AMAS Course on High Performance Cement Based Materials
HPCBM'03 – (pp.37–81) – Warsaw, October 16-18, 2003

High performance cement based materials holistic design for sustainability in construction

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The cement/concrete industry is faced with two major challenges – an infrastructure crisis, and a sustainability problem. Both are worldwide issues, with tremendous implications not only for ourselves but also for the lives of generations to come. The focus of this paper is to show that a holistic approach to the formulation and fabrication of concrete materials with emphasis on durability, ductility, environment and sustainability can lead to the development of a large number of eco-friendly and innovative cement-based construction materials for a wide range of applications in infrastructure regeneration and reconstruction. Quality of Life is the one single goal that all humanity wants and aspires, for, and a judicious combination of pozzolanic/cementitious materials, chemical admixtures, fillers, fibres and other appropriate constituents can meet the insatiable demand for basic infrastructure facilities, and at the same time contribute to sustainable growth with the least damage to our environment. The paper illustrates this philosophy of manufacturing and designing sustainable concrete materials for *Durability rather than for Strength* with various examples such as fly ash/slag concrete, high volume fly ash concrete, structural lightweight aggregate concrete, low energy-cements, and fibre reinforcement. It is also shown that the philosophy of *Holistic Design* with emphasis on *Material Stability* and *Structural Integrity and Ductility* can successfully meet the challenges of the Infrastructure Crisis and Sustainable Development of the Concrete industry.

1. Introduction

There is a unique, undeniable and unbreakable inter-relationship between the human race and this planet. From time immemorial, the earth has provided clean air, clean water and all the basic essentials to sustain life from cradle to grave. However, the world we live in is a live organism: it never stands still. When the changes that occur are slow and gradual, and take place over a long period of time, we hardly notice or feel their effects and impact on our day-to-day life. When the changes are fast and immediate, and the effects are huge as when earthquakes, heavy floods, cyclones or hurricanes occur, it is not only the lives of those affected that are turned topsy-turvey for good, but the damage and destruction caused to the engineering infrastructure will be phenomenal, horrendous, and long-term.

Such an upheaval occurred in the world during the latter half of the 20^{th} century. Although these changes were individually, and by themselves, gradual and progressive, and probably never felt too deeply, they have, over a period of five decades or so, totally and dramatically changed the scientific, technological, industrial and social face of the world. The advancements that have taken place in every facet of human life during this period have been unbelievable and unimaginable, and the benefits of these changes have been immeasurable, although reaped by only a small proportion of the world's population.

2. The infrastructure crisis

These unparalleled and unprecedented sociological changes that have occurred as a consequence of technological revolutions, evolutionary industrialization, population growth and world-wide urbanization have resulted in several crises:

1. massive and wasteful consumption of the world's non-renewable material and energy resources,
2. unrestrained creation of waste, and unacceptable and uncontrolled pollution of, and damage to, our environment, and,
3. absence of a viable infrastructure system, and progressive deterioration and damage to existing infrastructure.

But the ultimate consequence of these global changes has been the creation of a massive and widespread *Infrastructure Crisis* that humanity has ever seen. This Infrastructure Crisis is worldwide and has been heavily fuelled by ageing, human conflict, wanton destruction, world poverty, and global warming [1-10]. And because the construction industry is the major "mentor" involved in the rehabilitation and regeneration of the world infrastructure, and because construction technology is equally closely interlinked with materials, energy and the planet's resources, further unredeemable environmental degradation can only be prevented by *Sustainable Development* of the construction industry which alone can give some hope for a better world order and better *Quality of Life.*

3. Sustainable growth

But *Sustainability in the Construction Industry* is not a simplistic process nor can it be achieved overnight. It will remain a pious hope and a pipedream unless all sectors of the industry harmonize together for its achievement. The concept of *Sustainable Development* imposes unique responsibilities on all of us that we meet the social and economic needs of the present generation without wasting, polluting or destroying our resources and environment in such a way that will not deny future generations the ability to meet their needs. *We can then achieve Sustainable Growth only if the materials we manufacture and use, and the structures we design and build give durable and trouble-free service performance for their specified design life, are cost-effective and environmentally-friendly.* Further, we need to ensure that the engineering capabilities of the materials and structural elements we use are fully utilized and maximized in their service life.

Lack of Durability is one of the greatest threats to sustainable growth, [1-10]. However, we seem to think of *Durability* only in terms of hostile environments or intrusion of aggressive ions such as sulfates and chlorides or destructive material interactions such as alkali silica reaction, freezing and thawing or delayed ettringite formation. We now know that *Durability* must include not only *resistance to material degradation* but also *resistance to structural damage,* and particularly resistance to sudden, catastrophic failures caused by seismic loads or other unforeseen dynamic forces such as floods, hurricanes and tornadoes and mud slides, or a combination of material degradation and unexpected loads.

4. Concrete – the universal eco-friendly material

Concrete and cement-based construction materials are now seen as the only salvation for the rehabilitation and regeneration of the infrastructure problems facing the world. Sustainable concrete incorporating portland cement (PC) and pozzolanic/cementitious siliceous materials and chemical admixtures can provide that unique core property of *impermeability* and *a refined pore structure* that will ensure the long-term durable performance of reinforced concrete construction. The *synergistic interaction* between the constituents of such a concrete will lead to *low porosity* and *high impermeability,* and a high resistance to chemical attack by the development of a tight and refined pore structure. This portland cement plus fly ash (FA)/ground granulated blast furnace slag (GGBFS, slag)/silica fume (SF)/pozzolanic material (rice husk ash, metakaolin, calcined clays etc) plus chemical admixture system can bring out two outstanding benefits – engineering and economic.

From an engineering point of view, this synergistic interaction can enhance the properties of the concrete both in the fresh and hardened states, [11-18]. A judicious combination of these materials can enhance flowability and pumping qualities, reduce segregation, bleeding and plastic shrinkage, improve resistance to thermal cracking through reduced heat of hydration, and significantly reduce the permeability of the concrete [11-18]. From a sustainability point of view, the PC-pozzolan/slag system can directly contribute to conservation of material resources, reduced energy consumption and protection of the environment through reduced carbon dioxide emission [12, 17, 19]. We can perhaps now define "*Sustainable Concrete as a material of high durability which is designed to give optimised performance characteristics for a given set of load, usage and exposure conditions consistent with the requirements of cost, trouble-free service life, ductility and environment*".

5. Holistic design

It should, however, be recognized that *sustainable development* of the concrete industry can not be achieved by merely utilizing pozzolanic and cementitious industrial byproducts as an essential constituent of concrete. This is indeed the first and vital step towards sustainability – but sustainable growth demands that concrete construction be seen as a *total and holistic activity* which will integrate material characteristics, structural performance, "DESIGN" as a total concept and construction. Such an approach will embrace all aspects from conceptual design to material selection, concrete fabrication, structural calculations, energy efficient design, durable in-situ performance, structural health monitoring, whole life cycle maintenance, dismantling, reuse and recycling [20-29]. New structural systems would then form as much an integral part of *Holistic Design* as material innovations, and *structural ductility* as important a criterion as *material durability*. We cannot sacrifice structural ductility for material durability as the many recent natural disasters arising from global warming and earthquakes in Kobe, California, Turkey, Taiwan, Greece and Gujerat have so vividly but tragically demonstrated. By implication, *Holistic Design* thus advocates a new design philosophy of "*Strength through Durability*" rather than "*Durability through Strength*" and manufacture of materials for *Durability* rather than for *Strength*. *Holistic Design* would then also imply a new meaning and connotation to the engineering term *strength* – not merely to ultimate load capacity, but to signify resistance to failure in a general sense including monotonic, cyclic and dynamic loads, mechanical and thermal effects, environmental and chemical interactions.

Holistic Design will thus embrace two basic concepts:

Material Stability which will ensure sound, reliable and stable behaviour of the material under all possible conditions of load and exposure to which the material in the structure will be subjected to during its service life, and

Structural Integrity and Ductility which will ensure that the structure will maintain its stability and integrity under the cumulative and synergistic time-dependent and interactive effects of loads, exposure, climatic conditions and unforeseen dynamic loads.

6. Sustainable concrete: the pc-slag-hrwr system

So what is so special about *Sustainable Concrete*? What additional properties can it impart that conventional portland cement concrete cannot? In this section this is typically illustrated by the design of a durable PC-slag system with particular reference to heat of hydration, bleeding and setting times, pore structure, and the property of impermeability – characteristics which contribute to long-term stability and durable service performance. It is then shown that such a concrete system can develop strength and stiffness adequate for almost all structural applications. In the tests reported here, a portland cement, ASTM Type I, with a specific surface of 323 m^2/kg, and slag of three different finenesses, namely 453 (S4), 786 (S8) and 1160 (S12) m^2/kg were used. The high fineness slags S8 and S12 were obtained using an air elutriator rather than by grinding. All the concrete mixes had 50% cement replacement by mass; mixes with a water to cement plus slag (w/c+s) ratio of 0.4 had a total cementitious content of 400 kg/m^3 whilst those with a w/c+s ratio of 0.3 had a total cementitious content of 533 kg/m^3. All the mixes were designed to give slumps of 160 to 200 mm with up to 2% entrapped air. The water content in all the mixes was kept constant at 160 kg/m^3, and to enhance workability and control slump loss, a polyether carboxylic acid high range water reducer (HRWR) was used in all the mixes.

6.1. Heat of hydration

Figure 1 shows the rate of heat evolution in PC and PC-slag mixes of 1:1 ratio at a water-binder ratio (w/b) of 0.4. The heat evolution profiles were obtained from conduction calorimetry tests carried out at 20°C. The results show that the HRWR has set retarding qualities whether the cementitious system consists of portland cement alone or a mixture of portland cement and slag. On the other hand, the presence of slag of different fineness is seen to be beneficial in reducing the peak heat evolution and in extending the

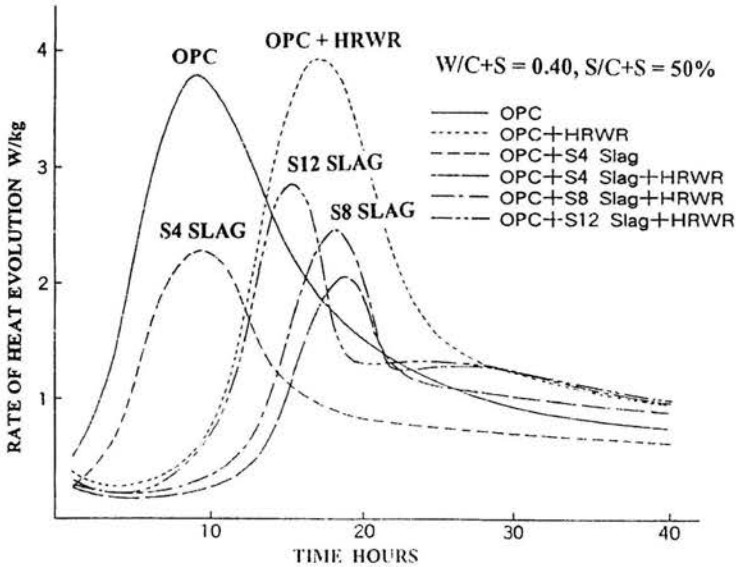

FIGURE 1. Heat of hydration of PC-SLAG-HRWR system.

time at which the peak heat evolution occurs. Heat of hydration is a major factor influencing the long-term durability of concrete. Early age thermal cracking arising from undesirable thermal gradients and thermal fatigue is slow to heal, and supplementary cementing materials can go a long way in controlling this internal microcracking. The data in Fig. 1 also confirm that moderate increases in slag fineness can still retain the benefits of pozzolanic addition to portland cement concrete.

6.2. Bleeding rates and setting times

Many ashes and slags, when used in concrete, cause some bleeding; they also act in many respects as retarders of time of setting, Swamy [17]. The principal factor influencing bleeding is the water-binder ratio (w/b), although both the replacement level on a mass basis, and the fineness of the ash or slag have also some influence on bleeding. The major factor influencing time of setting, on the other hand, is the level of cement replacement, although the w/b ratio has also some minor influence.

Bleeding is not merely a physical phenomenon affecting strength, abrasion resistance and diffusion characteristics of the surface concrete. A poorly proportioned concrete creating bleeding in the inner parts of the concrete can create weak matrix-aggregate interfaces, which in the long run, can affect adversely the permeability properties of concrete. The use of high levels of cement replacement, on the other hand, will prolong the time during which concrete remains vulnerable to plastic shrinkage cracking, and this way be undesirable in placements involving large exposed areas and deep sections.

TABLE 1. Bleeding rates and setting times of PC-SLAG system.

w/b	slag replacement %	slag fineness m^2/kg	bleeding rate %	setting time initial hour min	setting time final hour min
0.40	0	–	0.36	5 – 10	6 – 35
0.40	50	453	0.60	5 – 45	7 – 40
0.40	50	786	0.45	6 – 10	7 – 50
0.40	50	1160	0.00	6 – 30	8 – 15

These considerations emphasize that a judicious combination of w/b ratio, cement replacement level, and ash/slag fineness is necessary to effectively control heat of hydration, bleeding rates and times of setting. Table 1 shows the rate of bleeding and the initial and final setting time of the cement – slag system, all determined according to ASTM Standards. The results show that moderate increases in fineness can almost completely eliminate bleeding in highly workable high slump mixes with only moderate increases in setting times as shown in Table 1.

6.3. Fineness of FA and slag

As stated before, pozzolanic and cementitious cement replacement materials such as FA and slag not only act as retarders and enhance bleeding, but more importantly, they also exhibit a slow development of strength which can be an important drawback in practical applications, Swamy [17]. The data in Fig. 1 and Table 1 show that the fineness of slag, for example, in relation to that of PC, is a major factor that controls those properties in the fresh state of the concrete that influence the durability of the material. These data emphasize that producing industrial byproducts such as fly ash and slag to a slightly higher degree of fineness than normal can bring substantial technical benefits.

Field experience shows that pozzolans and mineral admixtures of very high fineness can often create problems of mixing and placing, and display subsequent poor field performance. Indeed, very high degrees of fineness, whether of the PC or of the cement replacement material, often bring in more practical problems than benefits, unless special attention is given to their treatment in the fresh state. Grinding fly ash may appear to be not so practical for obvious reasons, but intergrinding with PC can be widely and beneficially done to produce portland – fly ash blended cement. Grinding slag, on the other hand, is an established process in the production of slag. Grinding slag finer may appear to increase the initial cost of the material; however using an air elutriator to separate the fines can reduce this cost. The long-term overall benefits brought to the concrete by such moderate increases in fineness, in terms of fresh concrete properties, and strength development and durability (as shown later), far outweigh the moderate increases in initial cost or the benefits from using very fine pozzolans. Manufacturing pozzolanic/cementitious materials for *durability* rather than for *strength* can not only overcome their engineering limitations but also contribute significantly to their impermeability as discussed below [30, 31, 32].

6.4. Pore refinement and water tightness

In any exposure condition, the *pore structure and porosity* of the cement matrix are the key factors that determine the ability of any concrete to resist the intrusion of aggressive elements that damage it. In extreme and severely aggressive climatic conditions, field studies show that chlorides and sulfates can penetrate concrete even during the very briefest of exposure periods, after removal of the forms. These problems are further compounded if the ground water is also heavily contaminated with chlorides and sulfates, as it will only be a matter of time before the damaging ions intrude into the concrete through capillary action. The development of a tightly knit pore structure is thus an essential requirement for long-term durable service life.

The role of slag in developing a very fine pore structure and high water tightness is shown in Table 2. The pore volume data in Table 2 were obtained from mercury intrusion porosimetry tests, while the water tightness tests were carried out on 150×300 mm cylinders which were subjected to a water pressure of 1.5 MPa for 48 hours, and the depth of water penetration determined. The diffusion coefficient can then be easily calculated, Swamy [17]. These results show that the incorporation of even the coarsest slag of 453 m^2/kg fineness can substantially reduce water penetration and water permeability. Since almost all aggressive ions that destroy concrete are transported through the water medium, the implication of the data in Table 2 is that slag concrete, and similar concretes incorporating pozzolanic/cementitious admixtures, can provide the best resistance to damage from chemical attack. The results in Table 2 also emphasize that a moderate increase in slag fineness can impart a very substantial increase in the impermeability of concrete. A judicious combination of cementitious materials and chemical admixtures can thus produce high durability concretes that possess not only high strength but also high impermeability.

TABLE 2. Pore volume and water tightness of PC-SLAG system.

Mixture	$\frac{W}{C+S}$	Slag fineness m^2/kg	Compressive Strength, MPa			
			3d	7d	28d	91d
A	0.40	None	38.6	48.9	59.5	69.3
B	0.40	453	15.2	27.7	58.7	69.5
C	0.40	786	17.9	36.4	67.8	90.6
D	0.30	786	31.3	64.2	104.2	115.8
E	0.40	1160	34.5	64.8	101.8	122.3

Mixture	Total pore vol. mm^3/g				Water permeability	
	3d	7d	28d	91d	Penetration mm	Diff. Coefft $\times 10^{-2} mm^2/s$
A	64.9	57.4	46.7	33.5	12.3	2.27
B	60.4	55.9	30.7	13.0	8.1	0.99
C	68.5	47.6	22.8	12.0	7.1	0.76
D	46.1	38.0	20.0	15.5	3.5	0.18
E	41.5	31.6	16.8	11.9	2.9	0.13

6.5. Chloride diffusion into sustainable concrete

There is now incontrovertible evidence that even when specific building code requirements 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 [1-6, 33-35]. Many tests show that cracking, depth of cover and quality of both the cover concrete and internal concrete are the three predominant interactive and inter-related parameters than influence the initiation, rate and extent of corrosion [17, 23, 36-40]. When these influences are superimposed on the time-dependent and interactive effects of load, exposure and climatic conditions to which a structure is exposed, corrosion deterioration becomes cumulative and very rapid. But ultimately it is the pore structure and permeability properties of the concrete that will control and govern the penetration of aggressive ions into concrete and which will eventually destroy the electrochemical stability of steel in concrete.

Chloride diffusivity into concrete thus plays a major role in the progression of corrosion of steel in concrete. However the results obtained from short term laboratory tests on small scale test specimens cannot and should not be directly extrapolated into actual field performance, because of the interactive and interdependent nature of the many parameters that influence cracking and corrosion. Table 3 presents chloride diffusion data obtained from $1000\times500\times150$ mm reinforced concrete slabs subjected to cyclic ponding with a 4% NaCl solution and drying, each cycle consisting of seven days of wetting followed by three days of drying. The concrete in the mixes contained

TABLE 3. Chloride diffusion into concrete after 50 cycles of wetting and drying.

Slab No.	W/b ratio	Mineral admixture	Depth from concrete surface, mm				
			5-25	25-45	45-65	65-85	85-105
S2	0.60	–	4.52 (100%)	2.32 (100%)	1.39 (100%)	0.87 (100%)	0.47 (100%)
S7	0.60	65% GGBFS	2.58 (57%)	1.05 (45%)	0.59 (42%)	0.21 (24%)	0.08 (17%)
S8	0.60	30% FA	5.02 (111%)	1.41 (61%)	0.81 (58%)	0.32 (37%)	0.17 (36%)
S9	0.60	10% SF	2.05 (41%)	0.20 (9%)	0.10 (7%)	0.00 (0%)	0.00 (0%)
S3	0.75	–	5.72 (100%)	3.33 (100%)	2.31 (100%)	1.32 (100%)	0.76 (100%)
S10	0.75	65% GGBFS	5.45 (95%)+	2.35 (71%)	1.55 (67%)	0.78 (59%)	0.31 (0.31%)

* Ratio of chloride concentration in slab divided by concentration in S2 at the same depth.

\+ Ratio of chloride concentration in slab S10 divided by concentration in S3 at the same depth.

350 kg/m^3 of total cementitious content; a high water-binder ratio of 0.6 was used partly to simulate concrete used in practice, and partly to highlight the benefits of supplementary cementing materials even at high water contents. All the cement replacements were made by mass. The acid-soluble chloride contents in the concrete were determined from cores, by mass of cement, using Volhardt's method as described in BS 1881. The results shown in Table 3 emphasize the high "*impermeability*" properties of concretes containing fly ash, slag or silica fume (SF), and point the way to achieve high durability of concrete construction in salt-laden aggressive environments.

6.6. Strength and elastic modulus

We seem to be obsessed with *Strength* and assume that *high strength concrete is, per se, highly durable.* Many laboratory tests and field experience provide clear evidence that this relationship cannot be taken for granted. The PC-slag system reported here was designed primarily for *durability* as shown in Fig. 1 and Tables 1 to 3. However, in the construction industry, adequate early strength has important technical and economic implications whereas long term high strength is necessary for structural adequacy and to resist unforeseen unexpected loads. To check the development of engineering properties of the high durability PC-slag concrete discussed here, compressive strength, tensile splitting strength, and elastic modulus were determined from

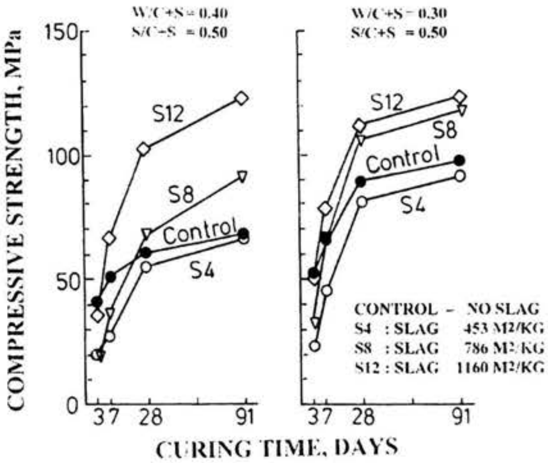

FIGURE 2. Strength development of PC-SLAG concrete.

100×200 mm cylinders subjected to various curing regimes. The compressive strength results under continuous water curing for three water/cement + slag (w/c+s) ratios from 0.30 to 0.40 are presented in Fig. 2. These data show that PC-slag concrete developed cylinder strengths of 18 to 35 MPa in 3 days increasing to 60 to 100 MPa at 28 days and 70 to 120 MPa at 91 days. The tensile splitting strength of these concretes under the same curing conditions ranged from 2.5 to 5.5 MPa at 7 days, and 4.0 to 6.0 MPa at 91 days. Seven day wet curing followed by air drying produced 50 to 105 MPa compressive strength at 28 days whereas prolonged air curing without any water curing developed 23 to 55 MPa at 7 days, 28 to 72 MPa at 28 days and 35 to 75 MPa at 91 days. The secant modulus of elasticity of these concretes ranged from 35 to 42 GPa as shown in Fig. 3 giving a strength (σ) – elastic modulus (E) relationship of

$$E = 20\left(\frac{\sigma}{20}\right)^{0.45} \cdot 10^3.$$

These results, and those shown in Figs. 2 and 3 confirm that concretes designed for high durability can also be designed to develop high early strength and high later strength to suit almost all civil/structural engineering applications. Indeed, the results presented in Figs. 1 to 3 and Tables 1 to 3 emphasize that concrete materials must be manufactured and designed for *durability rather than for strength*, and that with the *design principle* of *Strength Through Durability*, sustainability of concrete construction can be ensured.

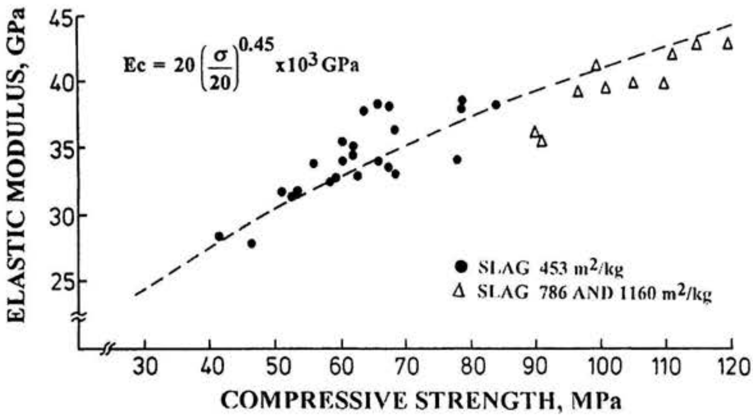

FIGURE 3. Strength-elastic modulus relationship of PC-SLAG concrete.

7. High-volume fly ash concrete

Of all cement replacement materials used in concrete, low-calcium fly ash, ASTM Class F, occupies a special position in concrete technology for a number of reasons. It is widely available, often in large quantities, and particularly in developing economies. It has been incorporated into concrete for over half a century, and the experience and reliability of the significant modifications that FA imparts to the engineering and durability properties of normal concrete are well understood, and equally well recognized in many national codes and standards [11-14, 17, 41].

High volume fly ash (HVFA) concrete, on the other hand, having a much higher fly ash content, of 50 to 60 percent by mass of the total cementitious material, has a particularly special attraction because of its suitability for a wide range of infrastructure construction. Although the concept of high volume replacement of cement with FA was recognized more than thirty years ago, systematic development of the material and its structural properties have only been recently established [42-44]. It is now known that it is possible to proportion HVFA concrete for structural applications to have good strength development, and excellent resistance to chloride ion penetration, sulfate attack, water permeability and freezing and thawing.

In the data presented here, the mix proportioning of HVFA concrete had the following special features:

(a) a small amount of a highly reactive pozzolan such as SF to accelerate early hydration reactivity, and to enhance pore refinement of the resulting concrete matrix [17, 23],

(b) a water-binder ratio of 0.40 to ensure continued pozzolanic activity and to enable continued hydration and densification of the cement matrix, particularly when exposed to hot/dry environments,

(c) the incorporation of additional FA as part replacement of sand, thus leading to a higher utilization of FA concrete in general.

The mix details are shown in Table 4, with two groups of mixes having total cementitious content of 350 kg/m^3 and 450 kg/m^3 respectively. The PC content in the two mixes were 150 kg/m^3 and 200 kg/m^3 respectively, the minimum considered for these mixes. All the mixes incorporated a carefully controlled amount of a HRWR to maintain a slump in the range of 150-180 mm without causing segregation or bleeding. The PC used was a normal ASTM Type I with a specific surface of 354 m^2/kg, and a total equivalent sodium oxide content of 0.59%. The FA had a specific surface of 370-400 m^2/kg, and the SF was used in the form of a slurry with 50% solid content. The test specimens were subjected to continuous water curing or prolonged air curing after an initial 7 day water curing.

The cube strength development of these mixes is shown in Tables 5 and 6. The results show that with HVFA concrete, strengths of 6 to 7 MPa were achieved in 1 day, increasing to 20 to 30 MPa at 7 days and 30 to 40 MPa at 28 days. With prolonged water curing up to 18 months, cube strengths of 60 to 70 MPa were obtained. At these high cement replacement levels, even 7 day initial water curing is not sufficient to realize the full strength potential of HVFA concrete, and under prolonged air drying, cube strengths of 60 to 70 MPa were reduced to 45 to 60 MPa. These and other engineering and durability data show that HVFA concrete has good potential for use in many

TABLE 4. Details of HVFA concrete mixtures (kg/m^3).

Type of mixture and identification	Total binder content	Cement	Fly ash	SF	Water	Coarse aggregate	Fine aggregate
350C	350	350	–	–	140	1183	637
350F	350	150	200	–	140	1183	637
350SF	350	150	180	20	140	1183	637
350S	350	150	180 (340)*	20	140	1183	160(Fly ash) 477(Sand)
450C	450	450	–	–	180	1183	637
450F	450	200	250	–	180	1183	637
450SF	450	200	230	20	180	1183	637
450S	450	200	230 (390)*	20	180	1183	160(Fly ash) 477(Sand)

* total fly ash content

TABLE 5. Compressive strength (MPa) development of HVFA concrete – water curing.

Age (days)	350F	350SF	350S	450F	450SF	450S
1	6.2	6.5	7.2	6.4	6.7	7.1
3	12.3	15.0	19.3	14.5	16.3	19.1
7	20.0	27.8	31.1	24.1	29.7	32.1
28	33.2	37.1	41.4	31.0	39.1	39.5
90	42.7	47.9	61.6	43.9	55.5	60.0
180	49.3	61.4	59.4	53.5	61.7	65.2
360	55.0	58.4	61.9	57.5	59.3	63.0
540	62.2	60.1	64.8	62.4	63.8	67.5

TABLE 6. Compressive strength (MPa) development of HVFA concrete – air curing.

Age (days)	350F	350SF	350S	450F	450SF	450S
1	6.2	6.5	7.2	6.4	6.7	7.1
3	12.3	15.0	19.3	14.5	16.3	19.1
7	20.0	27.8	31.1	24.1	29.7	32.1
28	28.4	29.9	38.9	28.6	38.1	39.3
90	41.0	46.0	56.3	42.7	56.0	58.5
180	42.0	56.5	61.9	51.7	54.6	63.0
360	46.8	54.8	60.9	47.0	55.7	62.0
540	47.1	52.6	58.2	45.9	56.4	57.2

structural and mass concrete applications in infrastructure rehabilitation and regeneration [45, 46].

8. Concrete with ternary blends

One of the great advantages of concrete as a construction material is that it can be formulated and fabricated to the precise needs of a particular application. It has been shown above that the incorporation of pozzolanic and/or cementitious industrial byproducts in concrete can enhance its engineering and durability properties. However, there are many situations where FA, slag or SF alone cannot give the range of properties required for long-term durable concrete performance in extreme environments. The data presented below show how to develop concretes capable of attaining high early strength and at the same time withstand attack by very aggressive agents and reduce the risk of deterioration in extreme environments.

The approach adopted to achieve this is to use a minimum PC content with combinations of FA/SF and slag/SF, and to examine their influence on the engineering properties, pore structure and oxygen permeability of such concretes, Swamy and Darwish [47]. To develop high early strength prior to 7 days, a minimum PC content is required, and in the tests reported here, an amount of $250\,kg/m^3$ was specified. To ensure early chemical activity, and to enhance pore refinement, a controlled small amount of a highly reactive pozzolan such as SF was incorporated. Fly Ash and slag were then added to ensure continued long-term pozzolanic and cementitious reactivity, and enhance durability. The total binder content was kept at $350\,kg/m^3$ or $450\,kg/m^3$. The water-binder content was kept at 0.45 to ensure continued hydration. All the mixtures were proportioned to have a slump of 100-150 mm through a HRWR. The PC had a specific surface of 354 m^2/kg; the FA was Type F low calcium, and the slag had a fineness of 417 m^2/kg. The SF was used in the form of a slurry with 50% solid contents.

Table 7 summarizes the mix proportions of the concretes used in this study. The early age strength development of all the concretes water cured to 7 days is shown in Tables 8 and 9. As is well known, FA and slag additions slow down strength development at early ages, Swamy [17]; nevertheless, one day cube strengths of 15 to 24 MPa were obtained with moderate replacements of PC, compared to about 27 MPa for the PC concrete. Seven day strengths of these concretes varied from 35 to 50 MPa.

TABLE 7. Mix proportions for concretes with ternary blends, kg/m^3.

Mix	Cement OPC	Silica fume	Fly ash	GGBFS	Water	Fine aggregate	Coarse aggregate	Superplasticiser*
W	350	–	–	–	157.5	600	1225	1.2
X	300	20	30	–	157.5	600	1225	1.2–1.5
Y	250	20	80	–	157.5	600	1225	1.2–1.5
Z	250	20	–	80	157.5	600	1225	1.2–1.5
ZX	300	25	–	125	202.5	600	1225	0.60
ZY	250	35	–	165	202.5	600	1225	0.68

* superplasticiser: weight % of cementitious content.

TABLE 8. Cube strength development of FA/SF concretes at early ages.

Concrete mixes, kg/m^3	Age, days	Compressive strenght, MPa	Percentage of 28 day strength
350 OPC	1	27.3	49
(W)	7	47.5	85
300 OPC+20 SF+30 FA	1	24.0	40
(X)	7	45.7	76
250 OPC+20 SF+80 FA	1	18.1	30
(Y)	7	40.8	69

TABLE 9. Cube strength development of SLAG/SF concretes at early ages.

Concrete mixes, kg/m^3	Age, days	Compressive strength, MPa	Percentage of 28 day strength
350 OPC (W)	1	27.3	49
	7	47.5	85
250 OPC+20 SF+80 slag (Z)	1	15.6	23
	7	48.6	70
300 OPC+25 SF+125 slag (ZX)	1	16.7	27
	7	39.6	64
300 OPC+35 SF+165 slag (ZY)	1	9.6	16
	7	36.6	60

TABLE 10. Long-term strength development.

Mix type, kg/m^3	Age, days	Compressive Strength, MPa		
		Wet	7d wet/air	Air
350 OPC (W)	28	55.7	57.9	52.9
	90	60.8	63.2	59.6
	260	68.5	71.5	62.2
300 OPC+20 SF+30 FA (X)	28	60.1	63.6	60.1
	90	75.5	77.3	71.1
	260	78.3	80.1	73.0
250 OPC+20 SF+80 FA (Y)	28	59.4	64.0	57.1
	90	67.8	72.7	61.0
	260	71.4	76.2	63.0
250 OPC+20 SF+80 Slag (Z)	28	67.9	70.9	61.7
	90	74.8	78.4	67.5
	260	84.8	88.0	70.1
300 OPC+25 SF+125 Slag (ZX)	28	–	62.1	48.6
250 OPC+35 SF+165 Slag (ZY)	28	61.6	61.0	44.4
	120	69.7	72.1	52.0

The long-term strength development of all the concretes is shown in Table 10. The 28 day cube strength of the FA/SF and slag/SF concretes ranged from 50 to 71 MPa compared to the PC concrete strength of 53 to 58 MPa. Between 4 and 9 months, FA and slag concretes reached 60 to 90 MPa, compared to 60 to 70 MPa for the concrete with PC alone.

Prolonged exposure to air drying slows down the strength development of all concretes, irrespective of whether they contain FA/slag/SF or not. However, with an adequate and minimum PC content and sufficient water content, it is possible to continue the hydration process albeit at a slower rate when FA and slag concretes are continuously exposed to a drying environment. The results in Table 10 show that up to about 30% cement replacement, FA and slag concretes can be designed to develop strength with time although at a slower rate, provided the mix contains an adequate amount of PC and water content to support continued hydration and pozzolanic reactivity even in a drying environment.

8.1. Postscript

The use of pozzolanic materials in concrete is not new. However, it is the availability, virtually all over the world, of industrial byproducts with pozzolanic properties that has refocused and rekindled the use of these cement replacement materials as an essential cementitious component of concrete. What we need to remember is that the ability of fly ash, slag, rice husk ash and other cement replacement materials to contribute to strength and durability is chemically bound within them. To extract and mobilise these qualities, we need to adopt the Holistic Design approach to optimise the improvements in workability, bleeding, heat of hydration, strength development and durability properties. Mix design then becomes very critical, particularly when high levels of cement replacement are employed. Field experience shows that low w/b ratios and very high superplasticizer dosages lead to susceptibility to early age cracking. This may occur as early as 15 min. after placing, and extend anything up to 5-6 hours. thereafter. Cracking under these conditions is very much influenced by lack of workability, and the very quick drying at the open surfaces caused by the dual effects of lack of bleeding, and the inability of whatever bleed water is present to move up to the surface. Field experience again shows that the early occurrence of such cracking may produce wide cracks of 1 to 3 mm width, whereas later age cracking results in a greater number of hairline cracks. The mechanism of this very early age cracking of plastic concrete may involve a combined effect of plastic shrinkage, thermal gradients and autogenous shrinkage. Durability thus needs to be designed for and a Holistic approach to design can mobilize the synergistic interactions of the portland cement – pozzolanic material – superplasticizer system to produce high performance concrete materials.

9. Structural lightweight aggregate concrete

As mentioned earlier, fly ash, as an industrial byproduct, occupies a very special place in this scenario of sustainable development. Fly Ash offers not only an efficient pozzolanic cement replacement material but also provides the basic ingredient for the production of good quality lightweight aggregates by the sintering process. In particular, a combination of fly ash aggregates and PC-FA cement matrix can create an excellent aggregate-matrix bond which is a key factor contributing to the durability of structural lightweight aggregate concrete (SLWAC) [48, 49]. Tests show that there is a close chemical affinity between, and within, the constituents of this type of concrete, and there is evidence that this contributes to the enhanced strength and durability of the material [49-53].

9.1. Mixture composition

From a large number of mixture design studies developed for sustainable construction, typical data on four mixture compositions are presented here. The composition of the concrete matrix was the main variable in these mixtures, (Table 11). The concretes were proportioned to have a minimum portland cement content of 250 kg/m^3, and a total cementitious content of 350 kg/m^3, incorporating a small amount of a highly reactive pozzolan such as silica fume (SF), and the balance made up with a low calcium type F fly ash (FA) or ground granulated blast furnace slag (GGBFS) or both. The mixtures were designed to have the same amounts of fine and coarse aggregates, and the same free water-binder ratio of 0.40; a superplasticizer was added, the amount of which was adjusted to give constant workability as measured by slump of 100 to 150 mm.

TABLE 11. Mix proportions for SLWAC.

Mix No.	Cement (kg/m^3)	SF (kg/m^3)	Slag (kg/m^3)	FA (kg/m^3)	Sand (kg/m^3)	Lytag (kg/m^3)	Free W/B*
N	350	–	–	–	635	715	0.4
F	300	20	–	30	635	715	0.4
S	300	20	30	–	635	715	0.4
SF	250	10	45	45	635	715	0.4

* W/B – free water to binder ratio.

The portland cement was of ASTM Type I with a specific surface of 365 m^2/kg, and a total equivalent sodium oxide alkali content of 0.83%. The slag had a fineness of 417 m^2/kg, whilst the fineness of the fly ash expressed as the mass proportion of the ash retained on a 45 μm mesh was 7.6%. The silica fume was used in liquid form with 50% solid contents. The fine aggregate was natural sand, and the coarse aggregate was the lightweight aggregate made from sintered pulverized fuel ash with a maximum size of 14 mm. The coarse aggregates were initially dried to a constant moisture content of 0.6%, and an average water absorption value of 12% was used for mix proportioning purposes [48, 51-54].

For the data presented here, two curing regimes were adopted after an initial 24 hours in the mould, namely, continuous water curing or 7 days water curing followed by air drying under ambient conditions.

9.2. Engineering properties

The development of compressive strength of the lightweight concretes tested in this study is shown in Figs. 4 and 5. The compressive strength reported here is the modified cube strength obtained by testing the broken halves of flexural test specimens. The results in Figs. 4 and 5 show that with these mixture compositions, strengths of about 25 MPa, 30-40 MPa and 50-55 MPa were obtained at 1 day, 3 days and 28 days respectively. At six months, the strength averaged 60 MPa. The results clearly demonstrate the effectiveness of a highly reactive pozzolan in compensating the loss of early age strength caused by the lower cement content, whereas the pozzolanic reactions contribute to the continued development of strength. With the porous lightweight aggregates capable of retaining moisture, prolonged air drying has much less adverse effect on strength development, compared to normal weight aggregates.

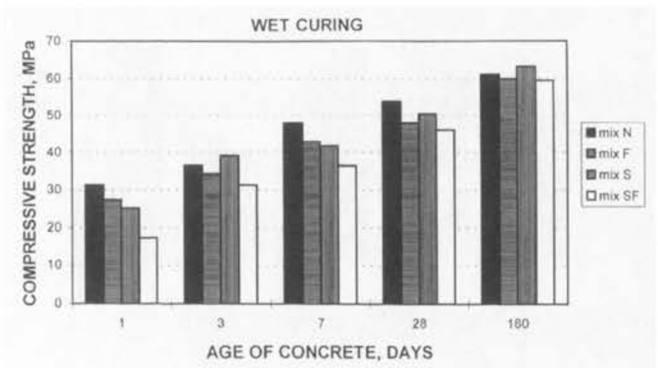

FIGURE 4. Development of cube strength of SLWAC (structural lightweight aggregate concrete) – wet curing.

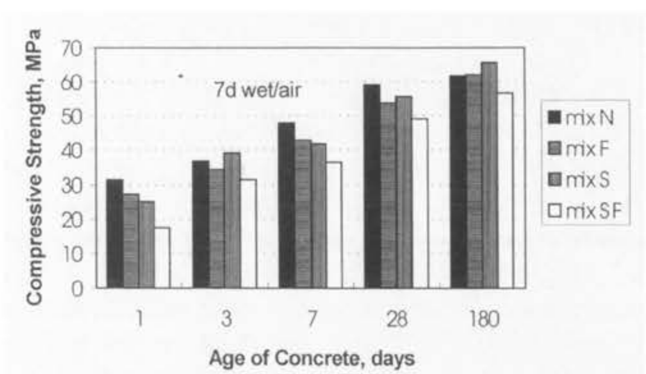

FIGURE 5. Development of cube strength of SLWAC under air drying.

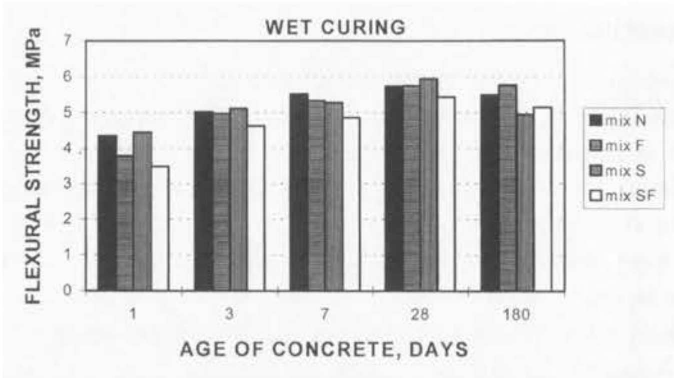

FIGURE 6. Development of flexural strength of SLWAC under wet curing.

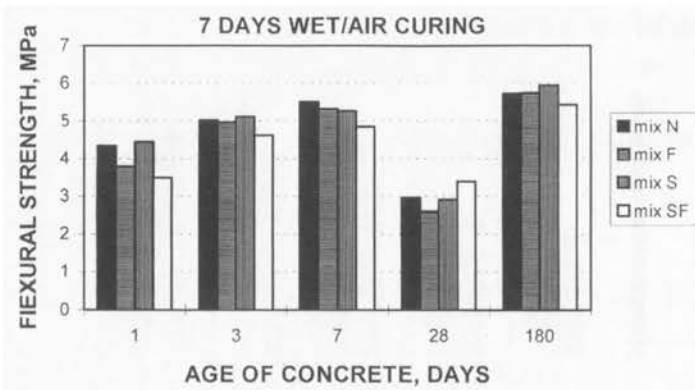

FIGURE 7. Development of flexural strength of SLWAC under air drying.

Figures 6 and 7 show the development of flexural strength with age for the two curing conditions. These results show flexural strengths of 5 MPa at 3 days, and 5.5 to 6.0 MPa at 28 days and beyond. Air drying has a much more significant effect on flexural strength than on compressive strength, as shown in Fig. 7, where a loss of strength occurs as a result of microcracking due to the presence of moisture gradient. However, once moisture equilibrium is reached, the microcracks heal and this loss in strength is fully recovered as shown in Fig. 7, and there is little difference in the flexural strength results between prolonged water or air curing at the age of six months and beyond.

The more interesting effect of the cement replacement materials is on the dynamic modulus of elasticity shown in Fig. 8. All the concretes containing supplementary cementing materials have a higher dynamic modulus of 10 to 15% compared to that of portland cement concrete. Even when exposed to

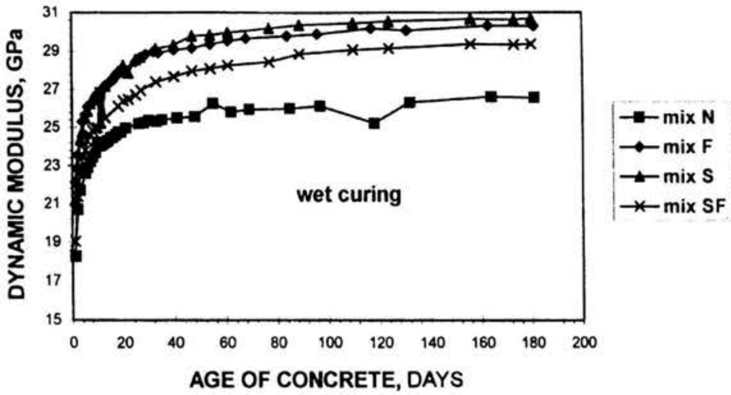

FIGURE 8. Dynamic modulus of SLWAC under wet curing.

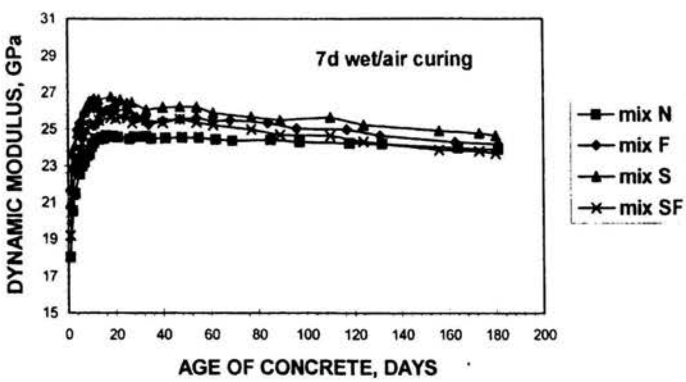

FIGURE 9. Dynamic modulus of SLWAC under air drying.

prolonged drying, concretes with SF and FA or slag are able to better retain their elastic modulus than portland cement concrete, (Fig. 9).

The results of the pulse velocity tests shown in Figs. 10 and 11 confirm the trend shown by the dynamic modulus values, and emphasize the contribution of mineral admixtures to the development of a more sound and dense internal microstructure compared to that of portland cement concrete, particularly when exposed to air drying for a long time. A reduction in pulse velocity is a measure of internal microcracking, and the results in Figs. 10 and 11 highlight the ability of mineral admixtures to develop a tightly knit microstructure compared to concrete with portland cement alone. These results partly explain why concretes with mineral admixtures show a much better long term durable performance than concrete without such admixtures.

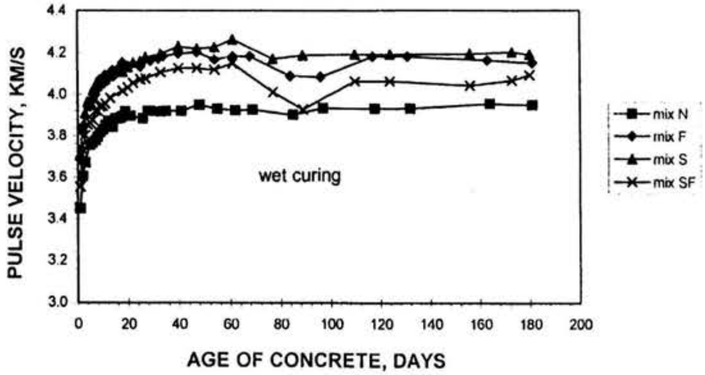

FIGURE 10. Pulse velocity of SLWAC under wet curing.

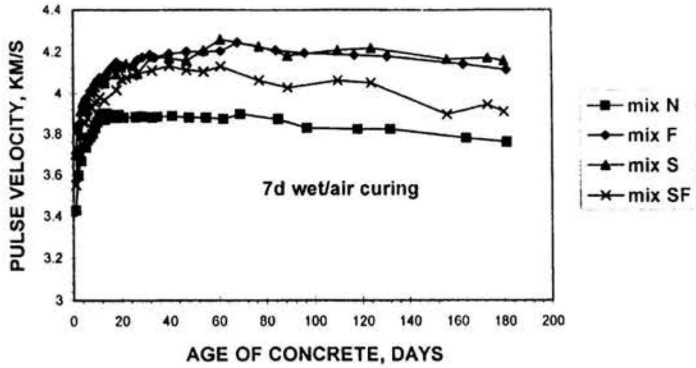

FIGURE 11. Pulse velocity of SLWAC under air drying.

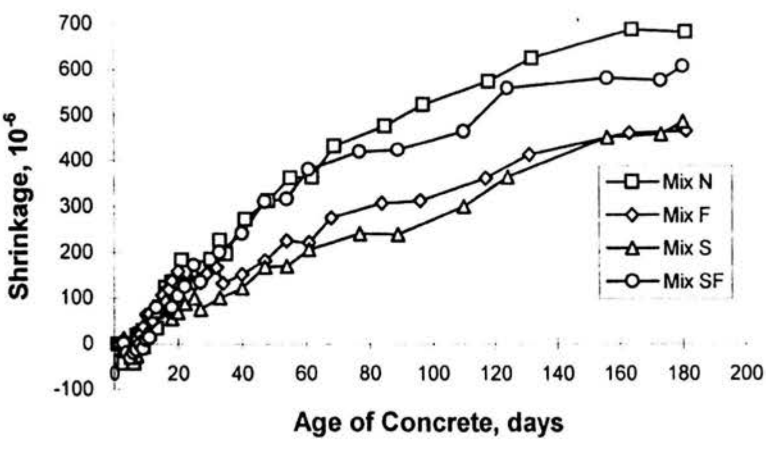

FIGURE 12. Effect of cement replacement materials on the drying shrinkage of SLWAC.

Figure 12 shows the effect of cement replacement materials on the drying shrinkage of *SLWAC*. The control concrete N without cement replacement materials is seen to have the highest drying shrinkage compared to all the other mixtures containing SF combined with FA or slag or both. The best results are shown by concretes with SF + FA or SF + slag – with a shrinkage value of 450 to $500 \cdot 10^{-6}$ compared to about $700 \cdot 10^{-6}$ of portland cement concrete.

The engineering properties of *SLWAC* highlighted in Figs. 4 to 12 emphasize several important implications. Firstly, the composition of the concrete matrix can be a significant factor in the development of the engineering properties and internal microstructure of *SLWAC*. A judicious combination of a small quantity of a highly reactive pozzolan together with FA or slag or a combination of both can make a substantial contribution to produce a sound and dense structure that maintains the material integrity even when the concrete is exposed to prolonged air drying conditions. Secondly, it appears that with aggregates which have an inbuilt physical porosity, a certain degree of initial moisture content in the aggregate can overcome the problems associated with the use of dry or fully saturated aggregates. Indeed, these results point to the undesirability of complete drying or complete saturation of structural lightweight aggregates, which has its own economic disadvantage. But, above all, the real significance of these results is that with no more than a total cementitious content of 350 kg/m^3, and structural lightweight aggregates, it is possible to obtain compressive strengths of the order of 25 MPa at one day, and strengths of 50 to 60 MPa at 28 days, and be able to harness the benefits of pozzolanic reactions for a long time, even when the material is exposed continuously to air drying conditions. These results also imply that very low water-binder ratios of the order of 0.30 are, perhaps, not desirable if we are to derive the full benefits of long term hydration and pozzolanic reactions in concrete matrices, particularly when the exposure environment is dry.

9.3. Oxygen permeability

The oxygen permeability measurements reported here were made on 50 mm dia × 35 mm high core specimens, carried out in a specially designed oxygen permeability cell, Swamy, Darwish [47] following the work of Lawrence [55] and Cabrera and Lynsdale [56]. Two test specimens were obtained from each 100 mm long core, drilled from the untrowelled face of the 100 × 100 × 500 mm long prisms; the top and bottom 15 mm of each core was removed, and only the central part of the core was used for the tests. The

TABLE 12. Oxygen permeability of SLWAC.

Mixes	Cementitious Materials (kg/m^3)	Permeability, 10^{-16}, m^2		
		7 days	28 days*	28 days**
N	350(OPC)	2.77	2.11	1.98
F	300(OPC)+20(SF)+30(FA)	2.38	0.99	0.81
S	300(OPC)+20(SF)+30(Slag)	1.21	1.14	0.94
SF	250(OPC)+10(SF)+45(FA)+45(Slag)	1.79	1.49	1.09

* 7 days wet/air curing;

** continous wet curing.

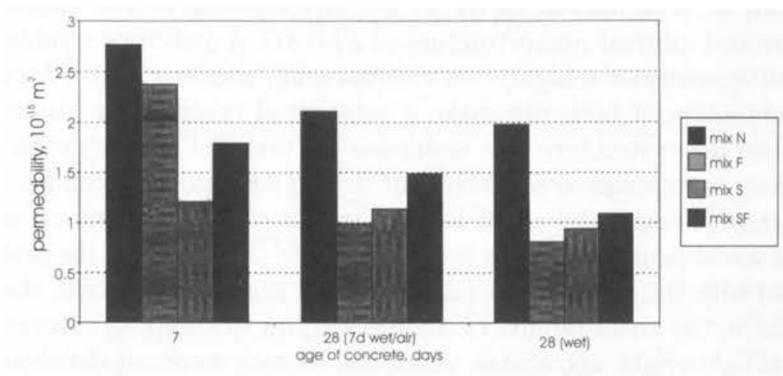

FIGURE 13. Oxygen permeability of SLWAC.

samples were conditioned by drying in an oven at $105 \pm 5°C$ for 24 hours, and this time of oven drying was kept constant for all the mixtures.

The experimental results of the oxygen permeability tests are shown in Table 12 and Fig. 13. The data clearly show that a concrete matrix based on SF and FA, slag or both greatly reduces the oxygen permeability of the concrete. This was evident even at 7 days, and by 28 days of wet curing, all the concretes with mineral admixtures had about one half of the permeability of the control concrete. The air drying affected mixture SF more than the mixtures F and S, emphasizing the inadequacy of 7 day water curing, and the need to water availability for the pozzolanic/cementitious reactions to continue when larger amounts of FA and slag are incorporated in concrete.

9.4. Pore structure

The pore structure analysis reported here was carried out using mercury intrusion porosimetry on the mortar fraction of the concretes at the age of 180 days. The results of these tests are summarized in Table 13. The results point out straightaway the benefits of incorporating cement replacement ma-

TABLE 13. Pore structure analysis of mortar in SLWAC at 180 days.

Mix No.	Total Pore Volume ml/g	Porosity %	Pore Size Distribution						Dc#
			0.1-9 μm		0.01-0.1 μm		<0.1 μm		μm
			ml/g	%	ml/g	%	ml/g	%	
N*	0.0569	12.19	0.0209	36.73	0.0338	59.40	0.0022	3.87	0.0722
F*	0.0593	12.23	0.0222	37.44	0.0332	55.99	0.0039	6.58	0.0722
S*	0.0439	9.24	0.0152	34.62	0.0235	53.53	0.0052	11.85	0.0301
SF*	0.0557	11.14	0.0193	34.65	0.0302	54.22	0.0062	11.13	0.0301
N**	0.0550	11.79	0.0179	32.55	0.0344	62.55	0.0027	4.91	0.0721
F**	0.0495	10.38	0.0099	20.00	0.0348	70.30	0.0048	9.70	0.0362
S**	0.0395	8.35	0.0083	21.01	0.0260	65.58	0.0052	13.16	0.0301
SF**	0.0507	10.70	0.0085	16.77	0.0338	66.67	0.0084	16.57	0.0226

Dc# – maximum continous pore diameter;

* – 7 days wet/air curing;

** – continous wet curing.

terials in the concrete matrix, even when the material is exposed to prolonged air curing after the initial 7 day water curing. It is seen that under continued wet curing, the mortar in the concrete containing SF, FA or/and slag have much smaller intruded pore volume than the control sample without cement replacement materials, with the mortar containing SF/slag having the smallest intruded pore volume. Even under prolonged air curing, the incorporation of cement replacement materials has a significant beneficial effect on the pore volume.

Table 13 also summarizes the results of the pore size distribution of the mortar in the concretes tested at 180 days. These results show clearly that cement replacement materials impart two important characteristics to the pore structure of the cement paste matrix. They enhance the volume of fine pores while decreasing the volume of large pores. They also substantially reduce the "maximum continuous pore diameter" [57,58]. Under continuous water curing SF in combination with FA and/or slag has a distinct and favourable refinement effect on the pore structure, and this effect is enhanced with increasing amounts of these cement replacement materials. In prolonged air drying environments, the effect of incorporation of these materials is not so pronounced, but the data show that even under such circumstances, there is a tangible refinement of the pore structure. The effect of drying conditions on the refinement of the pore structure is very much dependent on the composition of the cement matrix - what these results emphasize is that the potential for enhanced durability is inherent in these materials, but that the full benefits of their pore refinement capability can only be derived by adequate and well planned favourable curing conditions in the early stages of the development of the concrete matrix.

The clear message of the data shown in Tables 12 and 13, and Fig. 13 is that durability, and the resistance to ingress of deleterious external agents into concrete need not be the sole prerogative of normalweight aggregates. The initial moisture absorbed by the porous aggregates provides an internal curing mechanism which has a significant effect on the durability properties of the resulting concrete, but the overwhelming implication of the results presented here is that the overall durability characteristics of *SLWAC* are influenced predominantly by the nature and quality of the concrete matrix. These results simply reinforce other published data, and field experience, that *SLWAC* can provide all the necessary strength and stiffness for the long term durable performance of concrete structures made with lightweight aggregates. The invaluable and priceless bonus of *SLWAC* is that its utilization contributes directly to the philosophy of sustainable development of the construction industry throughout the world.

9.5. Shear strength

Unlike flexural failures, shear failures of reinforced concrete beams deserve special consideration in design because they not only reduce flexural strength and the associated ductility, but they also lead to sudden, brittle type of failures. Compared to dense aggregates, there is only limited data available on the shear resistance of lightweight aggregate concrete beams. Nevertheless, there is enough evidence to show that the failure pattern and the mechanisms of shear failure of *SLWAC* beams are very similar to those of normalweight concrete beams, and that no significant differences exist between the two concretes [59-61]. There are, however, differences relating mainly to the diagonal tension resistance of the two types of concrete. These arise from differences in bond stress, strength under combined stresses, and more importantly, from contributions to shear strength through aggregate interlock. Tests show that with lightweight aggregates, the diagonal cracks at failure tend to be wider, and the diagonal cracks fracture a much higher percentage of aggregate particles compared to gravel and crushed rock aggregates, resulting in a reduction in aggregate interface shear transfer [59-61]. With this better understanding of *SLWAC*, it is now possible to predict the ultimate shear strength of *SLWAC* beams, and establish permissible shear stresses at the ultimate limit state for the design of shear reinforcement [61-62].

9.6. Durability of steel

Many tests show that cracking, cover and the quality of concrete are the three predominant interactive and inter-related parameters that influence the initiation, rate and extent of corrosion of steel in concrete. Experience with lightweight concrete confirms that both corrosion and carbonation depend on these three parameters rather than on the type of aggregate used [49, 50]. Exposure tests of reinforced lightweight concrete prisms to sun, rain, wind and snow over a period of 10 years in an industrial area with high atmospheric pollution show low carbonation depths and that *SLWAC* can be as effective, if not better, in protecting steel against corrosion as normal weight concrete of similar quality [49, 50].

10. Portland limestone cements

The addition of fillers, such as ground limestone, to cements dates back to the late 19$^{\text{th}}$ century, primarily for more energy efficient manufacturing processes but without substantially affecting the properties of the cement. With the current emphasis on sustainable construction, portland limestone cements (PLC) have a great attraction for a variety of structural applications [63]. Portland limestone cements have been manufactured, for example, in France since 1976 – in 1990, there existed sixty seven brands of composite cements, of which sixty one contained limestone as a filler, whilst twenty nine of them had filler contents of 15 to 25%. The new Pre-European Standard, DD ENV 197, allows the addition of up to 35% by mass of limestone, whereas in the UK, the addition of finely divided limestone to PLC is restricted to a maximum of 20%, and such cements are recommended for use only in Class 1 sulfate conditions in accordance with BS 7583-1996. However, under BS12 "specifications for portland cement", 5% of limestone addition has been permitted since 1991 to be used in all the environments in the UK.

In many countries, limestone is available in abundance, and cement plants are often built close to limestone quarries. The practice of intergrinding limestone with clinker then becomes economically and technically attractive. Although fillers are generally considered to be non-hydraulic, it is now well known that the addition of ground limestone does affect the properties of the cement, and that the filler is not completely chemically "inert". Most of the early impetus for the use of PLC came from the belief that concrete strength is the major factor determining the performance of concretes. Experience had also shown that filler cements which were able to meet the requirements of the appropriate strength classes performed as well as traditional cement concretes. The general feeling was that, strength being the

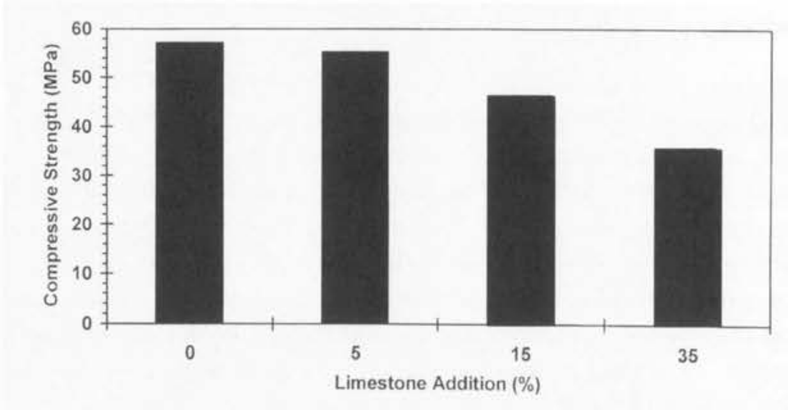

FIGURE 14. 28 day compressive strength of PLC mortar [64].

controlling factor, PLC that satisfied the appropriate specifications also possessed adequate durability for many applications. Excepting severely aggressive environments, blends of portland cement with limestone fillers, within specific limits of blending, were thus considered to offer improved concretes with similar strength and durability qualities as conventional concretes.

Tests show that the 28 day compressive strength of PLC mortar is reduced roughly in proportion to the limestone content as shown in Fig. 14. These results show that at 5% addition level, there is only a nominal loss in strength of less than 5%, but the 15% and 35% replacements can produce significant strength reductions of about 20% and 35% respectively. In spite of this, ageing in air appears to restore the loss in strength as shown in Fig. 15 – all the mortars with 0%, 5% and 15% limestone developed more or less the same compressive strength at 5°C and at 20°C in air. These results seem to indicate that limestone does not remain totally inert in the hydration process, and that it does participate, to some degree, and with increasing time, in the strength development process. However, there appears to be some progressive loss in strength at the 35% replacement level when exposed continually to drying at 20°C (Fig. 15).

The results shown in Figs. 14 and 15 confirm that the effects of carbonate additions to PC are not completely understood, and there are many conflicting views concerning their contribution, particularly, to durability [63, 64]. More importantly, concerns have centred recently on the formation of "thaumasite", a product of sulfate attack, which has been identified in a number of concrete structures containing limestone fines and/or limestone aggregates [65-68]. The effect on compressive strength of PLC mortar when exposed to magnesium sulfate attack is shown in Fig. 15. Prolonged exposure to $MgSO_4$

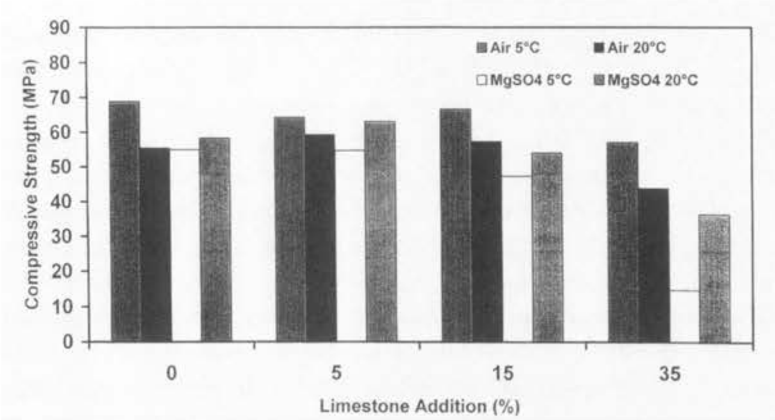

FIGURE 15. One year compressive strength of PLC mortar [64].

solution produced similar one year strengths up to 5% limestone content, and at 15% level, the strength loss is only about 10-15%. High compressive strength losses, however, occur at the end of one year at the 35% limestone content – about 40% when exposed to $MgSO_4$ solution at 20°C, and about 75% when exposed to the sulfate solution at 5°C.

The data in Figs. 14 and 15 confirm that *strength and durability* need to be considered together, particularly when long-term serviceability performance is considered, and when, in our quest for sustainability in concrete construction, new material technologies are used in practice. There is now considerable evidence to show that PLC concrete can be used safely in concrete construction but in exposure conditions where concrete is vulnerable to sulfate attack such as in foundations, sulfate-bearing soils and marine structures, extreme care as to the amount of filler content needs to be exercised [68,69]. More recent test evidence shows that the addition of slag and pozzolanic cement replacement materials can significantly counteract the adverse effects of the thaumasite form of sulfate attack [70, 71].

11. Low energy ecological cements

Although portland cement is the most eco-friendly construction material compared to steel and plastics, it still consumes a large amount of energy in its production process, Lawrence [72]. The sintering of the raw feed takes place at about 1450°C, and this is followed by grinding the clinker with the addition of 3-5% gypsum. The clinkering process thus utilizes about 60% of the total energy involved. The calcining of the $CaCO_3$ component absorbs about 1350 kJ/kg clinker, whereas the net heat balance for PC varies from 1674 to 1799 kJ/kg clinker. In practice, heat losses push the energy consumption up to about 3100-3600 kJ/kg. The production of ordinary portland cement is thus an energy – intensive process.

Recent studies show that the substitution of a high lime by a low lime cement should result in considerable energy saving as well as a reduction in CO_2 emission arising from the decarbonation of the limestone. A reduction in the firing temperature should enable low-grade fuels to be used, and this will also reduce the emission of greenhouse gases, Popescue et al. [73]. Tests show that low energy cements such as belite cements, sulphoaluminate belite cements and sulphoferroaluminate belite cements can be successfully manufactured with reasonably good properties from limestone, burnt clay, fly ash, pyrite ash, and gypsum or phosphogypsum. Such cements can provide a cheaper alternative to portland cement for many applications with the added benefit of improved durability and environmental friendliness [73].

12. Fibre reinforced concrete

When one looks back at the many innovations in concrete technology that have taken place during the last fifty years, the use of chemical admixtures, and in particular, the use of water-reducing and air-entraining agents would probably rank as one of the most relevant, and critical developments which has significantly enhanced the quality of concrete, and its overall durable performance. The use of fibre reinforcement and of pozzolanic materials, on the other hand, dates back to more than two millennia. Asbestos fibres, for example, are known to have been used almost 4500 years ago to strengthen clay pots, whereas straw, reed, horse hair and similar fibres are known to have been used in the early history of mankind to enhance fracture resistance and toughness of materials [74]. Pozzolanic materials for construction were used over two thousand years ago. The Pantheon in Rome, for example, is a standing monument to the ingenuity and skills of Roman civil engineers who used a mixture of lime, volcanic ash and crushed brick with tuff and pumice aggregates to create a structure that has withstood the ravages of time, the elements and human vandalism. It therefore stands to reason that the combined use of chemical admixtures, mineral admixtures and fibre reinforcement can be expected to forge a synergistic interaction to bring out the unique properties of each of these concrete constituents, and produce a new class of construction materials that are tough, placeable, compactable, crack resistant and durable [17, 18, 74]. It is therefore not surprising that the last three decades have seen phenomenal developments and advancements in the field of fibre reinforced cement and concrete (FRC) [75-77] – it is now possible to produce a wide range of engineered high performance fibre cement composites that are characterized by multiple cracking, extensive strain hardening and high energy absorption properties.

However, the greatest challenge of the 21^{st} century is the need for cost-effective, durable and eco-friendly construction materials that will meet the global needs of infrastructure regeneration and rehabilitation which at the same time can enhance the quality of life for all the peoples of the world. We have now enough technical data to utilize a judicious combination of portland cement, pozzolanic/cementitious industrial byproducts, chemical admixtures and fibres that can produce a wide range of FRC materials that are durable, strong and stiff, highly crack resistant, very ductile and capable of large amounts of energy absorption [78-81]. Fibres are also very effective in acting compositely with conventional steel reinforcement, and the fibre-reinforcing bar synergistic interaction is highly capable of resisting structural deformations at all stages of loading from first crack to failure. This is illustrated in Table 14 for SLWAC FRC slab-column connections subjected to flexural loads and punching shear failure. These results emphasize the role of steel fibres in transforming an inherently unstable and uncontrolled tensile cracking in concrete into a ductile structural performance of reinforced concrete (RC) elements.

TABLE 14. Strength properties of SLWAC FRC slabs.

Slag	Fibre Vol. %	A	B	C	D
FS-1	0	32.0	105.0	129.0	173.5
FS-2	0.5	42.5	120.0	162.0	225.0
FS-3	1.0	46.8	135.0	174.0	247.5

A – Visible first crack load, kN
B – Shear crack load, kN
C – Yield load, kN
D – Failure load, kN

Floods, mud slides, hurricanes and tornadoes impose severe dynamic forces, like seismic loads, on RC structural members, and this is an aspect that needs to be considered in future constructions if sustainable growth is to be achieved. As pointed out earlier, one of the basic properties of fibre reinforcement is its ability to transform a relatively brittle material to tolerate extensive damage and develop high post-cracking ductility and energy absorption capability prior to failure. These engineering properties are best expressed in terms of a structural parameter such as deflection or moment-rotation characteristic or energy absorbed as represented by the area under

TABLE 15. Post-yield ductility and energy absorption: SLWAC FRC slabs.

Slab	Fibre Vol. %	Ductility $\Delta 2/\Delta 1$	Increase in ductility	Energy absorption capacity (kNm)	Increase in energy absorption capacity
FS1*	0.0	23.5	1.00	3.30	1.00
FS4*	1.0	53.0	2.25	11.13	3.37
FS19†	0.0	21.2	1.00	2.40	1.00
FS20†	1.0	76.7	3.62	8.86	3.69

* steel ratio 0.5574, paddle fibres confined to 550 mm all round column

† steel ratio 0.3716, crimped fibres over entire slab

Ductility ratio based on deflection at 30% of maximum load

the load-deflection diagram, Fig. 16. Table 15 illustrates these concepts as applied to slab-column connections made of SLWAC, Theodorakopoulos and Swamy [80]. These data emphasize the need for material characteristics to be interpreted in terms of structural performance, and show that mechanical properties such as toughness indices may not always give a complete picture of their technical benefits when used in structures.

Although fibre concrete has been extensively used in a wide range of infrastructure rehabilitation and regeneration applications, its incorporation in RC structural members is very limited. One of the reasons for this situation is our lack of appreciation that ductility should form an important and inherent aspect of structural design. As pointed out earlier, lack of durability is one of the major obstacles to achieving sustainability in concrete construction and brittle failures and progressive collapse contribute significantly to this lack of durability. Flat slabs, a popular and economic form of construction with many practical advantages, are a case in point. These elements can often be subject to a major structural weakness characterised by a rather sudden and catastrophic type of brittle failure arising from punching shear. Many tests show that punching is a form of combined shearing and splitting, occurring without concrete crushing, under complex three dimensional stresses. Although the tension steel in the slab close to the column yields, especially when realistic reinforcement percentages are used, punching shear failure occurs in the compression zone before yielding extends beyond the vicinity of the column and before an overall yield mechanism can develop [80-85].

Steel fibre reinforcement, on the other hand, restrains cracking, and increases both the tensile strength of concrete, and the bond resistance of steel reinforcement. The main function of steel fibres is to control crack propagation and crack widening after the matrix has cracked. Control of cracking automatically enhances material and structural stiffness, and the non-linear post-cracking stage can impart the ability to absorb large amounts of energy

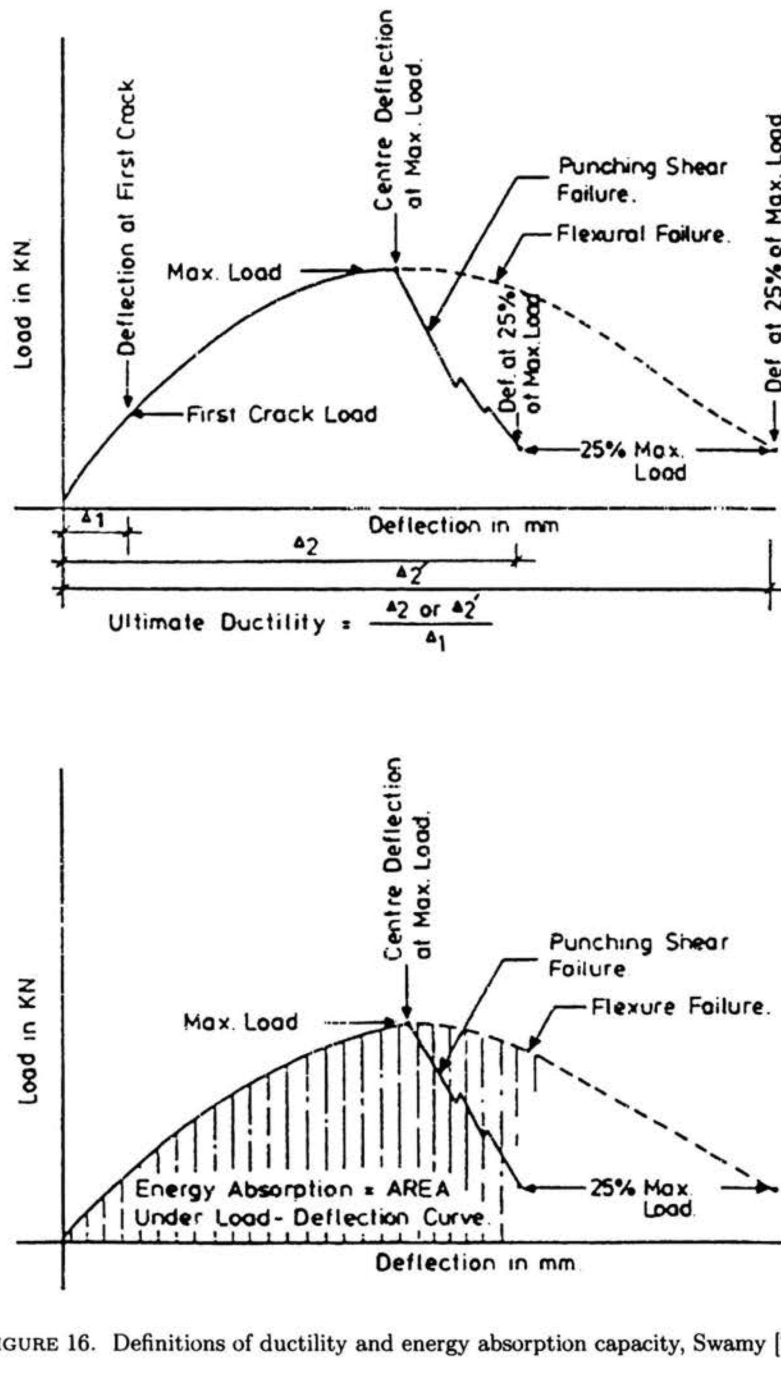

FIGURE 16. Definitions of ductility and energy absorption capacity, Swamy [79].

before failure and collapse. Extensive studies show that fibres can act compositely with conventional steel bars, and that such fibre-bar interaction is synergistic. A direct result of these synergistic interactions is that fibres become very effective in resisting structural deformations at all stages of loading, from first crack to failure, resulting in a better distribution of cracks, control of penetration of shear cracks, and more extensive multiple cracking as failure approaches. It is this transformation of an inherently unstable and uncontrolled tensile cracking behaviour of concrete into a slow, controlled crack growth that is primarily responsible for the increased flexural rigidity, better structural performance and overall ductility of the structural member. The net result is that the slab is able to develop an overall yield mechanism which can transform a sudden structural failure into a very ductile mode even if shear cracks appear at the failure stage.

Until recently, however, the use of steel fibre concrete to counteract brittle punching shear failures had been hampered by the absence of a reliable theoretical model and design equations. This is no longer the case [84-85]. Existing Code provisions do not account for the presence of fibre reinforcement in concrete, and they will therefore underestimate the ultimate loads of slabs with fibre reinforcement. There is now incontrovertible evidence that the new model and design equations are reliable, based on sound engineering principles, and reflect the true structural behaviour of slab – column connections. A critical evaluation of the structural behaviour of reinforced concrete slabs without and with fibre reinforcement and existing code provisions show that punching strength is not a simple function of concrete strength and the steel reinforcement ratio but a combined effect of the resistance offered by the shear and flexural sections of the slab.

Steel fibre concrete is an exciting construction material that possesses unique properties of high energy absorption capability and ductility. Its use in conjunction with flab slabs can lead to a new structural system having a high ultimate strength, characterized by a ductile mode of failure. Many tests on slab-column connections made with steel fibre concrete show that this new structural system can offer distinct advantages of structural integrity, structural stability and a high degree of ductility particularly when dynamic forces are involved.

13. Natural fibre cement composites

As explained earlier, fibre reinforcement of cementitious materials still remains an exciting and innovative technology because of the basic engineering properties of crack resistance, ductility and energy absorption that it imparts to concrete - properties that ensure long, trouble-free service life to many of the infrastructure constructions that enhance the quality of life, Swamy [81]. Natural fibre cement composites occupy a special place in this development of fibre reinforced cement and concrete, because of the luxurious abundance and availability of natural fibres in many parts of the world, and also because they lead directly to energy savings, conservation of a country's scarce resources and reduction in environmental pollution. The fact that one of the most easily and readily replenishable earth's resources can be used to solve one of the most acute forms of human deprivation, is just as challenging not only to the basic human instinct of fellow feeling, but also to the science and engineering skills of advanced technologies [86-88]. Their use has taken a special relevance and significance in the context of damage and destruction caused to infrastructure by natural disasters arising from global warming, the need to protect the environment, and to establish sustainable development of the construction industry.

Bamboo and wood fibre cement composites are exceptional in this respect, not only because of their eco-friendly nature but also because they provide the most economic and socially useful outlet for bamboo chips, wood residues and agricultural wastes. The combination of bamboo/wood particles and an inorganic cementitious binder can produce a new class of building products that can reflect the good characteristics of wood and concrete. Cement-bonded particleboards (CBP), as they are generally called, can be designed to possess good engineering properties for a wide range of applications in the building, housing and other commercial/infrastructure projects. The cementitious binder encapsulates the wood/bamboo particles, fibre and aggregates, and the composite can be designed to have high resistance to fire, termites, fungus and other bio-degrading agents. Further, their high weather resistance and low sound transmission properties combined with the ability to accept a wide range of surface treatments make these products highly attractive for a variety of applications such as partitions, internal and external walls, roof elements and permanent formwork.

One of the major factors challenging the development of durable wood/bamboo fibre cement composites is the many inherent weaknesses of the fibres themselves such as their low elastic modulus, high water absorption, susceptibility to fungal and insect attack, and lack of durability in an alkaline environment [86-89]. There is a lack of precise scientific information on the structure and engineering properties of the wide varieties of available fibres themselves, and their compatibility with the various cement matrices. Further, many plant fibres contain hemicellulose, starch, sugar, tannins, certain phenols and lignin, all of which are known to inhibit normal setting and strength development properties of the cement matrix. The water soluble extractives also prevent these composites from attaining their full durability characteristics [89, 90]. Nevertheless, extensive research to date shows that a combination of low alkali cementitious materials, chemical admixtures and modern production processes under controlled compaction and temperature conditions can lead to the manufacture of cost-effective, durable, and eco-friendly cement bonded particle boards for wide ranging applications in infrastructure regeneration and rehabilitation [86-95].

To illustrate the strength and durability potential of bamboo and wood fibre cement composites, Tables 16 to 18 are presented here, Sudin and Swamy [95]. Table 16 summarizes the strength and dimensional stability properties of bamboo cement-bonded boards (BCB) – the type of bamboo used in the study was *Bambusa Vulgaris* from Malaysia. The data presented in this Table relate to bending strength (BS), internal bond (IB), water absorption (WA) and thickness swelling (TS). Tables 17 and 18 relate to cement

TABLE 16. Strength and dimensional stability properties of BCB [95].

Bamboo Cement ratio	Chemical Additives	BS (MPa)	IB (MPa)	WA (%)	TS (%)
1 : 2.50	–	2.43	0.07	29.00	2.15
1 : 2.75	–	3.87	0.12	26.10	1.17
1 : 3.00	–	5.04	0.23	20.40	1.26
1 : 2.75	$CaCl_2$	5.48	0.19	24.64	2.26
1 : 2.75	$MgCl_2$	6.93	0.43	15.97	1.11
1 : 2.75	$Al_2(SO_4)_3$	9.25	0.63	14.40	0.76
1 : 2.75	$Al_2(SO_4)_3+Na_2SiO_3$	9.41	0.77	12.57	0.82
MS 934	–	9.00	0.50	–	<2.00

TABLE 17. Engineering properties of composite boards with OPT fibres [95].

Test series	Admixture	Cement replacement %	Board density (kg/m^3)	MOR (MPa)	MOE (MPa)	IB (MPa)
Control	–	–	1366	12.81	3909	1.087
FFA	FA	10	1274	10.06	3231	0.755
FFB	FA	20	1292	10.25	3365	0.713
FFC	FA	30	1260	5.61	1996	0.231
FRA	RHA	10	1323	10.77	3440	0.901
FRB	RHA	20	1263	9.44	2990	0.610
FRC	RHA	30	1165	5.93	1664	0.236
FLA	Latex	10	1341	11.68	3269	0.975
FLB	Latex	20	1336	9.70	2973	0.681
FLC	Latex	30	1215	6.16	1215	0.581
MS 934 (1986)			>1000	9	3000	0.5

TABLE 18. Dimensional stability properties of composite boards with OPT fibres [95].

Test series	Admixture	Cement replacement %	Average density (kg/m^3)	Water abs. (%)	Thickness swelling (%)
Control	–	–	1359	12.54	0.97
FFA	FA	10	1269	15.26	0.89
FFB	FA	20	1298	15.30	1.08
FFC	FA	30	1249	19.35	1.76
FRA	RHA	10	1327	13.51	0.66
FRB	RHA	20	1286	14.77	0.68
FRC	RHA	30	1209	15.32	1.03
FLA	Latex	10	1353	10.84	0.60
FLB	Latex	20	1365	11.71	1.54
FLC	Latex	30	1245	14.66	1.21
MS 934 (1986)			>1000	–	<2.0

boards made with oil palm trunk (OPT) fibres extracted from oil palm trees. Fly ash (FA), rice husk ash (RHA) and latex were used as cement replacement materials for these boards. Table 17 presents the engineering properties of these composite boards – modulus of rupture (MOR), modulus of elasticity (MOE) and IB. Table 18 summarises the dimensional stability properties of these boards. All the tests reported in these Tables were carried out to specifications to satisfy the International Specification for CBP, ISO 8335, 1987. The minimum strength and durability requirements for these boards according to Malaysian Standard MS 934 are also given in these Tables.

13.1. General discussion

The sugar content analysis showed that Bambusa vulgaris culm possessed a very high amount of sugars, about 4.92%. This had a significant retardation effect on the setting and strength development of the portland cement matrix. This, in effect, meant that portland cement matrix alone will not enable a bamboo cement board to be produced with the necessary engineering properties. A bamboo-cement ratio of 1:3 was considered maximum; beyond this ratio, the boards were likely to become uneconomic, and it was felt that a higher ratio may also lead to brittle behaviour of the boards. The incorporation of chemical accelerators was thus found essential to enhance the strength properties of the BCB. And as shown in Table 16, a bamboo-cement ratio of 1:2.75 and the addition of 2% of aluminium sulfate by mass of cement or a combination of aluminium sulfate and sodium silicate produced an acceptable board that satisfied the strength properties and dimensional stability requirements of the Malaysian Standard MS 934. The results of this study confirm that bamboo flakes can be successfully incorporated in the manufacture of bamboo cement-bonded boards.

Hydration tests were carried out to examine the implications of using FA, RHA and latex as cement replacement materials, and the results confirmed that FA, RHA and latex can all be successfully used as cement replacement materials in the production of oil palm tree fibre cement boards. These results, however, also confirmed that there is an optimum amount of cement replacement beyond which there was a significant reduction in bending strength and elastic modulus, and a progressive increase in water absorption and thickness swelling of the boards. The results also showed that locally burnt white RHA can be ground to have pozzolanic properties. At 10% replacement level, latex imparted better engineering properties to the particleboard compared to FA and RHA, and RHA gave better performance than FA. At 20% replacement level, FA gave better strength properties than RHA and latex. However, when dimensional stability is considered, the latex gave the best performance at 10% and 20% replacement levels. These results gain confirm that oil palm fibre cement boards can be successfully produced with 10-20% of cement replacement materials to satisfy the engineering properties and dimensional stability requirements of national standards (Tables 17 and 18).

The results of this study show that flakes produced from naturally occurring bamboo, and fibres extracted from agricultural wastes emanating from oil palm trees can be utilized to produce cement-bonded particleboards for applications in the housing and building industries and in infrastructure construction. These studies emphasize that with a holistic approach combining cement replacement materials, chemical admixtures and modem production processes, bamboo flakes and oil palm fibres can be successfully utilized to produce particleboards that will satisfy the strength and dimensional stability requirements of national standards and which can be used in a wide range of infrastructure construction applications. Practical applications of these cement composite boards again confirm that they possess excellent durability properties with very satisfactory levels of long-term performance under internal and external exposure conditions.

14. Concluding remarks

We live in a rapidly changing world. The construction industry is currently faced with two major challenges – there is a massive worldwide need for infrastructure regeneration and rehabilitation, and equally urgently, we need to achieve sustainability in the construction industry. These two challenges arise from a host of causes, but primarily because we have been consuming the non-renewable material and energy resources of the world far too quickly, and inequitably. In that process, we have also created uncontrolled environmental pollution and unacceptable creation of waste. The resulting massive increase in the emission of greenhouse gases and global warming, combined with human conflict, and world poverty, have fuelled damage, deterioration and destruction of world infrastructure. This paper advocates a holistic design approach, integrating material characteristics and structural performance, to create rehabilitation and regeneration of our infrastructure, and to achieve sustainable growth of the construction industry.

Sustainability is a complex, wide-ranging, global issue that, if neglected, will have devastating effects on the economic, social and environmental well-being of all peoples of the world. It has an impact on those who live on the planet now – and it will govern the lives of future generations. Whether global warming is the result of natural phenomena or human profligacy, the issues of sustainability demand that we protect and safeguard this planet, its peoples, its resources and its environment.

Concrete, and cement-based construction materials are widely recognized as the only materials that will satisfy the insatiable needs of the human race for basic infrastructure facilities that alone will give them a reasonable and decent quality of living. Use of cement replacement materials, the production of materials for durability rather than for strength, use of low energy cements, design for material stability and structural integrity, and design for sustainability are the key elements to achieve sustainable growth of the cement/concrete industry. The use of industrial byproducts such as fly ash, rice husk ash and slag, lightweight aggregates produced from industrial waste and natural fibres, for example, can give us a wide range of cost-effective, environmentally friendly, innovative and sustainable construction materials for a large number of applications in the civil and structural engineering sector. They can thus contribute to a *better quality of life for all mankind.*

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