Designing Concrete And Concrete Structures For Sustainable Development

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ABSTRACT: The unprecedented changes that have occurred in the world and society during the latter half of this century have placed insatiable demands on the construction industry in terms of the world's material and energy resources. In this complex world scenario, infrastructure regeneration and rehabilitation, and cement and concrete materials have an undeniable part to play in enhancing the quality of human life. If we are to avoid unredeemable environmental degradation globally, sustainable development of the cement and concrete industry has to be the foundation for all construction activity in the next millennium. This approach demands that cementitious materials are manufactured for durability rather than for strength, and that pozzolanic and other industrial cementitious byproducts are seen as vital and essential constituents of concrete. However, sustainability in the construction industry will remain a pipedream unless design for specified durable service life is the basis for all future construction. This would demand a fundamental change in our **DESIGN** approach which should be **HOLISTIC** integrating material characteristics and structural performance.

Keywords: Global urbanization, energy demands, sustainability, concrete for durability, cement replacement materials, holistic design.

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INTRODUCTION

Sustainable development in the cement and concrete industry is not a simplistic, fanciful pipedream. Nor it is an easily attainable goal as **sustainability** in any segment of our lives, and in any region or part of the world has many, interactive and interdependent repercussions far beyond the control of those who are immediately involved. The fundamental question is why don't we all recycle? Everybody knows, we think, that recycling makes environmental sense. For example, around half of all the waste produced in our homes is made up of recyclable materials, such as paper, textiles, glass, cans and plastic bottles. Yet, in the UK for example, currently only about 5% of all household waste is recycled - far less than the 40% needed to achieve **sustainability**. The keys to attain this level of recyclability are

Awareness
Availability, and
Accessibility.

It will be readily seen that if we are finding it difficult to achieve **sustainability** in the domestic waste industry, the problems confronting the cement and concrete industry are far more complex and entrenched.

To achieve sustainable development in the cement and concrete industry, we need to understand and appreciate what has happened to the world during our lifetime. The century that we live in is almost at its end. The world at the end of this century is very different to the world that we inherited at the beginning of this century. There have been, particularly during the last four to five decades, unprecedented social changes, unpredictable upheavals in world economy, uncompromising societal 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 population growth, technological revolutions, worldwide urbanization and uncontrolled pollution and creation of waste. But perhaps over-riding all these factors is **globalization**, - not merely in terms of economies, technologies 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 EFFECT

But perhaps the greatest impact of all these unparalleled changes in the evolution of the information technology era has been on the construction industry. Continued population growth and evolutionary industrialization have resulted in an endless stream of global urbanization. Whilst the world's population has doubled in the latter part of this century, it is now expected that the projected 6 billion total population will be reached by the year 1999 rather than in the year 2000, Further the end of this present century will see, for the first time in human history, that more people will live in and around our cities than in rural areas (1). It is estimated that by the year 2000, there will be at least 20 megacities with 10 million or more inhabitants, in addition to several big cities of more than 1,000,000 people. This explosion into an urban way of life will demand enormous resources and supply of construction materials required to build the infrastructure - such as housing, transportation, water supply and sanitation - needed to support life in these megacities and big cities.

World Energy Demands

The impact of global urbanization is not merely on the demand for construction materials; a more insidious implication is on world energy demand, which again impinges finally on the construction industry. In the present context of the world, some 25% of the world's population live in industrialized nations including the Soviet Union and Eastern Europe, but they account for nearly 75% of the global energy consumption. This disproportionate consumption of energy and world resources can be better understood if we consider that in theoretical terms, whilst the average individual world-wide has 2 kW years p.a. at his disposal, the average per capita consumption is about 11 kW years p.a. in North America compared 0.6 kW years p.a. in China or 0.43 kW years p.a. in South-East Asia or Africa (2). If we now assume 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 our environment. Whether fossil fuel 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 materials resources, all of which could contribute to unredeemable environmental degradation.

CONCRETE AND THE ENVIRONMENT

How does concrete come and fit into this complex world scenario? 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, of the quality of life because 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 aspect 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 THE TARNISHED IMAGE?

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

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. We have to accept that portland cement is both resource- and energy- intensive material - 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. We live in a world where the use of resources and energy, and the degree of atmospheric pollution do matter.

Deterioration of Concrete

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, (1, 3-8). The major reasons for this apparent fall from grace are numerous - partly out own 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 our 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 achieved as a normal and natural consequence of the process of concrete fabrication.

WHAT'S WRONG WITH MODERN PORTLAND CEMENT CONCRETE?

Changes in the Chemistry of Cement

The experience that even when specific building code requirements on durability in terms of concrete cover and concrete quality are achieved in practice, there is an unacceptably high risk of premature corrosion deterioration in concrete structures exposed to aggressive salt-laden environments, directly points to the fact that portland cement concretes are not totally resistant to chloride ion penetration, even when the water-cement ratio is as low as 0.40 (9-11). 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 our thinking about concrete and concrete quality made of portland cement concrete (11-13).

One of the major reasons for this much lower resistance of modern portland cement concrete to chloride ion penetration is the gradual but significant changes that have occurred in the chemical composition of portland cements during the last four to five decades (14). The two major changes in cement composition, and their implications on engineering and durability properties of the resulting concrete can be identified as:

1. 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 w/c ratios.

2. A direct result of the change 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 than half the time (14).

The high strength may appear 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, and hence durability, whatever be the nature of the concrete constituents (15)

Cracking and Quality

The three major factors that encourage the transport mechanism 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. Chloride and sulphate ions, and atmospheric carbonation, including that arising from the oxides of nitrogen and sulphur, are recognised 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 in determining the electrochemical stability of steel in concrete.

THE UBIQUITY OF EXPOSURE AND ENVIRONMENT

But perhaps the most devastating effect on the performance of concrete is brought about by aggressive, salt-laden climatic conditions - or rather, by the daily and seasonal unpredictable fluctuations in temperature and relative humidity which create a host of damage processes arising from cyclic thermal and moisture movements, thermal fatigue and freezing and thawing. 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 often observed at a much earlier age, and to a much greater extent, than that predicted by 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 in continually severe surroundings.

One of the clear messages of the time-dependent combined interaction of adverse environmental, climatic and geomorphological conditions is that their effects are cumulative, concomitant and synergistic, a complex combination of many individual 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 a unknown factor affecting the microstructure leading to increased permeability and decreased durability. Continually severe surroundings is thus one single predominant 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

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 cement replacement materials, or supplementary cementing materials, as they are often known and described, such as fly ash (FA), 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 PC and FA, slag and/or SF 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.

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

1. **Environmental aspects**
   Every tonne of cement clinker requires about 7500 MJ total energy for production whilst slag requires only 700 to 1000 MJ/tonne, and FA 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 - 1600 MJ of energy. Each tonne of cement replaced will thus save at least 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**
   It is now well-established that the incorporation of such industrial byproducts such as FA, slag and silica fume in concrete can significantly enhance its basic properties in both the fresh and hardened states (16-18). 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 (19-23). 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 durability problems arising from Delayed Ettringite Formation and Thaumasite.

21ST CENTURY CONCRETE CONSTRUCTION

Bearing in mind the technical advantages of incorporating FA, slag and SF 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 our environment, **FA, slag and SF need to be recognized not merely as partial replacements for PC, but as vital and essential constituents of concrete.** Indeed we have reached a stage 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 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.

High Rise Structures

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

High rise structures are highly sensitive to cumulative differential length changes of their vertical elements such as columns and shear walls. The effects 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 (24)

High volume FA concrete for foundations
High strength FA/slag normal weight concrete for columns
Normal strength structural lightweight aggregate concrete floor slabs
FA fiber 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 FA, slag and/or SF as essential constituents for concrete.

DESIGN FOR SUSTAINABILITY IN THE CONSTRUCTION INDUSTRY

Designing concrete materials for durability, and incorporating FA, slag, SF or similar natural or other pozzolans as vital and essential constituents of concrete is the first, and essential key step towards achieving sustainable development of the Cement and Concrete Industry. However, it would be flippant and facetious of us to believe that sustainable development in the construction industry can be achieved merely by utilizing siliceous industrial byproducts in concrete alone. Indeed we need to look at concrete construction as a whole - **globally**, **holistically** - as an industry that can only thrive if we integrate the characteristics of the material with structural innovations and durable performance. Such an approach would include the following:

NEW STRUCTURES
DESIGN FOR DURABLE ENVIRONMENTALLY FRIENDLY CONCRETE

- 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, FA, slag, SF, etc.
- Manufacture cementitious materials for **DURABILITY** and not for **STRENGTH**.

DESIGN FOR SUSTAINABLE DEVELOPMENT

- Design for site waste minimization
- Reduce waste, recycle waste
- Design for least damage to environment
- Innovative design: closer analysis of design loads: avoid overdesign
- Design for specified design life based on cost-benefit analysis
- Design for dismantling, e.g., demountable car parks

EXISTING STRUCTURES

- Justify demolition
- Regenerate, Rehabilitate
- Protect concrete from aggressive environments
- Repair, strengthen structures: Plate bonding technology for beams, slabs; Fibre wrapping for columns

STRUCTURAL MANAGEMENT STRATEGY

- Inspect, Monitor, Remedy defects
- Develop planned maintenance program

CONCLUDING REMARKS

The latter half of the 20th century has seen unprecedented social changes in the world in terms of population growth, technological 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 insatiable demands not only for infrastructure regeneration and rehabilitation but also for a more equitable distribution 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 our environment, a sustainable development of the cement and concrete industry alone can avoid unredeemable environmental degradation and enable the maintenance and enhancement of the quality of life.

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 simply 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 global and holistic activity, integrating material characteristics and in-situ structural performance.

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