *Proc. Int. Conf. on Infrastructure Regeneration and Rehabilitation - Improving the Quality of Life Through Better Construction - A Vision for the next Millennium*, Ed. R. N. Swamy, Sheffield Acad. Press, 1999, 27-42.
3. Rasheeduzzafar, Dakhil, F. H., and Al-Gahtani, A. S., Deterioration of concrete structures in the environment of the Middle East", *Journal, American Concrete Institute*, **81**, no. 1, 1984, 13-20.
4. Shalaby, H. M., Case studies of corrosion and deterioration of reinforced concrete structures in the State of Kuwait, *Proc. 1st Int. Conf. on Deterioration of Reinforced Concrete in the Arabian Gulf, Bahrain,* 1985, **1**, 309-320.
5. Ingvarsson, H., and Westerberg, B., Operation and maintenance of bridges and other bearing structures, *Swedish Transport Research Board*, Publ. no. 42, Stockholm, Sept. 1986.
6. Al-Tayyib, A. J., and Khan, M. S., Concrete deterioration problems in the Arabian Gulf - a review, *Durability of Building Materials*, **4**, 1987
7. Wallbank, E. J., *The performance of concrete bridges*, Dept of Transport, HMSO, London, April 1989, pp. 96.
8. Brown, J. H., Factors affecting steel corrosion in concrete bridge substructures, IAB*SE Symposium*, Lisbon 1989, **2**, 450-464.
9. Mehta, P. K., Concrete technology at the cross-roads - problems and opportunities, *Concrete Technology, Past, Present and Future*, ACI Publ. SP-144, 1994, 1-30.
10. Read, J. A., FBECR - The need for correct specification and quality control, *Concrete*, **23**, No. 8, 1989, 23-27.
11. The state of the nation, New Civil Engineer, 25 May 2000, 15-17.
12. American Society of Civil Engineers, ASCE News, Am. Soc. of Civ. Engineers, Washington, USA, 24 Sept. 1998.

13. National Academy of Sciences, Concrete durability - a multibillion dollar opportunity, *Publication No. NMAB-437,* National Materials Advisory Board, Washington, 1987, 94 pp.

14. Mehta, P. K., Durability of concrete - fifty years of progress? ACI Publ. SP-126, Am. Soc. Inst., 1991, 1-32.

15. Gjorv, O. E., Durability of concrete structures in the ocean environment, *Proc. FIP Symposium on Concrete Sea Structures*, 1992, 141-145.

16. Swamy, R. N., Hamada, H., and Laiw, J. C., A critical evaluation of chloride penetration into concrete in marine environment", *Proc. Int. Conf. on Corrosion and Corrosion Protection of Steel in Concrete*, Sheffield, 1994, 404-419.

17. Tanikawa, S., and Swamy, R. N., Unprotected and protected concrete: on-site chloride penetration with time in an aggressive environment, *Proc. Int. Conf. on Corrosion and Corrosion Protection of Steel in Concrete*, Sheffield, 1994, 1069-1080.

18. Swamy, R. N., and Laiw, J. C., Effectiveness of supplementary cementing materials in controlling chloride penetration into concrete", ACI Publ, SP-153, **2**, 1995, 657-674.

19. Swamy, R. N., and Suryavanshi, A. K., Durability of blended cement concrete structural elements of higher water-binder ratio against chloride and carbonation attack, *The Arabian Journal for Science and Engineering*, **23**, No. 1B, April 1998, 17-32.

20. Rasheeduzzafar, Influence of cement composition on concrete durability, *ACI Materials Journal*, **89**, no. 6, Nov-Dec 1992, 574-586.

21. Al-Amoudi, O. S. B., Rasheeduzzafar, Maslehuddin, M., and Abduljaawad, S. N., Performance of plain and blended cements in high chloride environments, *Durability of Concrete*, ACI Publ. SP-145, 1994, 539-555.

22. Nixon, P. J., Changes in portland cement properties and their effects on concrete", BRE *Information Paper IP 3/86,* March, 1986.

23. Swamy, R. N., and Darwish, A. A., Effectiveness of mineral admixtures and curing regime on air permeability of concrete, *Durability of Concrete*, ACI Publ. SP-170, 1997, 207-230.

24. Swamy, R. N., and Tanikawa, S., An external surface coating to protect concrete and steel from aggressive environments, *Materials and Structures*, **26**, 1993, 465-478.

25. Almusallam, A. A., Abdul-Waris, M., Maslehuddin, M., and Al-Gahtani, A. S., Placing and shrinkage at extreme temperatures, *Concrete International*, **21**, 1999, 75-79.

26. Swamy, R. N., Alkali-silica reaction and concrete structures, *Structural Engineering Review*, **2**, 1990, 89-103.

27. Swamy, R. N., Alkali-aggregate reaction - the bogeyman of concrete, *Concrete Technology - Past, Present and Future*, ACI Publ. SP-144, 1994, 105-139.

28. Collepardi, M., Damage by delayed ettringite formation, *Concrete International*, **21**, 1999, 69-74.

29. Grammond, N. J., and Halliwell, M. A., The thaumasite form of sulfate attack in concretes containing a source of carbonate ions, *Advances in Concrete Technology*, ACI Publ. SP-154, 1995, 357-380.

30. The Thaumasite form of sulfate attack: risks, diagnosis, remedial work and guidance on new construction, *Report of the Thaumasite Expert Group*, DETR, 1999.

31. Swamy, R. N., Editor, Cement replacement materials, Vol. 3, Co*ncrete Technology and Design*, Surrey University Press, 1986, 259.

32. Malhotra, V. M., Editor, *Supplementary cementing materials for concrete*, CANMET, Ottawa, 1987, 428.

33. Malhotra, V. M., and Mehta, P. K., *Pozzolanic and cementitious materials*, Gordon and Breach Publishers, SA, 1996, 191.

34. Mehta, P. K. Pozzolanic and cementitious by-products as mineral admixtures for concretes - a critical review, ACI Publication SP-79, **1**, 1983.

35. Rasheeduzzafar, Al-Mana, A., Haneef, M., and Maslehuddin, M., Effect of cement replacement, content and type on the durability performance of fly ash concrete in the Middle East, *Cement, Concrete and Aggregates*, **8**, no. 2, Winter 1986.

36. Swamy, R. N., Fly ash concrete - potential without misuse, *Rilem Materials and Structures*, **23**, no. 138, 1990, 397-411.

37. Swamy, R. N., Concrete with slag: high performance without tears, *Proc. 4th Int Conf. on Structural Failure, Durability and Retrofitting*, Singapore, July 1993, 206-236.

38. Swamy, R. N., Design for durability and strength through the use of fly ash and slag in concrete, *Advances in Concrete Technology*, ACI Publ. SP-171, 1997, 1-72.

39. Asbridge, A. H., Jones, T. R., and Osborne, G. J., High performance metakaolin concrete: results of large scale trails in aggressive environments, *Proc. Concrete in the Service of Mankind*, Dundee, June 1996.

40. Swamy, R. N., Role and effectiveness of mineral admixtures in relation to alkali silica reaction, ACI Publ. SP-131, 1992, 219-254.

41. Construction Industry Research and Informational Association, CIRIA News, Issue 3, 1997.

42. Swamy, R. N., An integrated material/structural design approach - The strategy for high performance in tall structures, *Proc. First Int. Symp. for Innovative Concrete Technology*, Hanyang University, Korea, 1995, 1-15.

43. Swamy, R. N., and Hung, H-H, Engineering properties of high volume fly ash concrete, ACI Publ. SP-178, 1998, 331-359.

44. Swamy, R. N., and Jiang, E. D., Pore structure and carbonation of lightweight concrete after 10 years exposure, ACI Publ. SP-136, 1992, 377-395.

45. Swamy, R. N., Structural lightweight aggregate concrete - the Cinderella of Concrete Technology, *Odd E. Gjorv Symposium on Concrete for Marine Structures*, 1996, 121-137.

46. Swamy, R. N., and El-Abboud, M. I., Application of ferrocement concept to low cost lightweight concrete sandwich panels, *Journal of Ferrocement*, **18**, 1988, 285-292.

47. Swamy, R. N., Design - the key to concrete material durability and structural integrity, *Proc. Int. Conf. on Reinforced Concrete Materials in Hot Climates*, Alain, UAE, 1994, 3-36.

48. Swamy, R. N., Oshiro, T., and Tanikawa, S., Global strategy to enhance Service life of deteriorating structures, *Proc. IABSE Symposium Extending the Lifespan of Structures*, 1995, 457-462.

49. Swamy, R. S., Assessment and rehabilitation of AAR-affected concrete structures, *Proc. 10th Int. Conf. on Alkali-Aggregate Reaction in Concrete*, Australia, 1996, 68-83.

50. Swamy, R. N., High performance and durability through design, *High Performance Concrete*, ACI Publ. SP-159, 1996, 209-230.

51. Yamada, Y., Oshio, T., Tanikawa, S., and Swamy, R. M., Field evaluation of an acrylic rubber protective coating system for reinforced concrete structures, *Durability of Concrete*, ACI Publ. SP-170, 1997, 23-40.

52. Swamy, R. N., Designing concrete and concrete structures for sustainable development, *Proc. Int. Symp on Sustainable Development of the Cement and Concrete Industry*, Ottawa, Canada, 1998, 245-255.

53. Swamy, R. N., and Wu. L., Durable structural lightweight aggregate concrete - Design for sustainable development, *Shigeyoshi Nagataki Symposium*, 1998, 107-125.

54. Swamy, R. N., Design for durable service life - the linchpin for sustainability in concrete construction, *Proc. Int. Conf. on Performance and Quality of Concrete Structures*, ACI Publ. SP-186, 1999, 765-788.