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Sustainable Concrete for the 21st Century

Concept of Strength through Durability

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ABSTRACT

The world is passing through difficult and troubled times, and we live in a rapidly changing world. The construction industry is facing many challenges – global warming, climate change forces, and the capability to achieve sustainable development and economic progress without damaging our environment. The concrete industry in particular faces further challenges. There is extensive evidence to show that concrete materials and concrete structures all over the world are deteriorating at a rapid rate, and that we are unable to ensure their long-term durable service life performance. To confound this situation, we are also faced with an urgent need to regenerate our infrastructure systems if we are to eradicate poverty and provide a decent Quality of Life for all the peoples of the world. This paper shows that the current emphasis on high strength and very high strength, and the design philosophy of Durability through Strength for concrete materials and concrete structures is fundamentally flawed. It is this misleading concept and vision that is primarily responsible for the lack of durable performance of concrete in real life environments. To change this scenario, this paper advocates that concrete materials must be manufactured for durability and not for strength. It is shown that this concept of Strength through Durability can be achieved through careful design of the cement matrix and its microstructure. If concrete is to be an eco-friendly, and sustainable driving force and construction material for social change, the need is to produce durable concrete with strengths of

30 to 60 to 80 MPa rather than very high strength concrete without an assured durable performance.

Introduction

Engineers are, by nature, fascinated and indeed obsessed, by high strength and very high strength concrete. Part of this fascination arises from the widely-held misconception that high strength concretes are, *per se*, highly durable. This intuitive association of strength with durability is again partly due to the current Ultimate Strength Design approach which creates an implicit belief and illusion that if concrete is proportioned to give high compressive strength, and then, if prescriptive code specifications in terms of cement content, water/cementitious materials (w/cm) ratios, types of cement, steel cover thickness and types and amounts of mineral and chemical admixtures are adhered to, then somehow the durable service life of the concrete structure will be automatically and adequately assured. The impetus for higher and higher concrete strengths also came from demands for exceptional increases in the height of high-rise buildings and for long span bridges (1). Indeed, the higher concrete strengths also brought in visible economies in terms of use of materials, increased useable space and shorter times of construction. As a result the latter part of the last century saw the development and use of concrete with compressive strengths from about 40 to 100/120 MPa and beyond (1).

High Strength Concrete

In practice, high strength concretes, and many of the so-called high performance concretes, are characterized by high cement factors and very low w/cm ratios. Such concretes generally suffer from two major weaknesses. Experience shows that it is extremely difficult to obtain proper workability with such concrete mixes, and indeed, to retain the workability for a sufficiently long period of time. High dosages of high range water reducing agents (HRWR) then become a necessity, and the resulting cohesive and thixotropic, sticky mixes are equally difficult to place and compact fully and efficiently (2,3). These problems indicate that there is probably a critical limit – a threshold – for the water content below which high HRWR dosages become not only essential but also unhelpful and undesirable, and often even harmful from a durability point of view.

The other major casualty of very low w/cm ratios and very high HRWR dosages is the susceptibility of these concretes to very early age cracking (2-5). This may occur as early as 15 min after placing, and extend anything up to 5-6 hrs thereafter. Cracking under these conditions is very much influenced by loss 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. The quicker these phenomena occur, and the shorter the initial and final setting times, the more likely for this cracking in the plastic stage to be intense. Experience of full scale construction activities shows that the early occurrence of such cracking leads to wide cracks of 1 to 3 mm width, whereas later age cracking results in greater number of hairline cracks. The exact mechanisms of this very early age cracking of plastic concrete is not clear, but this seems to be a combined effect of autogenous shrinkage, plastic shrinkage, thermal gradients and plastic settlement.

Cracking is the scourge that will always haunt concrete durability. High strength concrete is particularly susceptible to cracking when subjected to restrained drying shrinkage since the higher the strength of the concrete, the higher the elastic modulus, and the lower the capacity for creep (5). Multiple surveys of 76 monolithic bridge decks in the States over an 11 year period show that as compressive strength increased from 31 to 45 MPa, cracking increased by more than threefold when subjected to restrained drying shrinkage (6). The use of high concrete strengths does not thus always imply a high level of durability for the concrete structure.

High strength vs durability

In spite of the technical and possible economic advantages of high strength concrete, and in spite of the significant advances that have been made in our understanding of the science, mechanics and engineering of concrete materials and structures, the overwhelming field evidence is the alarming and unacceptable rate at which our infrastructure all over the world are suffering from deterioration and damage when exposed to real and aggressive environments (7-9). Structures seldom fail due to lack of intrinsic strength, *per se*. Serviceability failures, on the other hand, appear to be the perennial and unending disease affecting the service life of concrete structures. The American Society of Civil Engineers 1998 Report graded the state of American Infrastructure with an average D (Poor). This report also required an investment of some \$1.3 trillion to put the roads, bridges, and water/waste/energy utilities to good working order. In 2005, the investment needed was \$1.6 trillion to raise the quality of America's infrastructure to a satisfactory level. The New Civil Engineer (NCE)/Institution of Civil Engineers (ICE) State of the Nation Report in Winter 2001 graded the overall quality of the UK Infrastructure as C- (C Average). It is reported that repair and maintenance make up some 40% of all construction work in the UK.

The overwhelming field evidence from all over the world, which is there in black and white for us all to see, is that we have an Infrastructure crisis facing the construction industry where we are unable to ensure durable service life performance during the design life of the structure.

There is unchallengeable and convincing evidence that compressive strength is rather a poor indicator – indeed, an insufficient and inadequate indicator - of concrete material stability and structural integrity. There is also extensive test data to confirm that there is no simple or unique relationship between strength and any of the parameters which can ensure durability. Lack of serviceability – leading to lack of safety, loss of strength, loss of ductility and loss of structural stability and integrity – is, without a shadow of doubt, the perennial disease afflicting concrete structures. All the evidence we thus have is that the concept of Durability through Strength, which is implicitly embodied in the Ultimate Strength Design approach, is neither valid nor attainable.

Strength through Durability

Whilst concretes of very high compressive strength in excess of 100-120 MPa will have application in specialist structures, the vast majority of buildings, bridges and other infrastructure constructions only need strengths in the range of 30-60-80 MPa. So the current challenge, bearing in mind the need for sustainable construction (10), is this – can we produce concretes of adequate strength with a high degree of durability against the time-dependant interactions of loads, ageing, cracking, ambient exposure conditions and climate change forces? What are the essential ingredients for the production of such High Durability Concrete, based on the concept of Strength through Durability – concretes that are cost-effective, environmentally friendly and sustainable?

Experience tells us that concretes with very high cement contents and very low w/cm ratios are extremely hard to place, compact and cure, and highly prone to cracking as discussed earlier. With the new generation of chemical admixtures, it is of course possible to overcome some of these difficulties, but even then, it is better to limit the total cementitious content and the w/cm ratio of high durability concrete (HDC) to a maximum of 400-450 kg/m^3 and a minimum/maximum of 0.40 respectively. There is now conclusive evidence that even when specific code requirements for durability in terms of concrete quality and concrete cover are achieved in practice, concretes made with only portland cement, as currently manufactured, are not totally resistant to deterioration when exposed to aggressive salt-laden environments (11).

The major weakness of modern portland cements is that, unfortunately, they are manufactured for strength. A critical review of the compound (Bogue) composition of many portland cements shows that there has been a significant increase in the C_3S/C_2S ratios of modern portland cements from about 1.5 to 5.0. This change in chemical composition results in higher strengths at early ages, with a lower proportion of strength developed after 28 days. An unwelcome implication of this change in chemical composition is that structural design strengths could be achieved with lower cement contents and higher water/cement ratios. Another direct result of this change in chemical composition, not always fully appreciated by structural engineers, is the increase in the heat of hydration, and more importantly, in the evolution of heat at early ages. The increase in peak temperature and its much earlier occurrence can give rise to undesirable thermal gradients. The internal microcracking induced by these thermal gradients is slow to heal and hard to stop (11). In addition, there is extensive test evidence to emphasize that whilst there is, in general, a qualitative relationship between strength and those properties that determine durability, there is no unique, single quantitative relationship between strength and durability (12). This explains why there have been widespread deterioration and damage to our infrastructure systems all over the world during the last few decades.

On the other hand, it is now well-established that one of the key ways of enhancing the durable quality of portland cement concrete in its fresh and hardened states is to ensure that pozzolanic and/or cementitious industrial byproducts form vital and essential constituents of the concrete (13-15). In the fresh state, a judicious combination of portland cement (PC) and these siliceous mineral admixtures, together with appropriate chemical admixtures, can enhance flowability, and pumping qualities, and reduce segregation, bleeding and the tendency for autogenous and plastic shrinkage. Fly ash (FA), slag, rice husk ash (RHA) and similar materials are excellent partners in this respect since they possess inherent water-reducing properties, and reduce the need for high dosages of high range water-reducing admixtures (HRWR) which are known to create problems of compaction and early age cracking. In the hardened state, such composite cement systems can effectively contribute to the control of high thermal gradients, depletion of alkalies, and continued microstructural development through long-term hydration and pozzolanic reactions. More importantly, the greatest contribution of the PC-FA/slag partnership is in pore refinement which is the one single factor enhancing the resistance of concrete to internal and external chemical and other forms of attack.

If we accept that **Durability** is the **sine qua non** for sustainable growth of the construction industry, then enhancement of the durability properties of the material is the first and key step forward to enhance the quality of concrete construction. Whilst properties such as setting times, workability and control of autogenous and plastic shrinkage can be tackled to some extent through mix design, durability characteristics such as control of the heat of hydration and pore refinement can only be advanced through changes either in the mineralogical composition and/or specific surface of the cementitious system. There are thus strong economic and technical arguments to change either or both of these for ordinary portland cement. Tests show that both high early strength and high final strength can be achieved by changing the specific surface of the portland cement (700-900 m^2/kg) or by modifying the chemical composition of the portland cement (high early strength cement, 16, 17). With these modified portland cements, compressive strengths of 60 to 80 MPa could be obtained with dense aggregates within 24 hrs, whereas with structural lightweight aggregates, strengths of 10 to 25 MPa and 25 to 45 MPa could be obtained in 12 hrs and 24 hrs respectively (16, 17). However the implications on structural behaviour and the adverse effects on cracking and durable performance of such cements and strengths have not been favourable (16-18).

On the other hand, experience all over the world, both historically and during the last several decades, shows that the portland cement – pozzolanic/cementitious materials composite system will always be inherently superior to the PC system in its microstructural and durability properties. This implies that there are strong technical and economic arguments and evidence to modify the fineness or specific surface of the industrial byproducts rather than that of the portland cement, and thus ensure that they are manufactured for **durability** rather than for **strength**. Such a step would also overcome the low and slow development of strength inherent in the PC-FA/slag system (13-15). Thus a judicious combination of FA/slag/RHA fineness, water/binder ratio, cement replacement level, and a high range water reducing agent can produce a sustainable high durability concrete (HDC) with very high strength. The ability of the cementitious/pozzolanic composite cement system to contribute to durability, strength and stiffness is chemically bound within the binder system, and it is only through **"Design"** that we can mobilize and extract this unique **"Synergistic Interaction"** between portland cement, mineral and chemical admixtures. Thus, if we are to achieve sustainability in construction compatible with economic development, and at the same time meet the challenges of climate change and the needs and aspirations of people to have a decent quality of life through an efficient and effective infrastructure system, then the starting point for concrete materials must be **Durability** rather than **Strength**.

The portland cement – slag system

To illustrate the concepts discussed above, the durability and engineering properties of the PC-slag system are presented here as an example of how eco-friendly concretes can be developed to have high durability and, through high durability, high strength. In the tests reported here a PC, ASTM Type I, with a specific surface of 323 m^2/kg, and slag of three different fineness, namely 453 (S4), 786 (S8) and 1160 (S12) m^2/kg were used. The higher fineness slags S8 and S12 with a specific surface of 786 and 1160 m^2/kg respectively were obtained using an air elutriator. The particle size distribution of the slags compared to PC is shown in Table 1. All the concrete mixes tested had a PC-slag combination of 1:1; the mixes with a water/cement + slag (w/c+s) ratio of 0.4 had a total cementitious content of 400 kg/m^3 whilst that 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 was used in all the mixes.

The particle size and the maximum specific surface chosen for the slag used in this project were based on extensive preliminary studies of the role of these two characteristics on the durability properties of the cementitious system. A particle size of about two to three times smaller than the average particle size of portland cement can be utilized and mobilized to contribute to both durability and strength. A very high specific surface can be highly reactive and beneficial, but it also brings problems and concerns associated with large losses in workability, shrinkage, cracking and unreacted silica. Further, grinding slag finer may appear at first sight to be more expensive, but in practice the technical benefits brought about by this modest increase in fineness will far outweigh any increase in initial costs as shown later.

Heat of hydration

Fig. 1 shows the rate of heat evolution in portland cement and cement-slag mixes with a cement replacement level of 50%, at a water-binder ratio of 0.40. The heat evolution profiles shown here were obtained from conduction calorimetry tests carried out at 20°C. The presence of slag of different fineness can be seen to be beneficial in not only reducing the peak heat evolution but also in extending the time at which the peak heat evolution occurs. When considering high strength concrete, one tends to ignore an important related aspect, the heat of hydration, which can affect the long-term durability of concrete, as pointed out earlier. The effects of strain differentials, and the associated internal microcracking arising from thermal stress gradients are slow to heal, and it is important to ensure at the construction stage that heat evolution is fully controlled to enable the concrete to develop a homogeneous, dense and crack-free microstructure. The results shown in Fig. 1 emphasize that the heat reduction together with the delay in the peak heat evolution i.e., a reduction in both thermal gradients and strain differentials can substantially reduce the risk of thermal cracking.

Bleeding rates and setting times

Bleeding is a characteristic of most concretes containing pozzolanic/mineral admixtures, which also act as retarders of time of setting. Excessive bleeding and high retardation of times of setting are undesirable properties for fresh concrete. They will prolong the time during which concrete is vulnerable to autogenous and plastic shrinkage cracking, and this will have adverse effects on the quality of the cement matrix microstructure in placements involving large exposed areas and deep sections. The principal factor influencing bleeding is the water/binder (w/b) ratio, although both the replacement level on a mass basis, and the fineness of the admixture have also some influence on bleeding. The principal factor influencing times of setting, on the other hand, is the level of cement replacement; the w/b has a much less significant influence on time of setting. A judicious combination of the cement replacement level, the fineness of the mineral admixture and the w/b ratio can then reduce substantially, or even eliminate completely, the amount of bleeding and control times of setting as shown in Table 2.

The data in Table 2 show the bleeding rates and setting times of PC-slag composite cement concretes with a w/b ratio of 0.40, and three different slag fineness, namely, 453 m^2/kg, 786 m^2/kg and 1160 m^2/kg respectively at a cement replacement level of 50 percent. These results show that increased slag fineness can almost completely eliminate bleeding with only moderate increases in initial time of setting of 25 to 45 min, and final times of setting of 10 to 35 min.

Bleeding should not be viewed as a merely physical phenomenon affecting strength, abrasion resistance and diffusion characteristics of the surface concrete. A poorly proportioned concrete developing 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. A recognition of the engineering implications of bleeding is vital to the long-term durable service life of concrete structures.

Pore Structure

The critical factors that contribute to the long-term environmental stability and chemical durability of concrete are a dense, crack-free microstructure, a fine pore structure and low capillary porosity. All these characteristics help to produce very low permeability and ionic diffusivity, and resist the intrusion of aggressive elements that damage concrete and destabilize the steel. In extreme and severely aggressive climatic/exposure conditions, chlorides and sulfates are known to penetrate concrete even during the briefest of exposure periods (11). These problems are then further compounded if the ground water is also heavily contaminated with chlorides and sulfates, as it is then only a matter of time that damaging elements will intrude into concrete below ground, and by capillary action, penetrate into concrete above the ground water table. The development of a tightly knit pore structure is thus an essential requirement for long term durable service life.

The role of the PC-slag composite cement system in developing low porosity, and a very fine pore structure is shown in Table 3. The pore volume data in this Table were obtained from mercury intrusion porosimetry tests. These data in Table 3 show the substantial reduction in total pore volume achieved by the PC-slag composite system compared to that of PC alone.

Water permeability

Permeability to water of concrete is a measure of its resistance to water-borne aggressive ions such as chlorides and sulfates, chemical reactions such as alkali-silica reactivity, as well as to steel corrosion. In the water permeability tests reported here, cylindrical specimens 150 x 300mm were used. They were initially cured in water at 20°C for 28 days followed by air curing at 20°C and 60% RH for 7 days. The test specimens were then subjected to a water pressure of 1.5 MPa for 48 hrs, and the depth of water penetration determined. The diffusion coefficient was then calculated from the equation.

$$\beta_1^2 = a\, D_m^2 / 4\left(te^2\right)$$

Where $\beta_1^2 =$ Diffusion coefficient in mm^2/sec

D_m = Average depth of penetration in mm

t = Time during which pressure is applied in secs

a = Coefficient related to t, 175.7

and e = Coefficient related to pressure, 1.301

The results of the tests are presented in Table 4. Again, these data emphasize the lower depths of water penetration and a much lower diffusivity to water of the PC-slag composite system compared to that of PC alone. These results confirm the inherent resistance of the PC-slag composite cement to penetration of aggressive ions. The results given in Tables 3 and 4 confirm the inherent superiority of slags of fineness of 1160 m^2/kg on their ability to contribute to the long-term durability of PC-slag composite concrete.

Chloride ion penetration

Corrosion of reinforcing bars associated with the ingress into concrete of chloride ions is now universally recognized to be the most prevalent form of destructive mechanism of concrete structures. Chloride ions are thus considered to be the major cause of premature corrosion of rebars in reinforced concrete structures that affect the integrity and long-term service life of concrete structures. Indeed, chloride ion penetration is the most frequently specified durability criterion/performance characteristic for durable performance of concrete structures. Chloride ions can only be transported into concrete or diffuse through it in liquid – phase water, and the mechanism of their intrusion is a combined effect of physical and chemical reactions (19). Resistance to chloride ion penetration can thus be considered to be the most positive, reliable and rational measure of the long-term durable service life of concrete structures in aggressive environments.

Table 5 presents the chloride ion penetration into RC slabs made with portland cement and a composite cement with 65% cement replacement by slag. These results were obtained from tests on RC slabs, 1000 x 500 x 150mm, simulating structural elements such as bridge decks. A high w/cm ratio was used in these tests, quite deliberately, to examine the role of cementitious materials at high water contents, even though such values should never be used in practice. The concrete mixtures used in the slabs had a total cementitious material content of 350 kg/m^3, and a normal slag with a fineness of 417 m^2/kg was used. The slabs were kept in moulds for 7 days – the first day covered by polythene sheets, and then cured by water ponding for 6 days. They were then sponge dried, demoulded and exposed to ambient conditions for 21 days further air curing. The slabs were then subjected to cyclic ponding with a 4% sodium chloride solution and drying, each cycle consisting of seven days of wetting followed by three days of drying. The acid-soluble chloride contents in the concrete were determined from drilled cores, by mass of cement, using Volhard's method as described in BS1881. The results presented in Table 5 give undeniable proof of the unique qualities of the PC-slag composite cement system, even at very high w/cm ratios of 0.60 and 0.75, in resisting the penetration of aggressive ions that destabilise steel reinforcement and damage the service life of concrete structures. Bearing in mind that these results relate to a slag fineness of 417 m^2/kg, the use of slags of higher fineness should result in very much higher resistance to chloride penetration. The data in Table 5 is a reflection of the porosity and water tightness results shown in Tables 3 and 4.

Strength and elastic modulus

The data presented in Tables 1 to 5 show conclusively that it is possible to design a composite cementitious system with a very high level of durability properties when exposed to aggressive environments. A specific surface of the order of 1200 m^2/kg for one of the components of the composite cement system is neither impossible nor expensive to achieve. A 50-50 combination of normal PC with a specific surface of 323 k^2/kg and slag with a specific surface of 1160 m^2/kg can produce a cement matrix which has been shown to possess a highly refined pore structure with very low pore volume and an excellent degree of water tightness and resistance to penetration of chloride ions when subjected to repeated cycles of wetting with chloride solutions and drying as occurs in a marine environment. Tests also show that such composite cements have also a high degree of resistance to sulfate attack and alkali silica reactivity, as would be expected from their crack-free tightly knit microstructure, and as exemplified by the data shown in Tables 3 to 5. The question now is – can we develop this highly durability cementitious matrix to produce concretes of high strength?

The strength development (cylinder, 100 x 200 mm) of this PC-slag composite cement concrete is shown in Fig. 2, and the major values are quantified in Table 6. The concretes were made with PC, containing 50% cement replacement with slag by mass at two w/cm ratios of 0.40 and 0.30. The concretes with 0.40 w/cm ratio had a total cementitious content of 400 kg/m^3 whilst those with 0.30 w/cm ratio had a total cementitious content of 533 kg/m^3. The concretes were designed for a slump of 150 to 200 mm by the use of HRWR which also helped to reduce slump loss. The air content of the concrete varied from 1.3 to 2.4%. The results shown in Fig. 2 are for continuous water curing at 20°C, whilst the last column in Table 6 relates to concrete strength after 6 days water curing followed by air curing at 60% RH, all at 20°C.

The compressive strength data given in Fig. 2 and Table 6 emphasize two significant conclusions. Firstly it is shown that with a total cementitious content of 400 kg/m^3 and slag fineness of 1160 m^2/kg, it is possible to achieve three day strengths of 35 MPa and 28 day strengths of 100 MPa. Secondly, it is not necessary to use very low w/cm ratios of 0.30, or very high cementitious materials contents in excess of 500 kg/m^3 - both of which are known to cause field problems of placing, compacting, curing and cracking - to achieve high concrete strengths if the cement matrix is initially designed for durability rather than for strength. These results show in no uncertain terms that the concept of **Strength through Durability** is sound and rational, and that it can be achieved in practice. The data on elastic modulus given in Fig. 3 confirm the strength data, and show that these concretes will also have a high elastic modulus of 35 to 40 GPa at 28 days.

Key to durability and sustainability

The key to concrete durability and sustainability, and therefore to high performance, is to enable concrete attain a tight, highly-impermeable pore structure. Since every property related to strength and durability development in concrete is a time-dependent process, one needs to choose concrete material constituents in such a way that will foster **synergic interaction** with time. The PC-slag composite cement system, for example, can just do that as portrayed in Tables 3 to 6, and Fig. 4, which show how both time and the degree of slag fineness can help to obtain progressive and substantial reductions in total pore volume, and therefore high resistance to water penetration. The dramatic decrease in the ability of water and water-borne deleterious agents to penetrate concrete is the direct result of the successful development of a **highly refined pore structure** that can lead to high and long durable service performance. The data shown in Fig. 4 again emphasize that very low water/binder ratios are not necessary to achieve this very high pore refinement. The secret to durable high strength concrete is thus not very low w/cm ratios, but a modest modification of the fineness of the cementitious system itself.

This reduction in the internal total pore volume is followed by a redistribution of pore sizes which again results very favourably for concrete containing pozzolans or slag. This is the kingpin of **synergic interaction** between portland cement and pozzolans or slag - the reduction in pore volume goes side by side with pore refinement which is the essential characteristic that leads to the goal of **"impermeability"**. The overall superiority of the cement-pozzolans/slag matrix over that of portland cement can be readily appreciated from the data presented in Tables 3 to 5. For normal environments, similar reductions in pore volume and pore refinement can be obtained by using pozzolans or slag of normal fineness. The implication of the data in Tables 3 to 5 is that it is necessary to design concrete mixes to take advantage in practice of the synergic, chemical interactions which can lead to better and more durable performance in real life exposure conditions.

The data in Tables 1 to 6, and Figs. 1 to 4 demonstrate how high early-strength and high long-term strength can be achieved through **"design for durability"**. High strength does not automatically guarantee a high level of durability, whereas a focus on high durability can be mobilized to produce high strength. This is where the choice of type and amount of pozzolans and slag becomes important. Pozzolans of very high fineness, of the order of 10,000 to 20,000 m^2/kg, will, of course be naturally highly reactive, and can give the advantages of reduced curing time needed to obtain a desired level of strength and water tightness. But such high levels of fineness are known to bring in many practical field problems, akin to low w/cm ratios. Moderately fine or reactive pozzolans with a fineness of 1200 to 1500 m^2/kg can, on the other hand, create a highly durable cement matrix with improved resistance to thermal cracking whilst maintaining continued strength development. The data presented here show a way forward in this strategy to develop a high durability, eco-friendly and sustainable high strength concrete based on moderate fineness of cementitious materials and without resorting to very low w/cm ratios or very high total cementitious contents and their associated field problems.

Concluding remarks

Engineers are obsessed with high strength and very high strength concrete with 28 day compressive strengths in excess of 100-120 MPa. This fascination for such high strengths is created by the current Ultimate Strength Design approach, where the main emphasis is on Strength with only relative lip service given to the Design for Durability. The belief that high strength concretes are, *per se*, highly durable has led to the development of a wide range of techniques to produce very high strength concretes. In practice, such high strength concretes, and many of the so-called high performance concretes reported in the literature, are characterised by very high cement contents and very low water/binder ratios. Field experience shows that such concretes are extremely hard to place, compact and cure, and are highly prone to cracking. This lurch towards high strength concretes should be seen in relation to the overwhelming evidence of the alarming and unacceptable rate of damage and deterioration of concrete structures all over the world when they are exposed to real and aggressive environments. The fact that structures seldom fail due to lack of intrinsic strength *per se,* and the fact that the major problem confronting concrete structures is not lack of strength but lack of durable service life strongly implies that the concept of Durability through Strength, implicit in Ultimate Strength Design approach is invalid, flawed and indeed unattainable.

This paper advocates a new concept of Strength through Durability to produce concretes of high durability with 28 day compressive strength of 60 to 100 MPa. The concrete mix design for this concept is focussed on Durability by taking advantage of the synergistic interaction between portland cement, mineral additions (slag) and chemical admixtures by a judicious combination of slag fineness, water/binder ratio, cement replacement level and a high range water reducing agent. It is shown that such a concrete can develop a homogeneous, dense and crack-free microstructure with reduced heat of hydration, vastly less bleeding and very little changes to setting time compared to normal portland cement concrete. Tests are also reported to confirm that such concretes can be designed to have a highly refined pore structure with very low diffusivity and very high resistance to water and chloride ion penetration. With a total cementitious materials content of 400 kg/m^3 and a water-binder ratio of 0.40, these concretes are able to develop compressive strengths of 35 MPa at 3 days and 100 MPa at 28 days. The results presented in this paper show a mix design strategy to develop a high durability, eco-friendly and sustainable high strength concrete based on moderate fineness of cementitious materials and without resorting to very high cement contents and very low water-binder ratios which create their own associated field problems.

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Captions for Tables

Table 1 Particle size distribution for PC and slag

Table 2 Bleeding rates and setting times of PC-slag system

Table 3 Development of porosity of the PC-slag composite system

Table 4 Effect of PC-slag composite cement on water tightness

Table 5 Chloride ion penetration in RC slabs after 50 cycles of exposure

Table 6 Strength development of high durability PC-slag system

Captions for Figures

Fig. 1 Effectiveness of slag on heat of hydration

Fig. 2 Strength development of PC-slag concrete

Fig. 3 Variation of elastic modulus with strength of PC-slag concrete

Fig. 4 Development of pore structure of the PC-slag cement

Table 1 - Particle size distribution of PC and slag

Description of Test	Portland Cement	Slag		
		S4	S8	S12
Physical Properties				
Fineness				
88 μm (passing) %	99.5	100.0	-	-
15 μm (passing) %	54.0	63.0	97.0	100.0
Average particle μm	14.0	11.7	5.1	3.1
Surface area				
Air permeability (m^2kg)	323	453	786	1160
Specific gravity	3.16	2.93	2.93	2.93

Table 2 – 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	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

Table 3 – Development of porosity of the PC-slag composite system.

Mix	Slag specific surface, m^2/kg	Cylinder compressive strength*, MPa		Total pore volume, mm^3/g			
		7d	28d	3d	7d	28d	91d
1	None	48.9	59.5	64.9	57.4	46.7	33.5
2	453	27.7	58.7	60.4	55.9	30.7	13.0
3	786	36.4	67.8	68.5	47.6	22.8	12.0
4	1160	64.8	101.8	41.5	31.6	16.8	11.9

* Water/binder: 0.40; Water curing
Cement replacement: 50%

Table 4 – Effect of PC-slag composite cement on water tightness.

Mix	Slag specific surface, m^2/kg	Cylinder strength*, MPa		Water permeability	
		7d	28d	Depth of penetration, mm	Diffusion coefficient, x 10^{-2} mm^2/s
1	None	48.9	59.5	12.3	2.27
2	453	27.7	58.7	8.1	0.99
3	786	36.4	67.8	7.1	0.76
4	1160	64.8	101.8	2.9	0.13

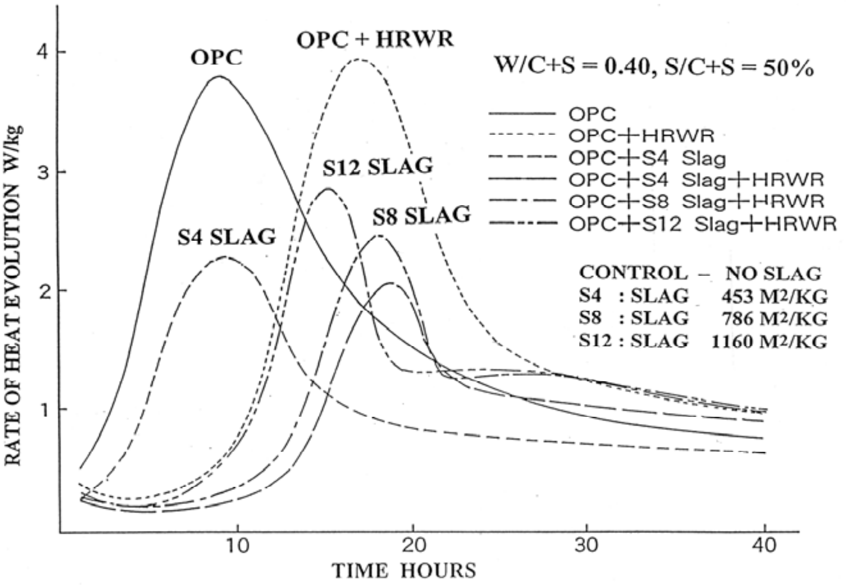
* Water/binder: 0.40; Water curing
Cement replacement 50%

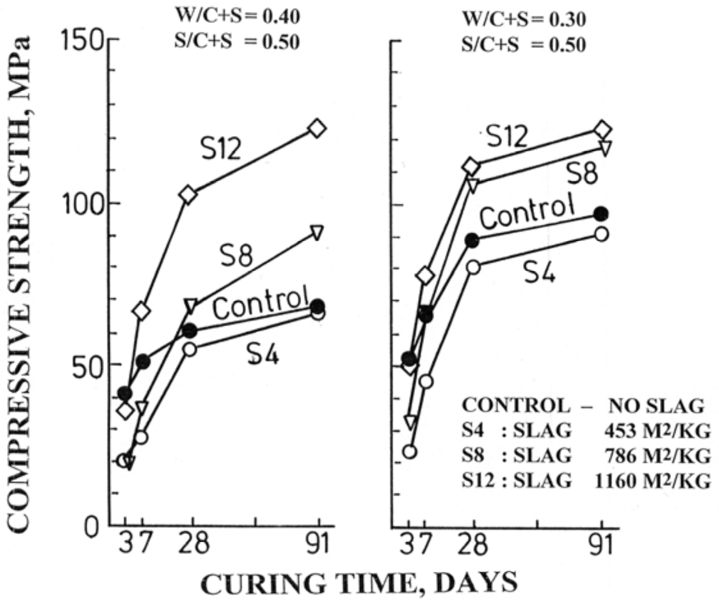
Table 5 - Chloride ion penetration in RC slabs after 50 cycles of exposure

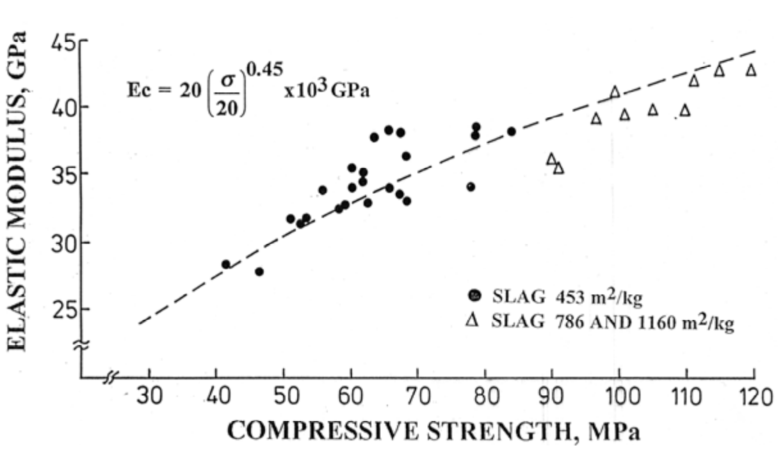
Slab No.	w/cm ratio	Cement system	Depth from concrete surface, mm				
			5-25	25-45	45-65	65-85	85-105
S2	0.60	Portland cement	4.52	2.32	1.39	0.87	0.47
S7	0.60	Composite cement	2.58	1.05	0.59	0.21	0.08
S3	0.75	Portland cement	5.72	3.33	2.31	1.32	0.76
S10	0.75	Composite cement	5.45	2.35	1.55	0.78	0.31

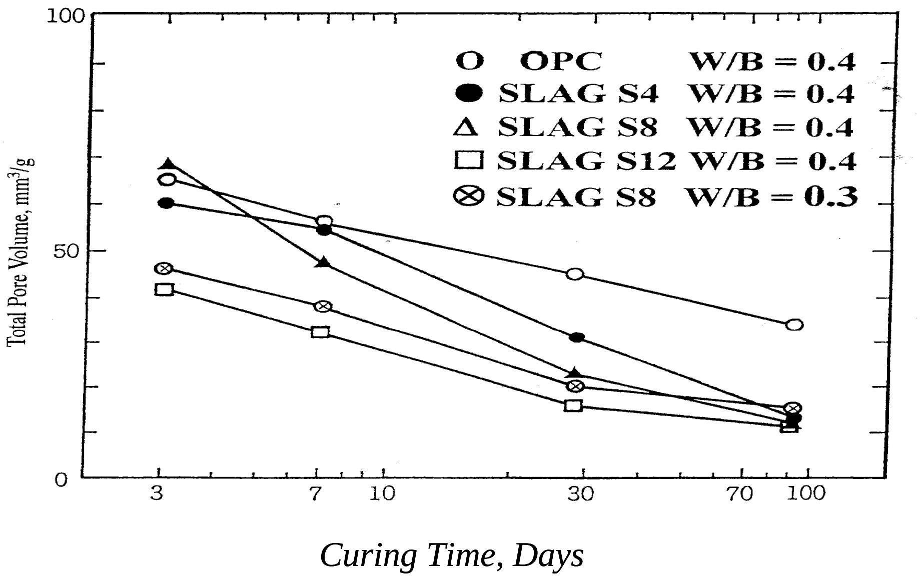
Table 6 – Strength development of high durability PC-slag system

Mix No	w/cm	Slag	Compressive strength, MPa				
			Wet Curing				Wet + Air
			3d	7d	28d	92d	28d
1	0.40	None	38.6	48.9	59.5	69.3	63.1
2		S4	15.2	27.7	58.7	69.5	52.3
3		S8	17.9	36.4	67.8	90.6	66.3
4		S12	34.5	64.8	101.8	122.3	104.8
1	0.30	None	51.1	65.0	88.6	96.6	92.1
2		S4	22.5	44.3	80.4	90.1	75.8
3		S8	31.3	64.2	104.2	115.8	106.1
4		S12	49.4	76.9	110.0	121.5	104.2


OPC
OPC + HRWR
W/C+S = 0.40, S/C+S = 50%
OPC
OPC+HRWR
OPC+S4 Slag
OPC+S4 Slag+HRWR
OPC+S8 Slag+HRWR
OPC+S12 Slag+HRWR
S12 SLAG
S8 SLAG
S4 SLAG
CONTROL – NO SLAG
S4 : SLAG 453 M2/KG
S8 : SLAG 786 M2/KG
S12 : SLAG 1160 M2/KG
RATE OF HEAT EVOLUTION W/kg
1
2
3
4
10
20
30
40
TIME HOURS


W/C+S= 0.40
S/C+S = 0.50
W/C+S= 0.30
S/C+S = 0.50
S12
S8
Control
S4
S12
S8
Control
S4
CONTROL – NO SLAG
S4 : SLAG 453 M2/KG
S8 : SLAG 786 M2/KG
S12 : SLAG 1160 M2/KG
COMPRESSIVE STRENGTH, MPa
0
50
100
150
3 7
28
91
3 7
28
91
CURING TIME, DAYS


Ec = 20 (σ/20)^0.45 x10^3 GPa
SLAG 453 m2/kg
SLAG 786 AND 1160 m2/kg
ELASTIC MODULUS, GPa
25
30
35
40
45
30
40
50
60
70
80
90
100
110
120
COMPRESSIVE STRENGTH, MPa


O OPC W/B = 0.4
● SLAG S4 W/B = 0.4
Δ SLAG S8 W/B = 0.4
☐ SLAG S12 W/B = 0.4
⊗ SLAG S8 W/B = 0.3
Total Pore Volume, mm³/g
100
50
0
3
7
10
30
70
100
Curing Time, Days