CONTRIBUTION TO DURABILITY FROM MATERIALS MIX PROPORTIONS AND CONSTRUCTION METHODS

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ABSTRACT

The paper considers the climatic conditions existing in the typical Gulf environment and chloride-induced corrosion, the main process leading to premature damage of concete structures. It then moves on to examine the factors controlling rates of deterioration and methods by which performance may be enhanced by better equipping concrete. This is via the materials selected, their means of combination and methods of construction. It is demonstrated that available materials, including pozzolanic binders and their blends are very effective for chloride environments. It is also shown that the w/c ratio rather than the cement content is critical in relation to durability and that it is possible to enhance performance by minimising the voidage of the constituents materials via the mix proportioning. Some of the more novel developments in relation to the construction process for improving performance, including self-cure concrete, controlled permeability formwork and surface coatings are considered. It is illustrated that some techniques have more to offer than others, but all can be used to extend service life.

KEYWORDS

Concrete durability; Gulf exposure conditions; chloride ingress; enhanced concrete performance; material selection; material combination; construction methods; service life.

INTRODUCTION

The last 20 to 30 years has seen a growing awareness amongst engineers of the need to ensure provisions are made for durability in concrete structures. This has arisen, largely as a result of the increasing incidence of premature deterioration over the period and the substantial repair and maintenance requirements that have arisen (Department of Transport, 1989; Mallet, 1994). While the specific problems encountered and their severity have varied from region to region around the world, this has very much become an issue of global concern.

A significant research effort has gone into developing an understanding of the factors influencing deterioration for the various damaging processes (Lawerence, 1994; Sommerville, 1996). However, the transfer of this knowledge has been slow and durability specifications, almost universally, remain by mix prescription (or limitation) in relation to environmental conditions (pr EN 206, 1995; BS8110, 1997). This has been workable and ensures that concrete of a certain pedigree is provided. However, it does not take direct account of the processes of deterioration and factors relating to concrete controlling these. Developments in this area are on-going, but full evaluation and implementation will take time (Concrete Society, 1996).

It could, therefore, be argued that currently the most effective route to achieving improved durability in concrete lies in considering each of the stages of design and construction and identification of where modification and refinement may be possible to enhance performance. Critical elements of this are likely to lie in the selection of appropriate materials, their effective combination and concrete production towards the provision of a dense concrete cover, capable of interacting with the prevailing environment.

Given this background, the aims of this paper are to examine each of these issues in turn and determine how they can be exploited for enhanced concrete performance. This is considered in relation to the needs of concrete in temperate climates and, given the conditions in the Gulf region, issues of use in these environments also addressed.

ENVIRONMENT CONDITIONS AND DETERIORATION IN THE GULF REGION

Conditions in the Gulf region are generally recognised as being among the most severe anywhere in the world (Fookes, 1993). This is the result of the combined effects of the surrounding geology and the extreme climatic effects that can occur.

Indeed, in coastal regions and locally inland, conditions of excessive salinity, with calcium, magnesium and sodium salts of sulfates, chlorides and carbonates extensively contaminating the ground, groundwater and moisture-laden air (Rasheeduzzafar et al, 1984) exist. Their presence at the surfaces of outcrops is the result of weathering action on the salt-bedded rocks or wind blow in the salt atmosphere. In addition, because much of the coastal area of the region is flat, low lying and has a high water table, this can lead to leaching, transportation and deposition of salts throughout the strata (Rasheeduzzafar et al, 1984). These have direct implications for recovery of suitable material for concrete and for the exposure conditions to which concrete is subject.

Seasonally and locally there can be a wide range of conditions found in the Gulf region. There also tends to be substantial variations in daily conditions, which may be as high as 20°C for temperature and 60% for relative humidity over 24 hours (Rasheeduzzafar et al, 1984). Solar radiation also tends to be high, because of the lack of cloud cover, and the occurrence of high winds (greater than 17 km/h) is more frequent than the majority of Western European locations. The annual rainfall, although relatively low, varies over the region, but tends to fall intensively over short time periods when it occurs (CIRIA, 1984). The climatic effects again have direct implications for concrete production practice and to processes of deterioration, which, in general, increase with temperature and are greatly influenced by the moisture level present in concrete

Reference to the literature indicates that most of the processes of deterioration occurring in Western Europe and in the USA are also encountered in the Gulf region to varying degrees (Rasheeduzzafar, 1984; CIRIA, 1984; Fookes, 1993; Al-Amoudi, 1995; Fookes, 1995; Novokshchenov, 1995;Maslehuddin et al, 1996). For example, coverage is given to alkali-silica reaction (ASR), carbonation and sulfate attack. There is, however, general agreement that the most pressing and serious problem is that caused by corrosion of reinforcement due to chloride ions. While these may be present in concrete as a result of contaminated constituent materials, a tightening of limits should help prevent this and, therefore, ingress from the environment is likely to represent the most serious threat to future construction.

A summary of the different mechanisms by which chloride may enter concrete is given in Figure 1 (Concrete Society, 1996). As indicated, this may be by diffusion through the pores in saturated concrete, or by a combination of diffusion and absorption where wetting and drying can occur. In some situations, chloride may also be transported by the action of a pressure head (permeability) or through the effects of capillary rise (wick action) where moisture variations exist in concrete. In addition, as noted above, chloride may be transported externally in salt saturated air.

The environment conditions mean that deterioration by additional factors, can also occur in some situations, potentially intensifying rates of chloride-induced damage (Rasheeduzzafar, 1984). Therefore, the paper will concentrate on this main type of damage, but also give brief coverage to the influences of these other forms of attack on this process.

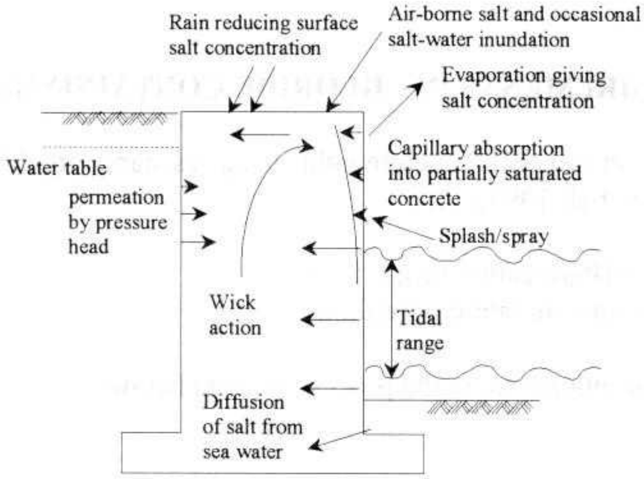

Fig 1. Mechanisms of chloride ingress into concrete (Concrete Society, 1996)

CONCRETE PRACTICE AND SPECIFICATIONS

A summary of the changing phases of construction in the Gulf region has been given by Fookes (1993), who divided this into three parts, viz. 1977, 1977-1984, post 1984. In the early period referred to, conditions existing in the Gulf region were not directly considered and practices of other countries, which may not have been appropriate to the local climate, tended to be used. This was followed by a period during which there was a growing awareness of the special requirements for hot weather concreting and data on the performance of structures also started to become available. This culminated in the production of CIRIA Report 31, which provided specific guidance on the use of concrete in the Gulf environment. The most recent period has seen consolidation of what has been learnt from early construction and the preparation of an updated CIRIA Report covering construction practice and concrete requirements for the Gulf, which is to be published shortly.

The concrete specifications given in CIRIA Report 31, which reflect specifications used in the Gulf region during the preparation of the document are given in Table 1 (CIRIA, 1984). As mentioned above, the exposure classes relate to the conditions found in the region. Mix limitations in terms of minimum cement content, maximum w/c ratio and requirements for cover are included. No requirement for concrete grade is given.

The corresponding specifications for durability of the British Standard (BS 8110, 1997) are given in Table 2. In comparing these, it can be seen that the minimum cement contents of 300 to 400 kg/m^3 and maximum w/c ratios of 0.4 to 0.5 across the range of exposures for the Gulf region are not significantly different to those of the UK standard. While in some exposures, the use of sealants is recommended, it is also clear that, with the exception of marine structures, concrete cover depths are also not significantly different. This may explain why, as suggested by Fookes (1993), that, even with best practice and specification, the extremes of the environment make it very difficult for concrete to perform well over extended periods.

It could be argued that under such conditions, extra forms of protection may be essential towards ensuring longevity of concrete in-service. Clearly in order to achieve this, certain modifications to the characteristics of the basic concrete are necessary. The possible routes of achieving this, suggested above, are addressed in the following sections.

CONCRETE REQUIREMENTS IN CHLORIDE-CONTAINING ENVIRONMENTS

The main factors associated with concrete influencing resistance to chloride ingress may be summarized as (Jones et al, 1993),

- Microstructure (Permeation properties)
- Chemistry of concrete fabric/pore fluids

A brief review of their influences on the process is given below.

Microstructure

The quality of the concrete microstructure is influenced both by the quantity and type of binder used and the amount of water in the mix. In general, with reducing w/c ratio, refinement and densification of the microstructure can be expected. Similarly, the use of certain binders, if correctly proportioned can offer some enhancement to the microstructure, both through their chemical and physical influences on its development.

Curing of concrete is another important factor that can have a significant effect on the characteristics of the microstructure. This process involves ensuring that water is provided or contained in concrete, during and immediately after construction. This is critical to the promotion of continued chemical action between water and cement and secondary reactions with pozzolanic materials, and hence in the development of a dense microstructure.

Table 1. Local criteria for reinforced concrete in the Gulf region (CIRIA, 1984)

EXPOSURE CONDITION	RANGE OF SPECIFICATION LIMITS			
	Minimum cement content for 20 mm aggregates, kg/m³	Maximum water/cement ratio	Additional requirements	Minimum cover for reinforcement, mm
A	300 - 320	0.52 - 0.50	None	30
B	320	0.50	None	40
C	320 - 350	0.50 - 0.45	None	40 - 50
D (i)	300 - 320	0.50	None	40 - 50
(ii) or (iv)	320 - 400	0.50 - 0.42	Tanking/membrane	40 - 50
(iii)	Not separately mentioned in specifications: treat as D (i) and (iv)			
E (i) to (iii)	370 - 400	0.45 - 0.42	None	75 - 100
F	400	0.50	None	40

Exposure Conditions:

A Superstructures, inland with NO risk of windborne salts

B Superstructures, in areas of saltflats, inland or near the coast, exposed to windborne salts

C Parts of structures in contact with the soil, well above capillary rise zone, and with NO risk of water introduced at the surface by irrigation or faulty wastes, washing down, etc.

D Parts of structures in contact with soil within the capillary rise zone, below groundwater level, or where water may be introduced at the surface by irrigation, discharge of wastes, washing down, etc.
Soil and groundwater condition classes: (i) Free from significant contamination; (ii) Significant sulfate contamination only; (iii) Significant chloride contamination only; (iv) Significant contamination with both sulfates and chlorides

E Marine structures: (i) Splash zone; (ii) Intertidal zone; (iii) Submerged zone

F Water-retaining structures

Table 2. Durability requirements for concrete in the UK (BS 8110, 1997)

EXPOSURE CONDITION	BS 8110 DURABILITY REQUIREMENTS			
	NOMINAL COVER, mm	MAX W/C RATIO	MIN. CEMENT CONTENT, kg/m³	MINIMUM GRADE
Mild	25	0.65	274	C30
	20	0.60	300	C35
Moderate	35	0.60	300	C35
	20	0.45	400	C50
Severe	40	0.55	325	C40
	25	0.45	400	C50
Very Severe *	50	0.55	325	C40
	30	0.45	400	C50
Extreme	60	0.50	350	C45
	50	0.45	400	C50

* Seawater exposure

Chloride binding capacity

Chlorides entering concrete normally exist in one or more forms, viz, free, weakly (physi/chemi-sorbed) bound and strongly (chemically combined) bound. Their rate of transport is influenced by the state of chloride present. It is those free in the pore fluids that are considered to represent the main threat to steel reinforcement, since they are capable of further penetration into concrete and breakdown of the passive film when present in sufficient quantities at reinforcement sites. Weakly bound chlorides are adsorbed onto the pore walls of cement hydrates, their quantity depending mainly on the surface area and nature of the cement hydrates. Strongly bound chlorides are combined within the cement compounds.

The different phases of cement appear to have different capabilities in relation to chloride binding. The silicate phases probably make little contribution, while the alumina phases have a major role in the binding of chloride (Jones et al, 1993). The use of materials rich in alumina are therefore likely to bring benefits to concrete in chloride containing environments.

METHODS FOR ENHANCING CONCRETE PERFORMANCE

Clearly, methods of enhancing concrete performance should centre around control of either one or both of the concrete microstructure and chemistry. In attempting to achieve this, it was intended that for the methods considered as little change as possible to existing practice should be required. The three routes considered can be classified in general terms under (i) material selection, (ii) material combination and (iii) other means, relating to construction methodology. In each of these, all concretes are water-cured (to 28 days) unless otherwise indicated.

A summary of the methods considered and the philosophy behind each is given below,

i) **Material Selection.** There are an increasing number of different binder materials available beyond that of Portland cement (PC). These are physically and chemically different to PC and there is therefore potential for manipulating there combinations to achieve optimum chloride binding capacity and densification of the microstructure.

ii) **Material Combination.** The importance of the mix limitations for concrete durability provision in concrete standards is evident from the wide use of the approach. The basis for this has, in the main, been local experience and little work to evaluate the significance of the parameters carried out. The role of these parameters in relation to mix proportioning is clearly important for effective material use by engineers.

Recent developments have also seen the introduction of mix proportioning techniques, which are aimed at physically minimising the void space of concrete prior to concrete production. Again, combination of these with suitable materials to physically and chemically improve concrete is likely to offer benefits in chloride environments.

iii) **Construction/Post-Construction Techniques.** Several novel methods of enhancing concrete performance have been developed recently. These include, self-cure concrete and controlled permeability formwork (achieved by the use of an admixture and applying a liner to the formwork surface to allow water drainage respectively), aimed at enhancing the concrete microstructure and silane coatings, at modifying the characteristics of concrete to prevent ingress of liquids.

MATERIAL OPTIONS

Alternative Binders

In the last few years there have been gradual moves towards the use of alternative (pozzolanic) materials to Portland cement as part of the binder in concrete construction. Among the main materials finding use in Western Europe include, pulverized-fuel ash (PFA) and ground granulated blastfurnace slag (GGBS). More recently, other materials including condensed silica fume (CSF) and metakaoline (MK) have also been introduced.

The characteristics of these materials mean that they can contribute one or all of the following towards the provision of chloride resistance.

- High alumina content, (except silica fume; which in PFA is 6 times that of PC, in GGBS 2 times and in MK 8 times). This is also likely to be in amorphous form, with a high chloride binding capacity.
- Large number of well dispersed fine particles available to absorb chlorides
- Potential for blocking and increasing the length of pathways into concrete.

The results from work examining the use of PFA and GGBS are shown in Figure 2 (Lee and Dhir, 1994; Diah and Dhir, 1994). For concrete containing these pozzolanic materials and of equivalent design strength, substantial reductions in chloride diffusion were obtained compared to PC concrete. When the levels of these materials were increased to what may be considered their upper limit for practical use, greater performance still was attainable.

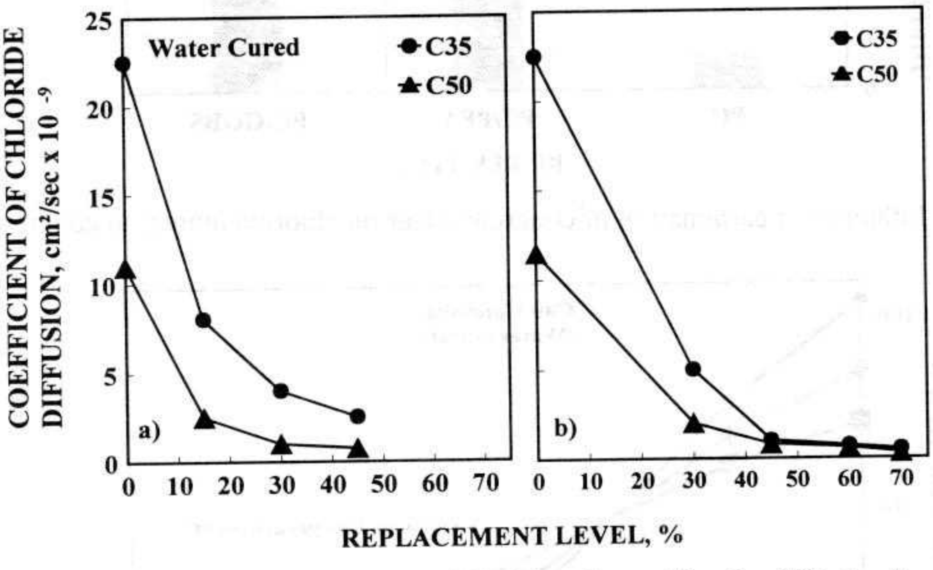

Fig.2. Influence of (a) PFA and (b) GGBS levels on chloride diffusion in concrete

Other work (Dhir et al, 1990) examining the effect of curing suggests that the use of these materials may also, to some extent, excuse limited moisture curing, with respect to chloride resistance. As might be expected, limited curing is detrimental to the concrete microstructure, as indicated by permeation tests, so this highlights the importance of the chemistry of these binders in contributing to enhanced chloride resistance.

Where there is the risk of more than one process attacking concrete, for example, combined carbonation and chloride, then the benefits of some binders may be reduced. An example of this is shown in Figure 3 (Henderson and Dhir, 1997), where the effects of carbonation of the cover caused an increase in chloride diffusion, which became greater as the carbonation depth of the concrete under test increased. It is, however, clear that while the overall performance of all binders was affected, those concretes containing PFA and GGBS, still provided improved performance. Other work (Dhir et al, 1994) examining effects of sulfate contamination of concrete on chloride diffusion suggests only a relatively minor influence with sulfate present.

Work to examine the chloride resistance of concrete at elevated temperatures, in line with those of the Gulf region (Dhir et al, 1993), indicates that for PFA, chloride diffusion had a tendency to decrease as the temperature increased, see Figure 4. However, for PC concrete the reverse occurred. It is believed that this reflects the influence of temperature on the rate of transmission and reaction, and the positive longer-term reactive nature of PFA compared to PC. Clearly, the benefits associated with PFA are likely to depend on concrete maturity at the time of chloride exposure. Given GGBS is similar to PFA, performance in Gulf conditions, should be equivalent or better than that obtained under the those used in the tests.

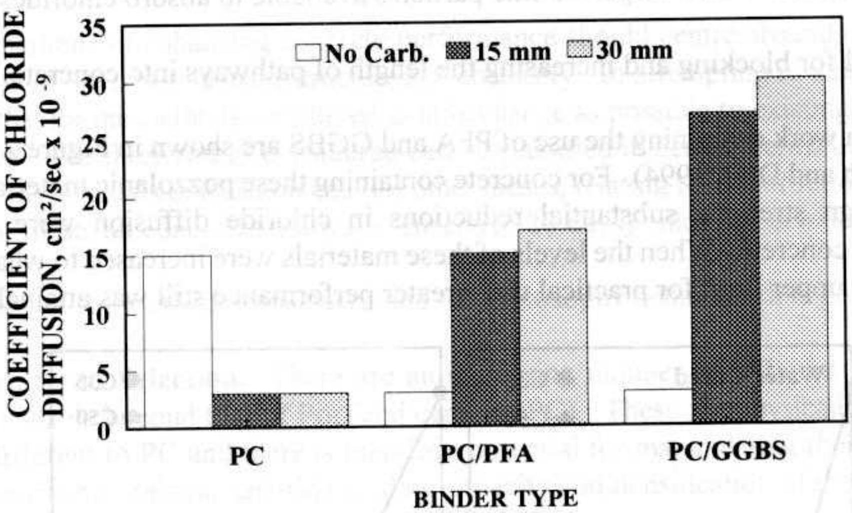

Fig.3. Influence of carbonation of concrete cover on chloride ingress in concrete

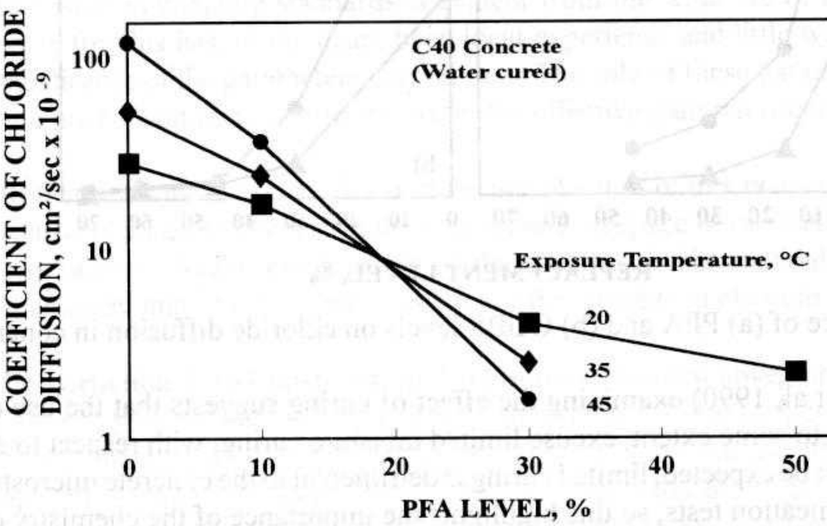

Fig.4. Influence of exposure temperature on chloride diffusion in concrete

Multi-blend materials

Despite the benefits achievable with some of the materials used in combination with PC alone, there has been a growing awareness that it may be possible to get further enhancement of performance by combining two or three materials with PC. This relates both to the need for higher strength and extended durability and has been used to achieve, what is often referred to as, high performance concrete. Developments in European cement standards (BS EN 197) where combinations beyond binary binders are permitted, means that the use of binders comprising a range of materials will start to become more commonplace. These materials should allow engineers, through careful selection and combination, to produce binder blends to achieve a required set of concrete properties.

Results obtained from accelerated chloride diffusion tests (Jones et al, 1997), carried out under the action of a potential difference across the test specimen within a two compartment cell, covering a range of binder combinations, with PC/PFA and PC/GGBS as the principle materials, at equivalent design strengths, are given in Figure 5. As indicated, the combinations of three materials gave substantial improvements at all design strengths compared to the reference (PC) and binary blend concretes. It is not really possible to single out a mix as having overall superior performance, although no chlorides were detected during the test for high design strength concrete containing ternary blend binders.

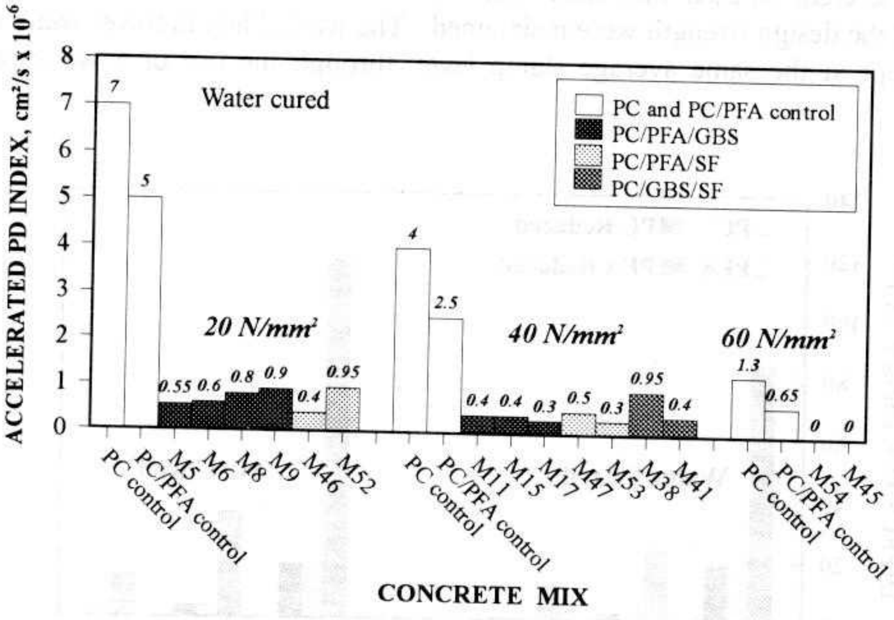

Fig.5. Chloride diffusion of multi-component binder concrete

Given the accelerated nature of these tests (they are typically complete within two weeks) and potentially limited pozzolanic reactivity, it would appear that benefits achievable are likely to reflect the enhancement of the concrete microstructure. Longer-term chloride penetration tests were also carried out with both total and water-soluble chloride measurements being made. These generally reflected the diffusion tests. A comparison of the relative alumina contents suggested that the results did not specifically reflect the quantities of these present in the mix, thereby providing further evidence that the benefits observed, reflect enhancement of the concrete microstructure. Although, clearly the influence of the chemistry would also be there.

No data is available for high temperature conditions, so it is not clear how combinations of blends would perform under Gulf conditions. There is evidence to suggest that the reduced alkalies resulting from these materials, potentially may reduce carbonation resistance. Given the dry conditions of the Gulf and increasing carbonation generally observed with temperature and low humidity, caution with respect to this process is required, although reinforcement corrosion under such conditions may not be too severe. The effects of combined carbonation/chloride attack for these materials may also be an issue of concern

MATERIAL COMBINATIONS

Role of mix limitation parameters

Mix limitation in the provision of concrete durability influences the mix proportions used in concrete. However, the significance of the parameters has never been fully established and they have largely been derived empirically. With the need to achieve dense concrete, the use of relatively low w/c ratios and high cement contents is generally always required.

Results from work (Dhir et al, 1996b) carried out using both PC and PC/PFA concrete to evaluate the significance of these parameters is shown in Figure 6. For these, a range of w/c ratios were considered. At each, the cement and water contents were proportionally adjusted so that this and the design strength were maintained. The workability in lower water content mixes was kept at the same average slump level, through the use of a water-reducing admixture.

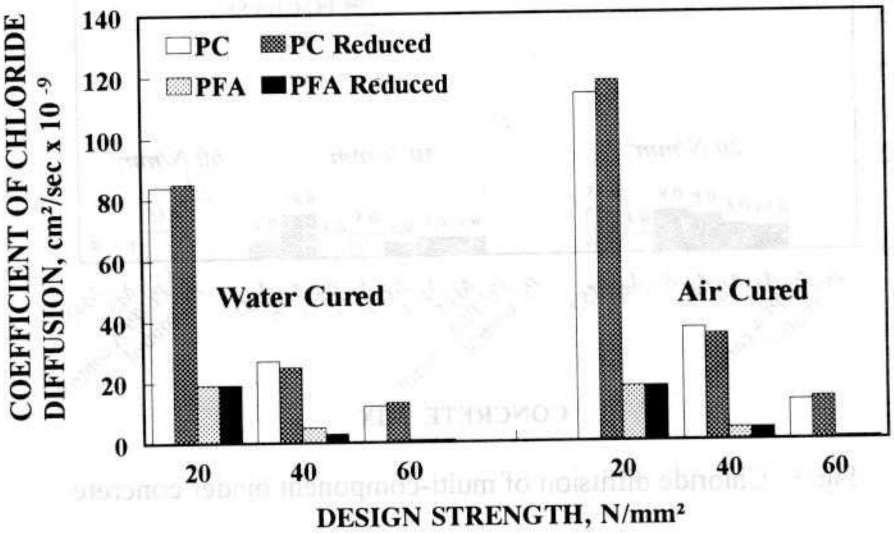

Fig.6. Chloride diffusion coefficients of binder reduced concrete

The results again indicate enhanced chloride resistance of PC/PFA concrete. The results also illustrate that with increasing w/c ratio and reducing strength, chloride diffusion increased. However, for a given binder type and w/c ratio, the chloride diffusion coefficients were very similar for control and cement reduced concretes. These results therefore suggest that the w/c ratio was critical, but that within certain limits the cement content could be reduced without compromising durability.

The observed effects are believed to relate to the better dispersion of the mix achieved through the use of the admixture and this is reflected in an enhancement of the concrete microstructure, which was observed in permeation tests. This therefore appears to offset any influences caused by reduced binding ability, through the reduced cement contents used.

The point that should be taken from this work is the importance of the parameters influencing durability, rather than the promotion of reduced cement contents. It would seem unlikely for the modifications made to the mix, that the performance observed in the conditions used should be any different for the Gulf environment.

Particle packing of concrete mixes

The majority of mix proportioning techniques for material combination in concrete tend to cover the particle size distribution or grading of aggregate, but do not consider the size and shape of the binder particles. The aim of producing concrete, in particular with respect to durability, centres around minimising voidage as the binder matrix develops. If this is controlled initially by considering the physical properties of all solid constituents and optimising their proportions to minimise voidage, then the demands on the developing matrix will be reduced and a denser material should be more readily achieved.

Such an approach to mix proportioning has been developed by Dewar (1994), and is based on the principle that when materials of different sizes are mixed together, smaller particles attempt to fill voids between larger particles to form a mixture with minimum voids. The structure will eventually be disrupted by interparticle interference when the quantity of particles within a particular size fraction become too great, creating some additional voids. The method seeks to minimise these to form a mixture with the minimum possible voids ratio by taking account of the physical characteristics of all the materials in the mix (including the mean particle size of all constituents, the voids ratio and the relative density) and provides optimum proportions of each constituent to achieve this.

This particle packing method has been used in a study considering the development of chloride resistant concrete where the intention was to produce a physically dense concrete cover to embedded steel and to take advantage of the chemical properties of PFA and GGBS in slowing down the advance of chlorides, through physical/chemical binding. Permeability results (Dhir and el Mohr, 1997) demonstrated the benefits of using the mix proportioning technique in enhancing the concrete microstructure.

The combination of this mix method and levels of PFA and GGBS of approximately 50% and 70% as a binder were found (Dhir et al, 1998a; Dhir et al, 1998b) to give substantially enhanced chloride resistance, as indicated in Figure 7 for PFA, which illustrates the relative importance of the different factors influencing the process.

METHODS OF CONSTRUCTION

Thus far, the paper has been concerned with the importance of materials and their effective combination to improve durability. Recent developments in construction mean that further enhancements are possible, as part of this process, without radically changing existing practice.

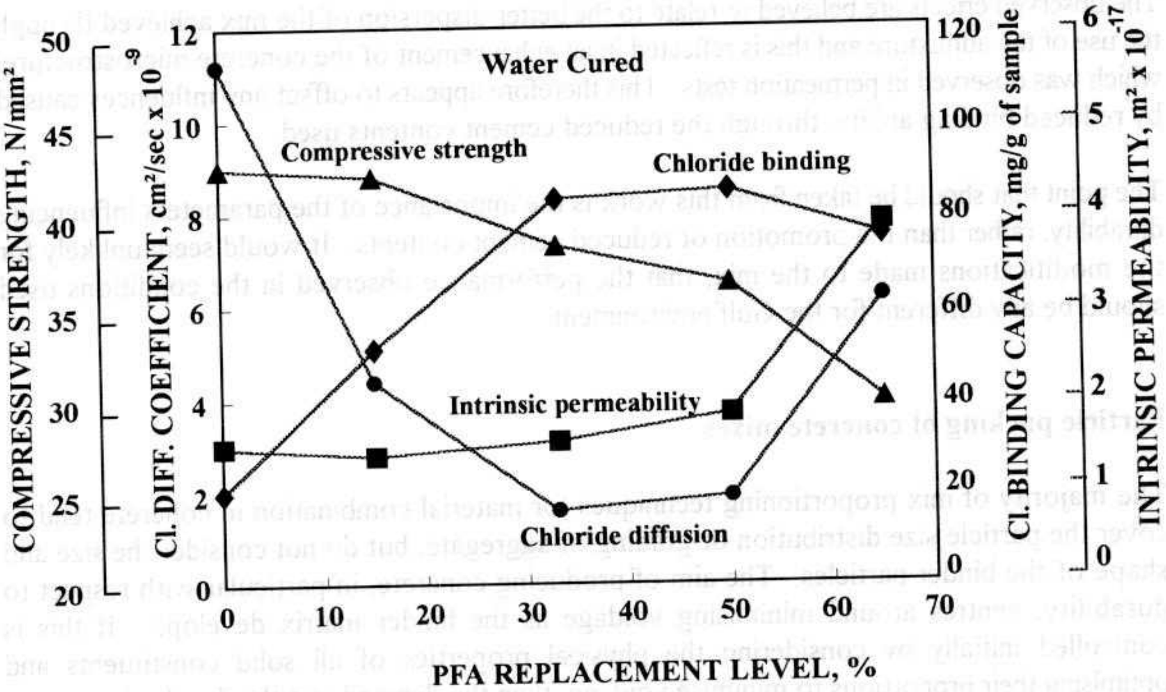

Fig.7. Influence of various factors on chloride diffusion in PFA concrete proportioned using particle packing method

Self-Cure Concrete

As highlighted above, one of the means of enhancing concrete performance is through the provision of curing to concrete, which ensures that moisture is available to promote hydration reactions and development of the microstructure. The main problem with all curing techniques is that they are time consuming and may place unacceptable constraints on the construction cycle. Consequently, they are seldom carried out to an adequate degree.

There is, therefore, a genuine need for a means of curing concrete which requires minimum effort after placing. An ideal solution would be a self-curing admixture which when added to a concrete mix would improve retention of water from the inside. Results using a self-cure agent developed at the University of Dundee (Dhir et al, 1996a), indicate that this can effectively enhance the permeation properties of concrete. Therefore, it might be expected that improved performance should be obtained in relation to concrete durability.

A comparison of chloride diffusion results for self-cure, air-cure and film cured concretes are shown in Figure 8 (Dyer and Dhir, 1997) This indicates that the benefits noted earlier for PFA and GGBS concretes are apparent for these curing conditions. The results also show that the self-cure concrete is almost as effective as the film cured concrete. Similar results have also been obtained from chloride penetration tests on immersed concrete.

Results obtained for permeation properties of concrete cured under high temperature conditions are shown in Figure 9 (Dyer and Dhir, 1997). These indicate that while poorer performance was obtained under the high temperature conditions than for those at 20°C, the relative performance of the self-cure concrete was better under the former conditions. Therefore, clearly, the system would provide benefits to concrete exposed to Gulf environments.

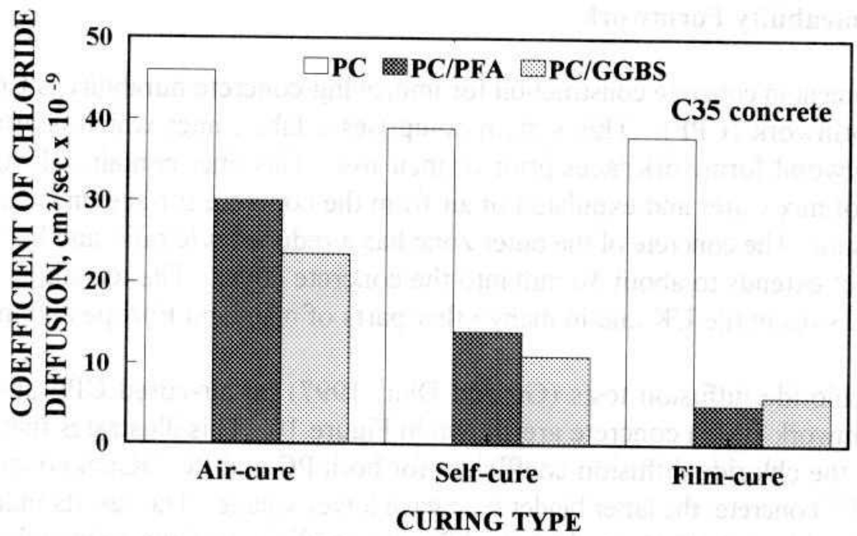

Fig.8. Chloride diffusion of self-cure concrete

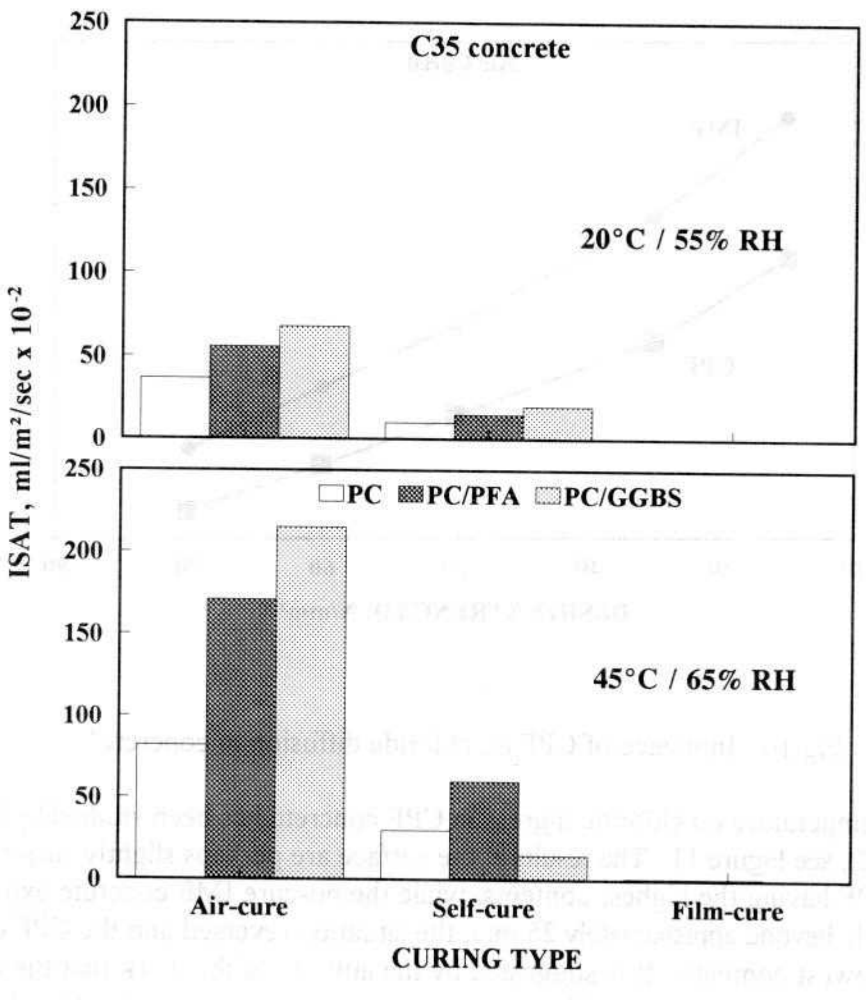

Fig.9. Effect of temperature on ISA of self-cure concrete

Controlled Permeability Formwork

A recent development in concrete construction for improving concrete durability is Controlled Permeability Formwork (CPF). This system comprises a fabric liner which is attached to conventional plywood formwork faces prior to their use. This liner contains all solids, but allows drainage of mix water and expulsion of air from the concrete surface under the action of concrete pressure. The concrete of the outer zone has a reduced w/c ratio and hence better quality. The effect extends to about 30 mm into the concrete cover. The technique has been used at over 200 sites in the UK and in many other parts of mainland Europe and in Japan.

The results of chloride diffusion tests (Gu and Dhir, 1997) on air-cured CPF and control impermeable formwork (IMF) concrete are shown in Figure 10. This illustrates that the CPF system reduced the chloride diffusion coefficient for both PC and PC/GGBS concrete. For both IMF and CPF concrete, the latter binder type gave lower values. The results indicate that the CPF system lead to reductions in chloride diffusion coefficient of approximately 15 to 35 units, with the greatest relative reductions obtained in low design strength concrete.

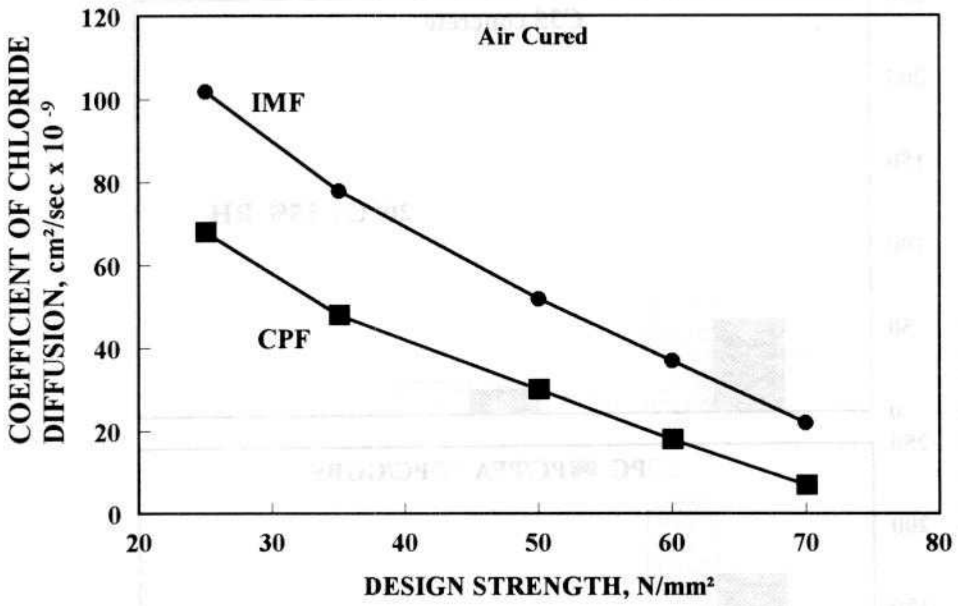

Fig.10. Influence of CPF on chloride diffusion in concrete

The effect of temperature on chloride ingress in CPF concrete has been studied by Price and Widdows (1992), see Figure 11. The results at the surface are perhaps slightly surprising with the no-cure CPF having the highest contents, while the no-cure IMF concrete exhibited the least. With depth, beyond approximately 25 mm, the situation reversed and the CPF concretes exhibited the lowest contents. It is suggested by the authors of the work that the effects of early age carbonation may be responsible, since as noted above, they modify chloride binding. However, given that carbonation should be less in CPF concrete, this is questionable. It is possible that denser concrete causes a greater build up of chloride at the surface, which is contained there, while poorer quality concrete leads to a greater overall transportation of

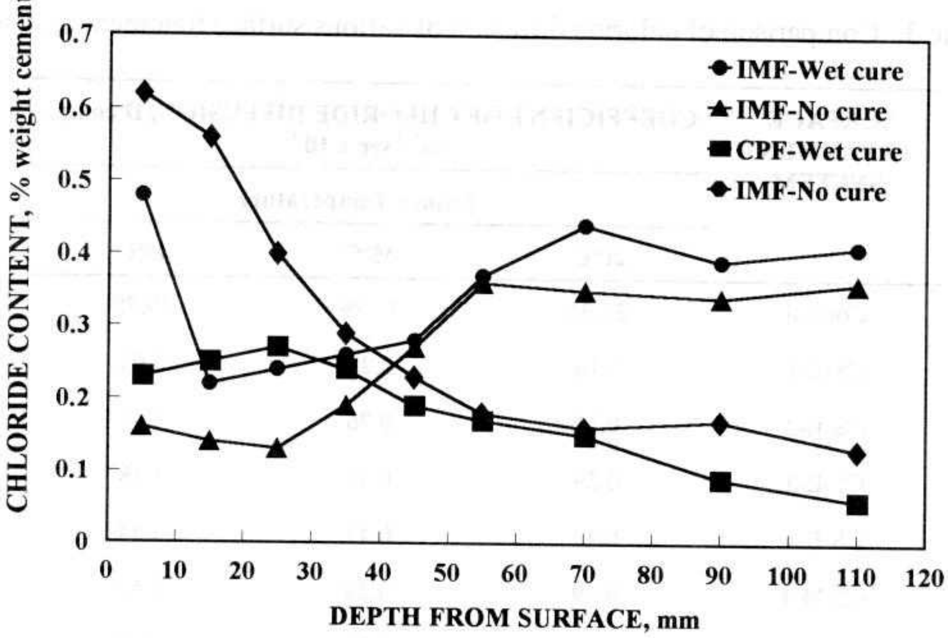

Fig.11. Chloride concentration profiles in CPF concrete under hot/dry exposure conditions (Price and Widdows, 1992)

chloride into concrete. It could also reflect rapid loss of water through the CPF liner under the high temperature conditions, thereby affecting the concrete surface. Clearly, further work is needed to firmly establish the cause of the observed effects. However, it is apparent that with depth, CPF leads to reductions of approximately 50% in chloride concentration. These reductions are in line with the chloride diffusion results referred to above, obtained at lower temperature conditions.

Such effects seem likely to reflect the densifying influence of CPF in preventing ingress and, in addition, to the limitation in moisture evaporation and thereby promotion of hydration reactions and associated influences on the microstructure.

Surface Coatings

The aim of surface treatment systems is to provide an impermeable barrier to the penetration of chloride. At the same time they should allow the concrete to breath, ie they should be water vapour permeable. These systems normally come in one or tow packs, ie they are applied directly to the concrete surface, or else are mixed with a curing agent before application, which can be either by spray or brush.

A range of different systems are available, including, silane/siloxane and epoxy. These and other systems have been tested in a comprehensive study (Jones et al, 1995), where they were applied to 35 N/mm^2 concrete. The results obtained from the study are given in Table 3. As indicated, at 20°C, all systems provided very good performance, with chloride diffusion coefficients indicative of very high resistance and long periods of service life before corrosion initiation.

Table 3. Comparison of chloride diffusion of various surface treatment systems

SURFACE TREATMENT SYSTEM	COEFFICIENT OF CHLORIDE DIFFUSION, D comp, $cm^2 / sec \times 10^{-9}$		
	Exposure Temperature		
	20°C	35°C	45°C
Control	25.94	37.79	39.78
CS-E-1	0.16	0.21	0.98
CS-E-2	0.31	0.76	1.42
CS-E-3	0.29	0.72	1.18
CS-E-4	0.43	0.47	3.54
CS-M-1	0.09	0.28	2.54
CS-A-1	4.20	7.04	10.30
P-S/Sx-1	0.07	2.17	7.10

Control PC
CS-E-1 Epoxy, high build
CS-E-2 Epoxy, pitch
CS-E-3 Epoxy, pigmented
CS-E-4 Epoxy, pitch
CS-M-1 Methacrylate, pigmented
CS-A-1 Acrylic, pigmented
P-S/Sx-1 Silane/siloxane blend

Increasing the temperature generally had a negative effect on the performance of the surface coatings, with the systems tending to work less well. However, in many cases performance could still be considered vey good and the general ranking remained the same as at lower temperature, with the epoxy giving the best performance and the silane/siloxane and acrylic tending to do less well at higher temperature.

While these offer promise in terms of the improvements they can bring to concrete performance and chloride resistance, the influence of the method of application, the concrete substrate characteristics and the effects of aging of the concrete, remain to be fully quantified.

CONCLUDING REMARKS AND PRACTICAL IMPLICATIONS FOR SERVICE LIFE

The results of the various methods for enhancing performance indicate that all have something to offer concrete.

Arguably the most effective means can be considered through the material selection, since this can provide substantial benefits compared to Portland cement concrete. The work described has also shown that w/c ratio, as a mix limitation parameter is critical, while the cement content may be of secondary importance for chloride environments. The use of pozzolanic binders at high levels can lead to substantial reductions in chloride diffusion coefficient. For example, using the estimation method developed by Dhir et al (1991) the service life of a C50 concrete, with a cover of 50 mm, and a critical threshold level of 0.2 % by weight cement, exposed to an environment containing 0.5M NaCl could be increased by 30 to 40 years through the use of high level PFA and GGBS concrete. Evidence available on the effect of temperature on these binders suggests that similar improvements to performance will be achievable for concrete in the Gulf environment.

It is possible to gain further benefits by using multi-component binders, which can take advantage of the physical and chemical differences of various binder components to provide a blend ideally suited to the conditions. Other means of improving chloride resistance lie in physically minimising the void space prior to producing concrete. These techniques can be used to produce very high chloride resistant concrete. Indeed, the measured coefficients obtained from these concretes can give service life in excess of 100 years in temperate climates.

The use of systems including self-cure concrete and CPF, because of there densifying effect to the concrete cover, will also offer enhancements to the concrete cover. For example, under the conditions described above, they could give increases in service life of 5 to 10 years for self-cure and 10 to 20 years for CPF.

The use of silanes can be very effective in reducing chloride diffusion coefficients and again can reduce values to the point where they can offer long periods of maintenance free service life, for example in excess of 100 years. However, issues relating to workmanship and achievement of adequate penetration will also influence their performance and time to corrosion.

It is not clear, however, whether the combination of several nethods of protection will be cumulative or not. Clearly, this is an area where further work is required. All of the above methods are, however, very promising means of achieving extra quality for concrete and have potential for very extreme conditions, such as those encountered in the Gulf region.

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