# Microsilica Concrete, Towards 2000 in the Arabian Gulf environment.

By,

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**Abstract.** Deterioration of reinforced concrete structures is a serious problem in the Arabian Gulf. Much of this deterioration is caused by chloride ingress through concrete, which results in the corrosion of the reinforcing steel. As we approach the year 2000, the practice of specifying microsilica in concrete is widening as engineers work, to improve the durability of concrete, subject to the severe exposure conditions of the region.

Current practice is to use microsilica additions ranging from 5% to 10% depending on the degree of exposure. Are these amounts of microsilica sufficient to maintain a realistic life span for concrete structures towards the year 2000?

How much microsilica is really needed to provide durable concrete under the varying exposure conditions?
How much cover is required to the reinforcement to protect the steel from corrosion?

In this paper, models are used to predict the chloride ion ingress into Portland cement concrete and microsilica enriched concrete under different exposure conditions. The results show that small amounts of microsilica are sufficient as long as appropriate covers to reinforcement are maintained and chloride exposure is correctly assessed.

**Keywords.** Concrete durability, severe chloride exposure, microsilica, chloride modelling, chloride profiles, surface chlorides, mix chlorides, chloride diffusion, design life.

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**Introduction.** Deterioration of reinforced concrete structures is a problem of serious proportions in the Arabian Gulf, with the most common form of deterioration being caused by chloride ingress through concrete, which results in the corrosion of the reinforcing steel [1]. When the steel rusts, it expands by up to 4 times its original volume, creating tensile stresses in the concrete, which lead to cracking and spalling of the concrete cover zone. Chloride ingress can then rapidly accelerate and eventually deterioration of the structure results. In 1992, Rasheeduzzafar [2] has shown in figure 1 the beneficial effect of using the pozzolans, Pulverised Fuel Ash, PFA, Ground Granulated Blast Furnace Slag, GGBFS and Microsilica, MS, with Type 1 ordinary Portland cement, OPC, over the more commonly used sulphate resisting cement, SRC, to achieve longer life in concrete structures subject to the extreme exposure conditions.

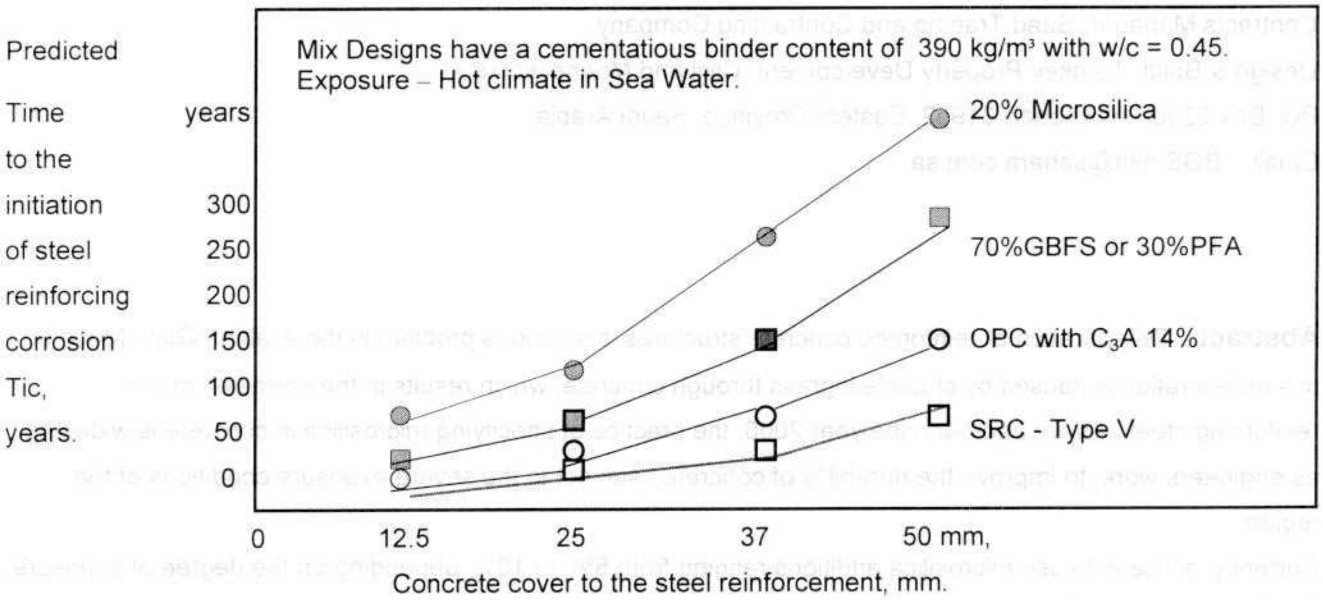


*Figure 1. Predicted time to the initiation of reinforcement corrosion, at various covers for concrete made with SRC, OPC, and OPC modified with PFA, GGBFS and microsilica under severe chloride exposure* [2].

In response to this research, engineers began specifying microsilica in structures subject to extreme chloride exposure conditions. The most immediate concern of the Client's was the high cost of the pozzolans specified. Microsilica sells for eight times the cost of cement in Saudi Arabia. Microsilica costs SR1500 to 1750 per ton, Portland Cement costs SR 200 to SR 220 per ton. When supplied from ready mixed concrete plants the quoted costs of concrete's containing pozzolanic materials are summarized in Table 1.

Table 1. Cost of adding pozzolans to concrete in Saudi Arabia.

| Mix Design | Mix Cost SR/m³ | Time to start of Corrosion(a) Years | Cost/Year of Design Life SR/Year |
|---|---|---|---|
| OPC + 20% MS | Not recommended as prone to cracking. | | |
| OPC + 10% MS | 250 | 380 | 0.66 |
| OPC + 5% MS | 220 | 240 | 0.92 |
| OPC + 70% G B F Slag | 620 (b) | 250 | 2.48 |
| OPC + 30% PFA | 335 (b) | 250 | 1.34 |
| OPC with $C_3A$ = 8% | 180 | 100 | 1.8 |
| SRC, with $C_3A$ = 2% | 185 | 60 | 3.1 |

*All mixes have total cementations content 390 kg/m³. Cover to reinforcement = 50mm.*
*(a) Rasheeduzzafar [2]. (b) Costs as quoted by a leading RMC supplier in August 1994. Other costs 1998*

Blast Furnace Slag with a high replacement level of 70% makes it a costly option. Microsilica, with lower replacement levels of 5 to 10%, is currently the most popular choice for durable concrete in the Gulf Region. Researchers have also shown that OPC mixes modified with microsilica are also resistant to sulphate attack [3]. The use of microsilica in the Eastern Province in recent years is shown in Table 2.

Table 2 Microsilica replacement levels used in Eastern Province 1993-7.

| Year | Project | Microsilica % | Cover mm. |
|---|---|---|---|
| 1993 | SCECO specification 71-SMSS-5 Rev2. | 10-15% | -- |
| 1993 | SCECO power line piles to Half Moon Bay. | 11% | -- |
| 1993 | Aramco, Executive Beach Club, Half Moon Bay. | 8% | 75 |
| 1993 | Beach Villa Foundations on Half Moon Bay. | 7% | -- |
| 1994 | Aziziyah Desalination Plant. | 7-10% | -- |
| 1995 | Aziziyah Beach Club. | 10% | 75 |
| 1995 | SCECO specification 71-SMSS-5 Rev3. | 8% | -- |
| 1995 | Royal Commission of Jubail & Yanbu. | 8.2% | -- |
| 1997 | Alkhobar Building Basement. | 5-7% | 75 |
| 1997 | Al Khaleeg Village on Half Moon Bay. | 8% | -- |
| 1998 | Sunset Beach development. Aziziyah. | 7% | -- |
| 1998 | Gazlan Power Station. Specification. | 10-15% | 85 |

*Cement + microsilica = 390kg/m³ unless noted otherwise.*
*% microsilica = microsilica as a percentage of the total cement + microsilica weight.*

In all cases, the engineers have specified that the concrete should be tested using the ASTM C1202 Rapid Chloride Permeability Test, and have a low chloride ion permeability as classified by AASHTO T 277, with a test result of less than1000 Coulombs.

Microsilica is a pozzolan like PFA and GGBFS and Table 3 shows typical properties of these materials.

Table 3. Physical and chemical properties of microsilica compared with other pozzolans.

| **Physical Data** | | **Cement** | **PFA** | **GGBFS** | **Microsilica** |
|---|---|---|---|---|---|
| Surface Area $m^2/kg$ | | 350-500 | 300-600 | 300-500 | 15,000-20,000 |
| Bulk density $kg/m^3$ | | 1300-1400 | 1000 | 1000-1200 | 200-650 |
| Specific gravity | | 3.15 | 2.3 | 2.9 | 2.2 |
| **Chemical Data** | | **Cement** | **PFA** | **GGBFS** | **Microsilica** |
| SiO2 | % | 20 | 50 | 38 | 85-98 |
| $Fe_2O_3$ | % | 3.5 | 10.4 | 0.3 | 0.2-2.5 |
| $Al_2O_3$ | % | 5 | 28 | 11 | 0.2-2 |
| CaO | % | 65 | 5 | 40 | 0.2 |
| MgO | % | 0.1 | 2 | 7.5 | 0.2 |
| $Na_2O + K_2O$ | % | 0.8 | 3.2 | 1.2 | 2.0 |

Microsilica will increase the strength of the hardened concrete and reduce the permeability by densifying the matrix and thus providing a more durable concrete with a longer life. The refined pore structure reduces the passage of harmful ions like chlorides [ 4]. However, experience in hot weather has shown that high doses of around 15% may be susceptible to plastic shrinkage cracks forming during the initial set of the concrete. To prevent this cracking, care is required to ensure the recommendations given in table 2.1.5 of ACI 305, the code of practice for hot weather concreting, are strictly adhered to. In particular cooling the concrete with chilled water and ice, and not pouring concrete on hot or windy days when humidity levels are low [ 5].

**Scope of this research.** As the development of codes of practice are lagging behind the development of new products and technology within the construction industry, this paper is intended to contribute to the body of knowledge on microsilica enriched concrete, and answer the following questions;

Are specification engineers justified in using microsilica levels ranging from 5 to 10% to obtain durable concrete?,

What are the expected years to the initiation of reinforcement corrosion for these mixes under various exposure conditions?

How much cover is required to the reinforcement?

This paper will answer these questions, firstly through a literature search of current codes, specifications and research on modelling chloride profiles, and secondly by proposing new models for calculating chloride diffusion coefficients for plain concrete and microsilica enriched concrete. Thirdly by predicting the time to the initiation of corrosion of steel reinforcement in a range of concrete mixes under varying exposures the life span can be estimated. Finally design life spans will be discussed.

**Literature review on current design guidelines for durable concrete mix design.**

Bamforth [6] has clearly shown in Table 4 the inadequacy of European codes in preventing corrosion of reinforcement in concrete subject to extreme chloride exposure.

Table 4. Inadequacy of European codes, when used in the Gulf region [6].

| Code | Exposure Condition | Cement $kg/m^3$ | Cover mm | Deff $m^2/s$ | Time to onset of corrosion - Years |
|---|---|---|---|---|---|
| BS8110 Structures | Seawater spray | 400 | 50 | 2.57e-12 | 5.4 |
| BS5400 Bridges | Seawater spray | 360 | 40 | 3.93e-12 | 5.5 |
| BS6349 Marine Str. | Seawater spray | 400 | 50-75 | 2.57e-12 | 5 to 12 |

**The CIRIA Guide** to concrete construction in the Arabian Gulf Region [ 7], provides guidelines for categorising environmental exposure conditions, then a range of specification limits are given for selecting the appropriate mix design and the recommendations are summarised in Table 5. However the recommendations are inadequate as shown by Bamforth [ 6]. *( Note that this guide is currently being updated.)*

Table 5 Exposure conditions and concrete mix design from CIRIA SP31 [7].

| Exposure Condition | Cement Min. $kg/m^3$ | Max W/C Ratio. | Min Cover mm | Additional Requirement. |
|---|---|---|---|---|
| A Superstructure not exposed to Cl | 300-320 | 0.52-0.5 | 30 | None. |
| B Superstructure exposed to Cl | 320 | 0.5 | 40 | None. |
| C Foundations not exposed to Cl. | 320-350 | 0.5-0.45 | 40-50 | None. |
| D Foundations exposed to Cl. | 300-420 | 0.5-0.42 | 40-50 | Tanking membrane |
| E Marine structures | 370-400 | 0.45-0.42 | 75-100 | |

The existing international codes are inadequate in providing realistic life spans for major structures in the extreme exposure of the Arabian Gulf region. Firstly, the chloride diffusion coefficients for ordinary Portland cement mixes are not low enough to provide an adequate service life. Secondly, increased cover is required to the reinforcement. Finally, concrete containing either pulverised fly ash, ground granulated blast furnace slag or micro silica is required to provide an adequate service life.

**Local specifications for concrete mix designs.** Comprehensive specifications used by local organisations such as SCECO East [ 8], ARAMCO [ 9] and The Royal Commission for Jubail and Yanbu [ 10], provide guidance to engineers working in Saudi Arabia. A summary of the requirements, for durable mix designs, are given in Table 6.

Table 6 Local Saudi Arabian specifications for durable concrete design.

| SCECO [ 8] | Environmental classifications<br>RMC Spec'n 71- SMSS - 5, Rev 3. | Design recommendations<br>Cement<br>kg | <br>MS<br>kg or % | <br>W/C<br>Ratio | <br>Coulomb<br>Test |
|---|---|---|---|---|---|
| Severe | Exposed to sea water, or raw water wash down,<br>exposed to Cl. concentration > 0.1% | 359 | 31 or 8% | 0.4 | <1000 |
| Moderate | In contact with soil, with chloride < 0.1%<br>Exposed to fresh water, occasional raw water. | 350 | nil | 0.4 | |
| ARAMCO [ 9] | | | | | |
| Severe | Exposed to sea water or near the coast,<br>*Specified on a case by case basis* | 370 | 30 or 7.5% | 0.4 | <1000 |
| | Structural concrete to 09-SAMSS-097 | 350-370 | nil | 0.4 | |
| Royal Commission of Jubail & Yanbu. [10] | | | | | |
| 1995 | Royal Commission of Jubail & Yanbu. | 315-405 | 28-36 or 8.2% | 0.4 | <1000 |

Traditionally, engineering codes of practice give minimum cement contents and minimum covers, and maximum water to cement ratios to ensure durability of concrete. These guidelines are largely based on research into the permeability of concrete [ 11]. However, today it is more appropriate to specify minimum amounts of pozzolanic additives to achieve the longevity needed in structures exposed to severe environments. The local specification's summarised in Table 6, provide better advice for engineers in the region, than the European codes of practice in Table 4 .

**Local specifications provide good advice in recommending the use of pozzolans to produce durable concrete. But how long will concrete mixes, containing between 5% and 10% microsilica, last under severe exposure? And how much cover is required to provide adequate protection, to the steel reinforcement, from the severe exposure experienced in the Arabian Gulf region? To answer these questions we require models, that predict the rate at which chloride ions diffuse through the concrete, for varying concrete mix designs. The models could then be used, to calculate the time to the initiation of steel reinforcement corrosion, and hence an estimate and the design life could be calculated for varying mix designs.**

**Literature review on chloride diffusion into concrete.**

The main transport process's leading to the deterioration of concrete in the Arabian Gulf, are water absorption from capillary forces and wick action, followed by water evaporation and the resulting salt crystallisation on the surface and in the pores of the drying zone. Once transported to the surface the chloride then diffuses through the concrete and eventually the reinforcement corrodes. This process occurs in all structures in contact with salty sea or ground water or damp salty soil. To model this chloride diffusion process, engineer's use Fick's Second law which enables the chloride profile in the concrete to be calculated [ 12, 13, 14 ].

**Fick's Second law.** Figure 2 shows a typical chloride profile calculated using Fick's diffusion laws for modeling the diffusion of chloride ions into concrete over a prolonged period of exposure,

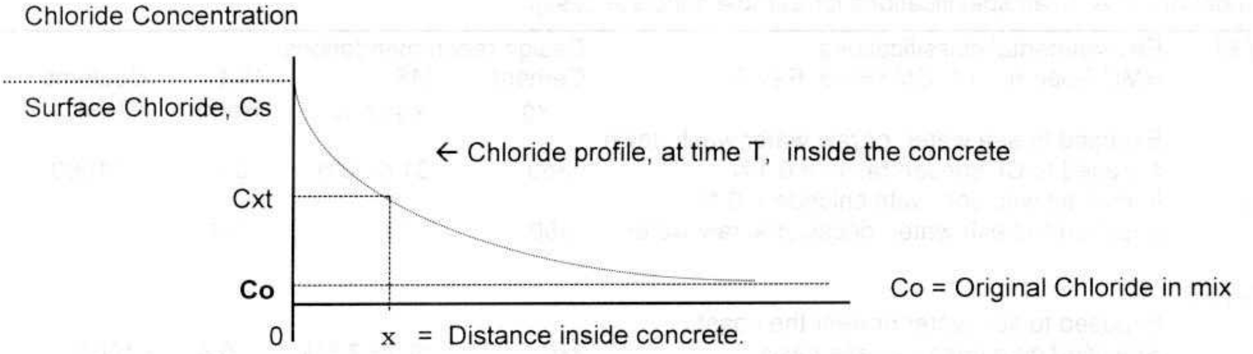


*Figure 2. Relation between Chloride concentration and distance from concrete surface, The chloride profile calculated using Fick's Second Law [ 15].*

This results in a solution that can be used to calculate Cxt, the concentration of diffusing atoms at a distance x inside a material after time T. The solution is referred to as the Fick's chloride profile equation.

**The Fick's chloride profile equation.** $$Cxt = Cs-(Cs-Co) * erf(x/(2\sqrt{(Deff*T)})) \quad (1)$$

Where;

Cxt = The concentration of chloride at a distance, x, inside the concrete after time T, as % weight of concrete.

Co = Original Chloride concentration in the concrete from all the mix materials, as a % of the concrete weight

Cs = Surface concentration of chloride, as a % of concrete weight.

x = distance from the surface in cm.

T = Time period for chloride buildup in the concrete in years.

Erf = the error function from standard tables [ 15 ];

Deff, the effective diffusion coefficient over the design life of the structure = Dei * Kti * Kte, in $cm^2$ / year. ( 2 )

Dei = the initial diffusion coeff at 28 days, in $cm^2$ / year.

Kti = time related effect on the diffusion coefficient.

Kte = temperature related effect on the diffusion coefficient.

**Original chloride concentration Co, in the concrete from all the mix materials.**

Local and international specifications, firstly limit the chloride content of the mix ingredients then secondly of the total mix as shown in Table 7. Practically we should aim to have the lowest chloride level possible with locally available materials, particularly for concrete exposed to sea water. That is a maximum Co < 0.10 % by weight of cement for all concrete. In some parts of the Gulf region this may not be achievable. If so then a higher grade of concrete should be specified, with more cement and microsilica, to compensate for a higher Co in the initial concrete mix. Alternatively corrosion inhibiting admixtures may need to be used.

Table 8 Local and International Code limits to the total chlorides in the original concrete mix, Co.

| Maximum acid soluble chlorides in a concrete when mixed, Co as a % by weight of cement. | | | | | |
|---|---|---|---|---|---|
| **Local limits** | SCECO | | ARAMCO | R.Comm.J&Y | |
| Type of concrete | 71-SMSS-5 Rev3 | | 09-SAMSS-097 | SAB 03347 | |
| Reinforced concrete in a moist environment and exposed to chloride | <0.10%. | | < 0.25% | <0.13% | |
| **International limits** | American ACI 201 | British BS 8110 | British BS 5400 | FIP Hot Weather | CIRIA SP31 Gulf |
| RC exposed to chloride in service | < 0.10 | | | | |
| Reinforced in SRC | | < 0.20 | 0.06 | 0.15 | 0.15 |
| Reinforced in OPC, | | | 0.35 | 0.15 | 0.30 |
| Reinforced in OPC & PFA or BFS | | < 0.40 | | | |

In the Gulf, it is also important to wash the aggregates, as the fines often contain high concentrations of deleterious substances like sulphates and chlorides.

Test measurements taken on concrete used in the Eastern Province of Saudi Arabia, presented in Table 11, show that with adequate quality control procedures, the original chloride level in the concrete, Co, can be kept below 0.1% by weight of cement or 0.017% by weight of concrete. **Hence, Co = 0.017% by weight of concrete will be used by the author to model chloride profiles and assess the time to the initiation of corrosion of reinforcing steel.**

**Environmental Chloride and the Concrete Surface Chloride Concentration , Cs.**

The concrete surface chloride ion concentrations Cs for different mix designs, which under varying exposure conditions, are required to predict the chloride ingress using Fick's law. The Surface Chloride values plotted in Figure 3, show typical values measured in hot marine environments.

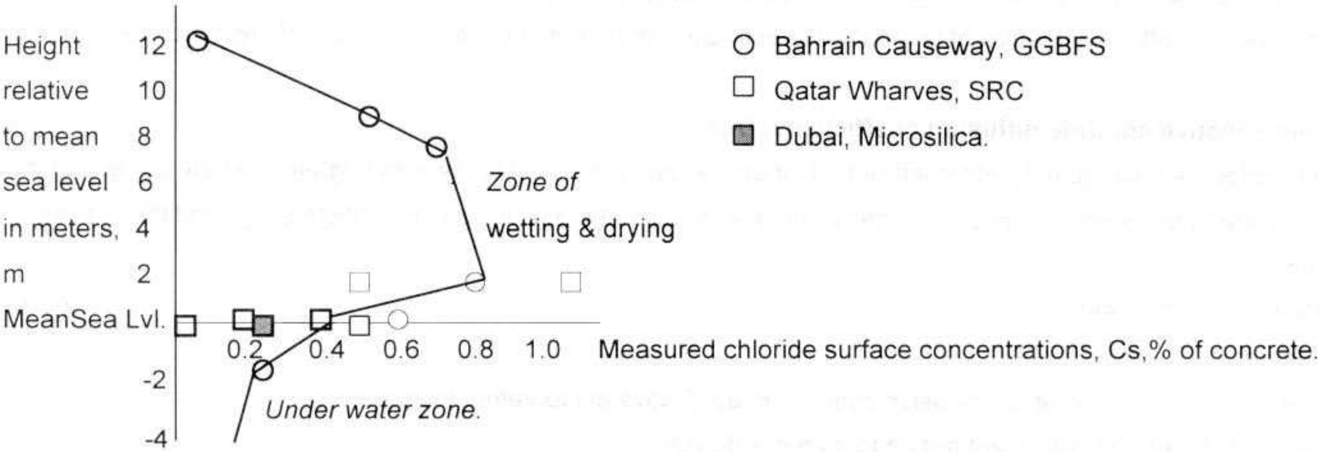


*Figure 3. Relation between the location of exposure, and the measured Surface Chloride Level, Cs, of the concrete in hot marine climates – Extreme exposure [ 16, 17, 18, 19 ].*

The Cs values are greatest in areas subject to wetting and drying. When salty water evaporates, any chloride in the water will remain in the surface zone in a crystalline form. In marine structures, the Cs value will be at a maximum just above the sea water level in the splash zone. In bridges and buildings, the Cs value will be at a maximum just above ground level where water is drawn through the concrete and then evaporates from the surface.

The values proposed by Bamforth[ 22] for blended cements containing PFA, GGBFS or microsilica appear high. The Cs=0.9% for extreme environments corresponds with values shown in figure 3 that were measured in GBFS concrete on the Bahrain Causeway, by Bijem et al [ 17, 19 ]. Similar high values have been measured at the Qatar wharves for SRC concrete by Akili [ 16]. However, for microsilica concrete, research done in Dubai [ 21], shows Cs values as low as 0.25, for mixes having low w/c ratios and exposed to sea water. One would expect Cs values for low w/c ratio microsilica concrete to be lower than OPC at the same w/c ratio as the pore structure is much finer, as demonstrated by Hussain [23].

**The range of surface chloride levels, Cs, expected under varying exposures, and the actual values used by the author for modelling chloride ingress are shown in Table 8.**

Table 8. Environmental and surface chloride levels, Cs, under varying exposure conditions.

| Exposure | Typical Condition | Cl concentration % Conc. | Cs range % Conc.[22] | **Cs modelled** % Conc. |
|---|---|---|---|---|
| **Extreme** | Sea water in hot climate | 3.5% in Gulf | 0.6-0.9 | **0.9** |
| **Severe** | Sea water in temperate climate | 2.5% in Europe | 0.3-0.6 | **0.6** |
| **Moderate** | In contact with ground water or raw water wash down. | 0.1-0.5% | 0.15-0.3 | **0.3** |
| **Low** | Foundation & Superstr. to $1^{st}$ Flr. in hot climates within 3m of water table. | <0.1% | 0-0.15 | **0.15** |
| Nil | Superstructures above $1^{st}$ Floor | Nil | Nil | |

Note that Cs values may also vary with the amounts of pozzolans used but more research is required before differentiating between Cs and mix type.

Once the maximum surface chloride level has been established, and the initial chloride level measured, then the chloride diffusion coefficient is required to estimate the chloride profile over the life of the concrete.

**The effective chloride diffusion coefficients, Deff,**

The effective chloride diffusion coefficient defines the rate at which chloride ions migrate from the surface of the concrete to the reinforcement. The rate varies according to the mix design, the concrete age and the exposure temperature.

Deff = Dei * Kti * Kte , (2)

Where;

Dei = The initial chloride ion diffusion coefficient, at 28 days at laboratory temperatures.

Kti = a time related coefficient dependant on mix design.

Kte = a temperate related coefficient dependant on exposure temperature.

**Chloride Diffusion and mix design.** Research by Malikakkal at KFUPM [ 14 ], has related the initial chloride diffusion coefficient in concrete to the water/cement ratio and cement content, as shown in equation 3. Malikakkal's Diffusion equation for SRC concrete in Dhahran;

$Dei = 0.315 * (82.7 - 426 * w/c + 568 * (w/c)^2 + 4.26 * C^{-6})$ $cm^2$/Year at 20°C. ( 3 )

Where, w/c = water to cement ratio, C = (cement content / 350) for concrete made with SRC.

Hussain [ 23 ] has shown that for OPC mixes, $Deiopc = 0.736 * Deisrc$. ( 4 )

Type 1 cement blended with pozzolans, will give much lower diffusion coefficients and hence far better resistance to chloride ion penetration, than plain Portland cements. [ 2, 23, 24 ] The benefit of pozzolans, and in particular microsilica is the reduced pore radii and the resulting reduction in chloride diffusion.

**Time related reduction in diffusion coefficients, Kti.** The addition of microsilica will reduce the diffusion coefficients by an order of magnitude, which, will extend the time to the onset of corrosion. Figure 4 shows the reduction of diffusion coefficients during a typical 100 year design life for a concrete structure, particularly when blended cements are used. Hence, in our model for calculating the time to the onset of corrosion of the reinforcing steel, which may be up to 100 years, we must take account of firstly, the effect of the dose of pozzolans and secondly, the time related drop in diffusion coefficients over the design life of the structure [ 12, 24 ].

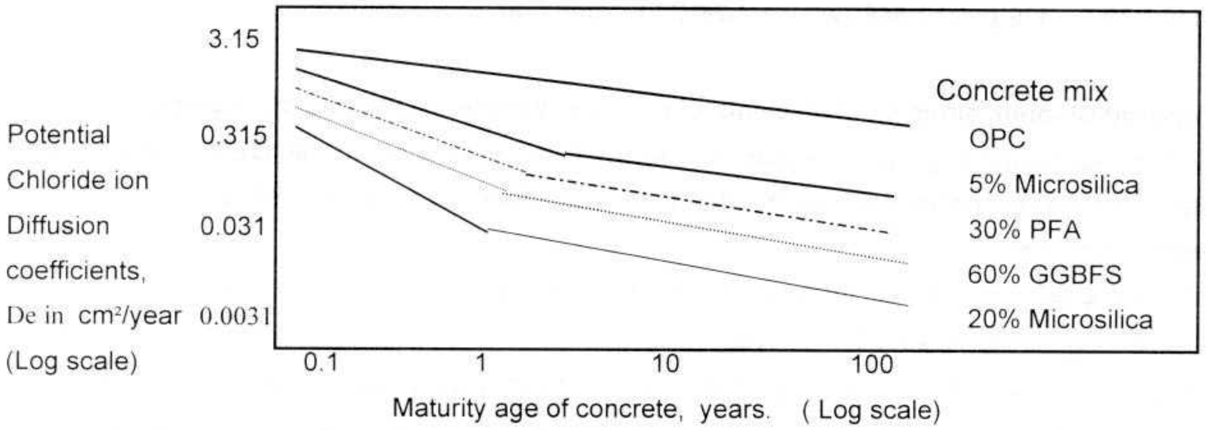


*Figure 4. Time related reduction in the chloride-ion diffusion coefficients for concrete containing pozzolans over the design life of a concrete structure [ 12,24 ].*

For OPC and SRC mixes the time related coefficient,

$Kti = 1/(1 + 2*\log(T+1))$, for T years of design life. ( 5 )

For microsilica the time related coefficient Ktims, is calculated as follows;

$Ktims = 1/(1 + 3 * \log(T+1) + 0.1*ms * \log(T+1))$. ( 6 )

**Theoretical models for calculating chloride diffusion into concrete.** For Saudi Arabian concrete's, containing local materials, models 1 to 3 are proposed to calculate the chloride ion diffusion coefficients for concrete containing OPC, SRC and microsilica. These modeled diffusion coefficients will then be used to calculate the relationship between mix design, cover and life expectancy of a concrete structure to ensure an appropriate durable mix is chosen at the design stage using Figures 5, 6 & 7.

**Model 1, Chloride diffusion coefficients of concrete made with sulphate resisting cements.**

This model is proposed to help engineers calculate the effective chloride-ion diffusion coefficients, Deff, over the design life of a structure, from the concrete mix design for a structure built with concrete containing SRC.

Deffsrc = Deisrc*Kti*Kte ,Where; (2)

Deisrc = The initial chloride ion diffusion coefficient, at 28 days at laboratory temperatures, for Saudi Arabian concrete's containing SRC, from Malikakkal's diffusion equation [ 14 ];

Kti = the time related coefficient from equation 5.

Kte = 2 for hot & tropical climates like the Arabian Gulf.

Thus, for modelling chloride diffusion, the effective diffusion coefficient for structural concrete made with SRC for a 100 year design life in the hot Arabian Gulf region.

$$\mathbf{Deffsrc = 0.126*( 82.7 - 426*(w/c) + 568*(w/c)^2 + 4.26*C^{-6})\ cm^2/year.} \quad (6)$$

**Model 2, Chloride diffusion coefficients of concrete made with ordinary Portland cement.**

The Chloride ion diffusion coefficients, for concrete containing OPC, are estimated using Malikakkal's diffusion equation 3 [ 14 ], but with a correction to lower the diffusion coefficient by thirteen percent, as a result of the research by Hussain [ 23 ].

$$\mathbf{Deffopc=0.110 *(82.7 - 426*(w/c) + 568*(w/c)^2 + 4.26*C^{-6})\ cm^2/Year.} \quad (7)$$

**Model 3, Proposed Chloride diffusion coefficients of concrete made with OPC and microsilica.**

This model is proposed to help engineers calculate the effective chloride-ion diffusion coefficients, Deffms, over the design life of a structure, from the concrete mix design for a structure containing microsilica.

Deffms = Deims * Ktims * Kte, (8)

Where Ktims is a time related coefficient from eqn 10 and Kte =2, the temperature related coefficient;

Deims =1.5 - 1.25 * log(ms+1) + $ms^2$/1500, $cm^2$/year (9)

ms = percentage replacement of microsilica = 100 * Ms/(C+Ms), And Ms is microsilica content in kg/$m^3$ of concrete and C is the OPC content in kg/$m^3$ of concrete. This equation is based on the diffusion coefficients published by researchers [12, 13, 19, 22, 24 ] at an age of 28 days. Equation 9 is only proposed for microsilica replacement levels between 5% and 15%. Concrete mixes must have W/(C+Ms) < 0.4 and be made of OPC cement. The concrete mixes should have between 370kg and 400kg of cement and microsilica per cubic meter . Super plasticising and retarding admixtures should be used to maintain the low w/c ratio. Now for 100 years in hot climates.

$$\mathbf{Deffms = 1/(7.01 + 0.2*ms) * (1.5 - 1.25 * Log(ms +1) + ms^2/1500) *Kte\ \ cm^2/year.} \quad (10)$$

Table 9. Estimated chloride ion diffusion coefficients and Coulomb values, for plain and microsilica enriched, concrete at an age of T=100yrs in the Arabian Gulf Climate from proposed equations 6, 7 & 10.

| **Concrete mix design.** Cement, kg/m3, | w/b, ratio, | microsilica Kg | % | Equation 6 Deffsrc $cm^2$/year | Equation 7 Deffopc $cm^2$/year | Equation 10 Deffms $cm^2$/year |
|---|---|---|---|---|---|---|
| 340 | 0.5 | 0 | 0 | 2.13 | 1.86 | |
| 360 | 0.45 | 0 | 0 | **1.23** | **1.07** | |
| 400 | 0.4 | 0 | 0 | **0.66** | **0.57** | |
| 370 | 0.4 | 20 | 5 | | | **0.136** |
| 361 | 0.4 | 29 | 7.5 | | | **0.088** |
| 351 | 0.4 | 39 | 10 | | | **0.059** |
| 342 | 0.4 | 48 | 12.5 | | | **0.040** |
| 332 | 0.4 | 58 | 15 | | | **0.029** |

**Note that in the Arabian gulf climate great care needs to be taken using more than 15% microsilica replacement, especially during the hot summer months, and it is not recommended.*

The diffusion coefficients calculated in Table 9, and shown in **bold** type, will be used to predict the time to the initiation of corrosion of reinforcing steel and the results plotted in Figures 5, 6 & 7.

## Model prediction of the time to the initiation of reinforcement corrosion, Tic in years, for various mix designs under different exposure conditions.

The life expectancy of structures can be estimated by using equation 1.

$$Cxt = Cs - (Cs-Co) * \text{erf}\,(x/(2*\sqrt{(Deff * T)})). \qquad (1)$$

By calculating the time taken for the concrete chloride level, Cxt, to reach the threshold chloride level that results in steel corrosion, Cic at the position of the reinforcement, x Cm from the surface of the concrete, we can calculate the time to the initiation of corrosion Tic and obtain a measure of the design life that can be expected for the concrete structure. By substituting Cic for Cxt and Tic for T in equation 1 the resulting equation is;

$$\mathbf{(Cs-Cic)/(Cs-Co) = erf\,(x/(2*\sqrt{(Deff *Tic)}),} \qquad \mathbf{(11)}$$

Where Tic is the years to the initiation of reinforcing steel corrosion at cover of x Cm.
Note that standard tables must be consulted for values of the error function, **erf** [ 15 ].

**The threshold chloride levels that result in the initiation of corrosion Cic**, for different cementatious materials, used for modelling are shown in Table 10.

Table 10 Threshold chloride levels, Cic for different cementatious materials.

| Cementatious material | Cic % by weight of cement | Cic % by weight of concrete |
|---|---|---|
| SRC | 0.35 | 0.058 |
| OPC | 0.60 | 0.100 |
| M'Silica | 0.60 | 0.100 |

Note that for microsilica concrete, researchers are divided, Bamforth [19] suggests lower values should be used for microsilica, while Talib et al [ 25] have shown higher values. Therefore, we assume Cic for microsilica will be the same as OPC for modeling until future research clarifies this.

**Using the model equations and constants it is now possible to calculate the time to the initiation of corrosion of the reinforcing steel for varying mix designs and concrete covers. The results are plotted in figures 5, 6 & 7.**

**Proposed figures for assessing the mix design and cover required, to provide durable concrete over a specified design life, in Saudi Arabia.** The following results, in terms of years to the initiation of corrosion, were obtained using the above mentioned models for extreme, severe, moderate and low chloride exposures, for various mix designs at various covers.

**Concrete mixes and cover requirements for Extreme chloride exposure of sea water in hot climates.**

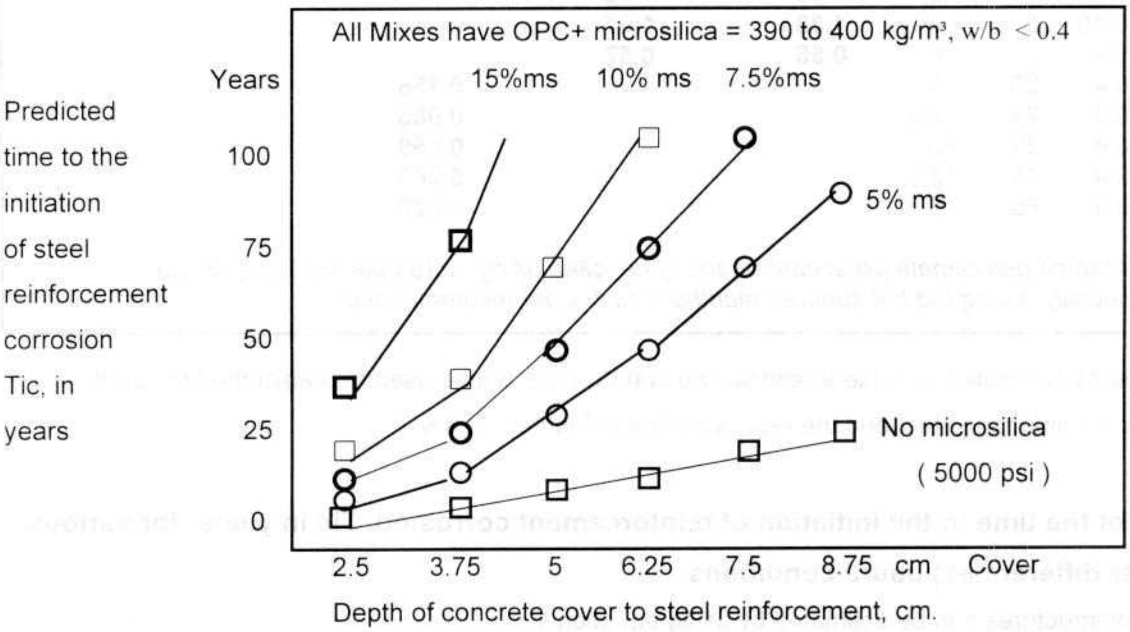


*Figure 5. Predicted time to the initiation of corrosion of steel reinforcement, at various covers in concrete under extreme chloride exposure in hot climates, using equations 6, 7, 10 and 11.*

**Concrete mixes and cover requirements for Moderate chloride Exposure. (Any structure in contact with raw water in hot climates.** Raw water with TDS from 4,000 to 5,000ppm. )

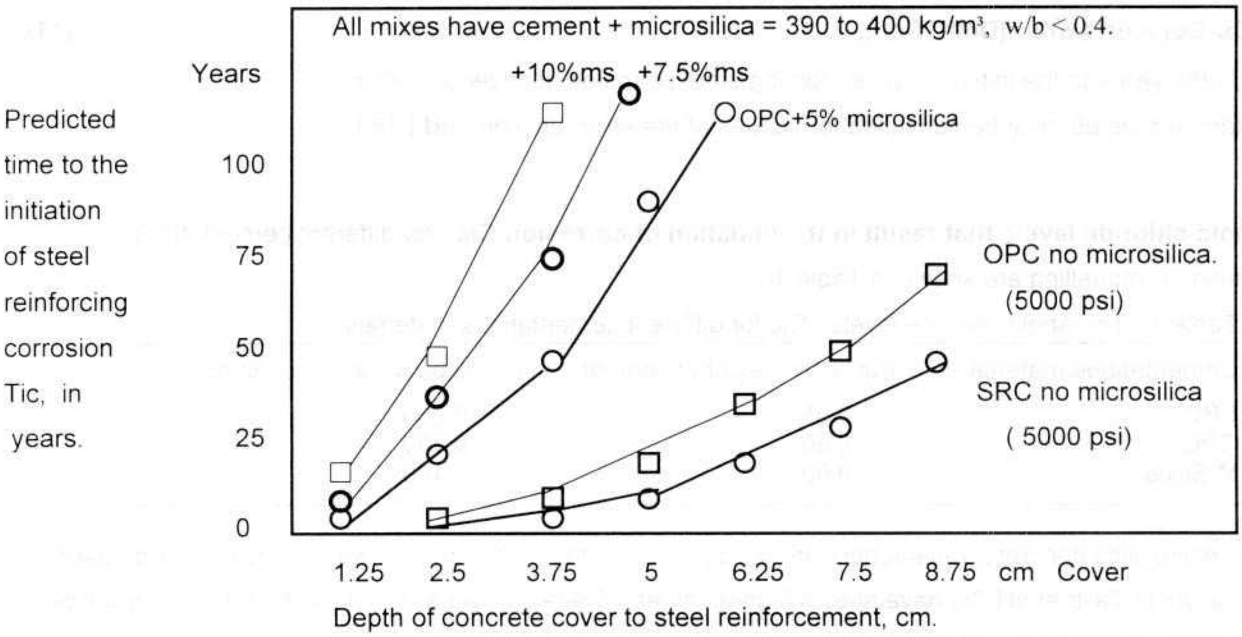


*Figure 6 Predicted time to the initiation of corrosion of steel reinforcement, at various covers in concrete, under moderate chloride exposure in hot climates, using equatios 6, 7, 10 and 11.*

**Concrete mixes and cover requirements for Low Exposure. ( Any structures in the ground within 3m of the water table, up to 3m above the ground level in hot climates. )**

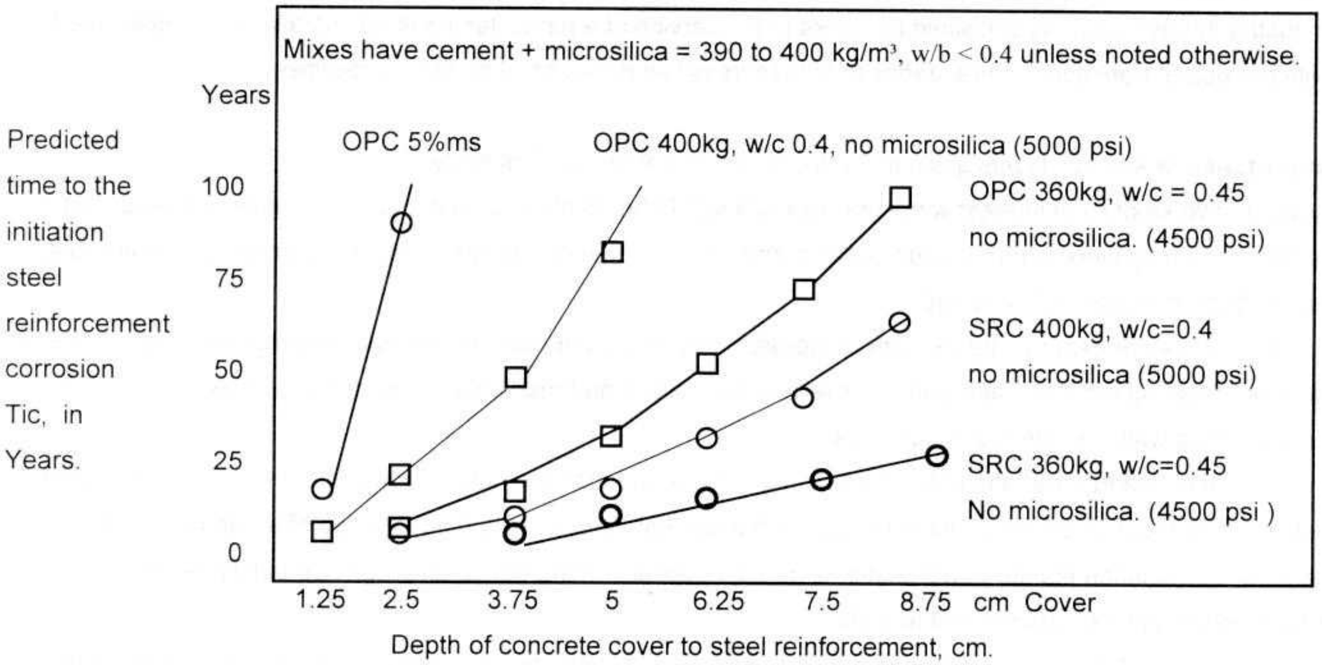


*Figure 7. Predicted time to the initiation of corrosion of steel reinforcement, at various covers in concrete under low chloride exposure in hot climates, using equatios 6, 7, 10 and 11.*

## Design life considerations.

What is a reasonable design life and time for corrosion initiation?

That depends on the clients intended use of the structure and the consequences of early deterioration in terms of loss of life, environmental damage and the cost of replacing the structure. Once corrosion starts, it is difficult and sometimes impossible to stop. The corrosion will only accelerate once spalling and cracking occur, leading to the eventual failure of the structure. The proposed design guidelines given in figures 5, 6 & 7 use the time to the initiation of rebar corrosion to give a conservative design life. The actual structural failure will take many more years to occur.

The design life of a structure could be defined as the utilisation period specified by the owner or consultant, with respect to structural safety, servicability and durability. That is the period for which the structure is to be used for its intended purpose with anticipated minimum maintenance but without major repair being necessary. Recommendations, for appropriate design lives of structures, can be made by subdividing the structures according to their use and importance as shown in Table 13.

Table 13. Design Life Recommendations for structures in years [ 26 ].

| Use Importance | Level 1 | Level 2 | Level 3 |
|---|---|---|---|
| General Infrastructure [ 26 ] | 25 | 50 | 100 |
| Buildings | 20 | 40 | 75 |
| Industrial Infrastructure [ 26 ] | 15 | 25 | 50 |

**Usage** can be categorised as follows;
General Infrastructure is classified as general works used by the general public, including public buildings.
Buildings are all structures intended for residential and commercial use.
Industrial Infrastructure is classified as works in the service of a particular industrial installation or associated with the use of transitory natural deposits of resources like mines or oil extraction facilities.

**Importance** or security levels given in Table 17 can be categorised as follows;
Level 1. Works of local interest with small risk of loss of human life or environmental damage in the case of failure. Including work in minor ports, small craft harbours, pavements, small towns, commercial installations and suburban residential buildings.
Level 2. Works of general interest with moderate risk of loss of human life or environmental damage in case of failure. Including work in major ports, out-falls of large cities and medium rise buildings in cities, road bridges and retaining walls on interstate highways.
Level 3. Works and installations for protection against inundation's or international interest, with an elevated risk of human loss or environmental damage in the case of failure. Including defense of urban or industrial centers, desalination plants, power stations, dams, hospitals, monumental and high rise buildings and international highway bridges and tunnels.
However, in the Gulf where good concrete materials are difficult to find it is virtually impossible to guarantee a structure for more than 50 years, as very few concrete structures are that old. We may conclude that the 50 to 100 year design lives of Level 3 structures will only be achieved by using pozzolanic materials in the foundations and parts of those structures that are subject to chloride exposure.

**Conclusion.**

While the above research is quite comprehensive, I must caution readers with regard to using figures 5, 6 & 7 for design purposes. Firstly, they are undoubtedly more reliable than existing codes of practice but the results of insitu testing of chloride profiles in existing structures after 25 to 75 years of extreme exposure is required to confirm the validity of the models proposed.
Secondly, there are areas in Eastern Province where high concentrations of both sulphates and chlorides exist simultaneously. Further research into the use of microsilica in concrete exposed to combined sulphate and chloride attack is required. We do know that the past widespread use of sulphate resisting cement, has proved inadequate in resisting chloride attack under combined exposure conditions, and the practice of specifying microsilica enriched OPC concrete is increasing in the Eastern Province of Saudi Arabia.

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