structure. If desired, this approach can be adapted to a probabilistic or semi-probabilistic approach. However, more input data on the interrelation between deterioration processes and external influences will be required before such an approach is possible.

INITIATION

Reinforcement embedded in concrete is normally protected from initiation of corrosion by the high alkalinity of cured concrete. The alkalinity causes a passive oxide film to be formed on the steel surface.

In order for corrosion to be initiated the passive film must be destroyed. Four main causes of film breakdown are;

- Chloride penetration
- Carbonation
- Cracking
- Mechanical failure of cover

These are all discussed below in terms of how the addition of silica-based products will influence the corrosion protection as compared to conventional concrete (OPC).

CHLORIDE PENETRATION

Chloride penetration can be a problem in a number of environmental circumstances. On shore, chlorides stem from de-icing salts used to keep the roads clear in winter. This salt is applied directly to bridge decks (and road surfaces), and cars bring the mess into parking structures which, in this manner, are also infested. In coastal regions and in the sea, chlorides from the sea can infest concrete far above the sea-level.

Since CSF uses $Ca(OH)_2$ for hydration of the silica to CSH-gel, the addition of microsilica results in a minor reduction in the pH of the concrete as compared to the unmodified material. This reduction in pH is accompanied by a reduction of the chloride concentration needed for breaking the passive barrier. Adequate experimental information on the magnitude of this change is not available, however the effect is considered to be small.

This small effect is more than compensated for by the enormous reduction in chloride diffusivity which results from silica-addition (Bickley(2), Marusin(3) and Gautefall(4). The reduction is caused by the change in pore-structure. This change is due to the mechanism by which silica interacts with concrete. As shown in figure 3, the reduction in chloride diffusion can be by a factor of 10 or more, which, converted to initiation time considerations, means that the initiation time is prolonged by the same factor.

CARBONATION

Carbonation is mainly a problem at relative humidities less than full saturation, (though liquid water must be present in the pore in order for the carbonation reaction to take place). In considering CSF-content versus carbonation two opposing effects are must be taken into account, namely the decreased permeability of the concrete versus the reduced buffer capacity available (micro-silica uses excess $Ca(OH)_2$ in hydration).

Permeability -- $CaCO_3$, the end product of carbonation, will be deposited in the pores of the concrete, thus reducing permeability. Furthermore, the differences in pore structure between the two types of concrete could make the time-dependency of the carbonation rate different. Whereas carbonation depth in ordinary concrete appears to closely approximate a root-of-time dependency, which would be expected if no major change in diffusion rate occurs (i.e. large pores with little effect from volume-increase), denser microstructure and changed pore-structure in CSF-concrete mean:

> Reduced initial diffusion rate, particularly at those relative humidities where capillaries (in none-silica concrete) would be empty.
>
> More effect of volume increase due to carbonation which means that the time dependency will no longer be root-time dependent.

Reserve alkalinity -- Silica uses $Ca(OH)_2$ in hydration. The reduction of alkalinity reserve can conceivably be significant if silica is used a cement replacement and strength is the only quality parameter.

If silica, on the other hand, is used as an additive, the total reserve alkalinity will, due to a relatively high initial cement content, be quite high and not seriously diminished by the addition of CSF to the mix.

Summary -- Considerations of carbonation rate will have to account for the complex interaction between reduced permeability on the one hand and reduced reserve alkalinity on the other. Where silica has been used as cement replacement, the carbonation rates may be increased compared to unmodified concretes. This is not likely to be the case where silica is part of a quality-improving additive.

Chemical -- The chemical resistance of concrete is much improved by the addition of CSF (e.g. Regourd (8) and Mehta (9). Compared to OPC concrete, the reductions in permeability and in content of easily dissolved $Ca(OH)_2$, makes for a chemically very resistant concrete.

At relatively high (15 % and more)[1] dosages of CSF, the resulting concrete exhibits sulphate resistance that is comparable to that made from Sulphate-resisting cements (SR) (Fiskaa (10), Mather (18).

Physical -- Physical degradation is here considered to be frost action. The testing procedures and their effects on the material response appear to cloud the real issue (e.g. Malhotra (11) vs. Yamato & al. (12), indeed the subject of frost testing is under close investigation several places. (e.g. Malhotra and Peterson (13). It is, however, recognized that air entrained CSF concretes (<15 % CSF) will also provide good frost resistance in CSF-concrete, as good as or better than ordinary concrete. (e.g. Malhotra (11) and Yamato (12)).

Mechanical resistance -- The mechanical resistance of concretes is significantly improved by the addition of CSF to the mix. Increased strength of the matrix along with superior bond to aggregate particles make for extremely wear-resistant concrete (Holland (14)).

Summary -- The effect of CSF is to improve the resistance of the cover to most external influences and to ensure that the cover provides enduring protection to the reinforcement.

PROPAGATION OF CORROSION

CATHODIC CONTROL

Cathodic control of the corrosion process in concrete will imply restrictions in the supply of oxygen to that part of the reinforcement which acts as cathode. The diffusion of oxygen has not been found to be much influenced by silica, at least not in water-saturated concretes (Vennesland (15), Fischer & al. (16)). In un-saturated concretes the influence should be more significant due to the differences in pore structure and the elimination of rapidly emptying large-diameter pores. See fig. 4 where the results from Vennesland have been plotted.

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[1] References to CSF content are as percent versus weight of cement.

All things considered, the main factor seems to be the water-cement ratio. Figure 2 shows the results from R.Johansen(5) as analyzed by the author. The three-year carbonation depth fits a linear regression versus actual water/cement ratio with correlation $R^2=0.88$. Thus, the two effects mentioned above appear to be more or less balance out.

CRACKING

Cracks in the concrete cover expose the reinforcement to the environment and give access to the media which may cause breakdown of the protective passive layer on the steel surface. The occurrence of cracks and their consequence depend on several properties of the material.

The occurrence of cracks depend on factors such as:

- The stress condition in the material,
- The ductility.
- Reinforcement detailing and
- The geometry of the structure

CSF-concretes often has higher strength than conventional concretes and consequently exhibits a more brittle behaviour (Helland & al. (6)). However, in conventional concrete construction it should not be any significant difference between the two concretes.

CSF-concretes are more sensitivity towards plastic shrinkage cracks than ordinary concretes, and improper curing during construction may therefore be of more consequence to CSF-concretes than to ordinary concretes.

As summed up by Schliessl(7): Crack width is of quite small consequence with respect to the initiation of corrosion, it is more of a binary situation; If a crack is present corrosion will take place. However, the rate of corrosion can be influenced by the width of the crack. Suffice it here to mention possible blocking of the crack by corrosion products and the I/R-drop down the crack.

COVER FAILURE

A sure way to reinforcement corrosion is to have the cover fail. Failure of the cover takes place as a result of deterioration of the concrete itself; by chemical, physical or mechanical means.

The reason for the small effect of CSF on the diffusion of oxygen in saturated, submerged concrete can be that CSF has negligible influence on the properties of the surface layer of concrete. The surface layer has shown to be the major barrier to oxygen diffusion in this type of exposure situation. (Fidjestøl & al (17)).

I-R CONTROL

Data show that the specific resistance of silica-concrete is several times that of a normal concrete. Fig.5 summarizes the findings of Vennesland. Here the typical and beneficial effect of silica-addition is shown.

At a water/cement ratio of .45, electrical resistance is increased by a factor from 6 (for 10 % silica-addition) to 16 (for 20 % addition). In those cases where the corrosion is under I-R-control, corrosion rates will be reduced correspondingly. The reasons for the reduction in conductivity can be:

- reduced number of large, continuous pores
- reduction in amount of charge-carrying ions
- overall denser concrete.

At higher w/c-ratios, the number of large pores will be increased, and thus the conductivity will be significantly higher, particularly for silica-concrete. This is so because the relative increase in the number of continuous pores is much higher for silica-concrete than for OPC-concretes.

TESTS, CORROSION RATES IN CARBONATED CONCRETES

In order to supplement and justify work on carbonation rates proceeding elsewhere, it has been found to be of vital importance to procure data on corrosion rates in carbonated concretes at different humidities. The tests will include plain concretes and concretes with varying amounts of silica-containing additives. This is the only way to decide if and when corrosion in carbonated concrete, and thus the carbonation itself, will need to be considered. When these tests are finished, it will be possible to determine when and if the actual carbonation rate should be considered.

Steps have been taken to initiate a program at Instituto Eduardo Torroja in Madrid. The linear polarization method will be used to determine corrosion rate of carbonated concrete at various humidities. The tests are meant to be sufficient to quantify the effect of CSF on corrosion rate.

Six series will be tested:

- OPC, 250 kg/m^3
- OPC, 400 kg/m^3
- OPC, 250 kg/m3 + 5 % CSF
- OPC, 250 kg/m^3 + 10 % CSF
- OPC, 250 kg/m^3 + 20 % CSF
- OPC, 400 kg/m^3 + 10 % CSF

In addition to these general series, a proprietary structural lightweight concrete ($_{char}$=25 MPa, =1.25 tons/m^3) will be tested in order to quantify the excellent properties of lightweight concretes observed elsewhere (Espelid & al, (19))

CONCLUSIONS

The availability of high-yield mineral additives based on refined condensed silica fume (CSF) has provided the opportunities for making concretes with strength and durability properties hitherto impossible to consider. However, the introduction of silica in the concrete mix change the chemistry of the hardened cement gel, an effect that has been considered a problem in some corrosion-respects.

It has been shown that the changes introduced in material structure and chemistry due to the introduction of microsilica will mostly be very beneficial, specifically this is the case for:

Chloride initiated corrosion,
Corrosion due to cover failure and
Corrosion in cracks.

In these cases the initiation period will be prolonged and/or the propagation rate is reduced. The question still remains as to the **precise** effects of CSF on carbonation **rate.**

The net effect of silica on initiation of corrosion can be summarized:

1.) Very significant decrease in chloride penetration
2.) Small effect on carbonation initiation
3.) Greatly increased durability and strength of the concrete cover.
4.) Little difference to formation and effect of cracks

The corrosion <u>rate</u> will generally be reduced. A test program is in execution, and the results will be presented as a supplement to this paper.

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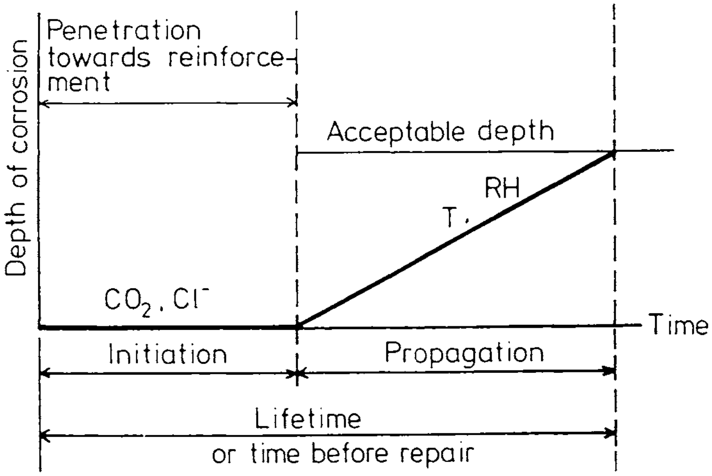

Fig. 1--Lifetime model (from Tuutti, Reference 1)

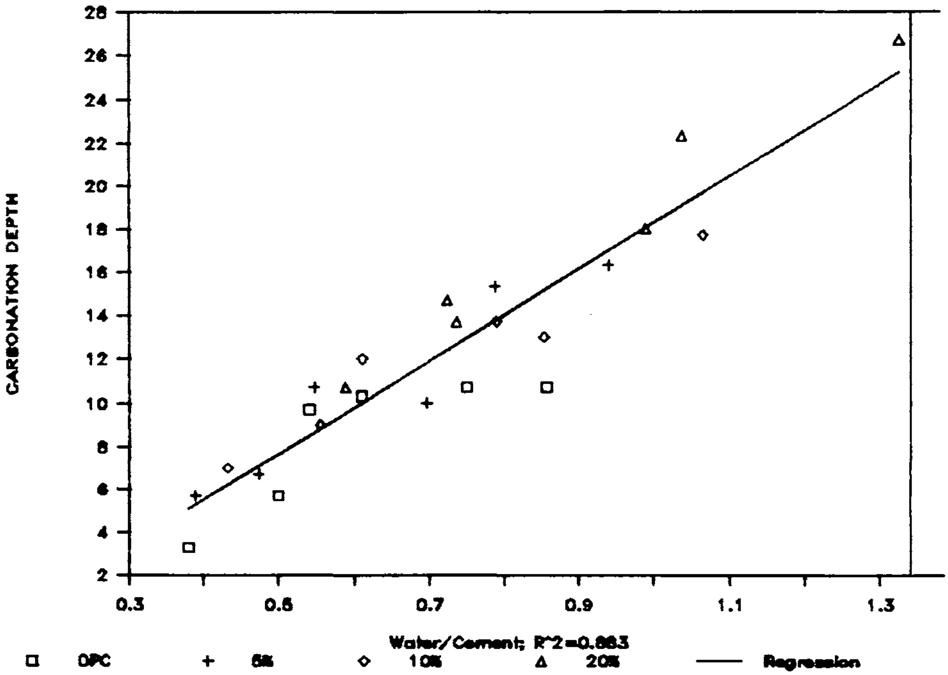

Fig. 2--Carbonation depth versus w/c ratio

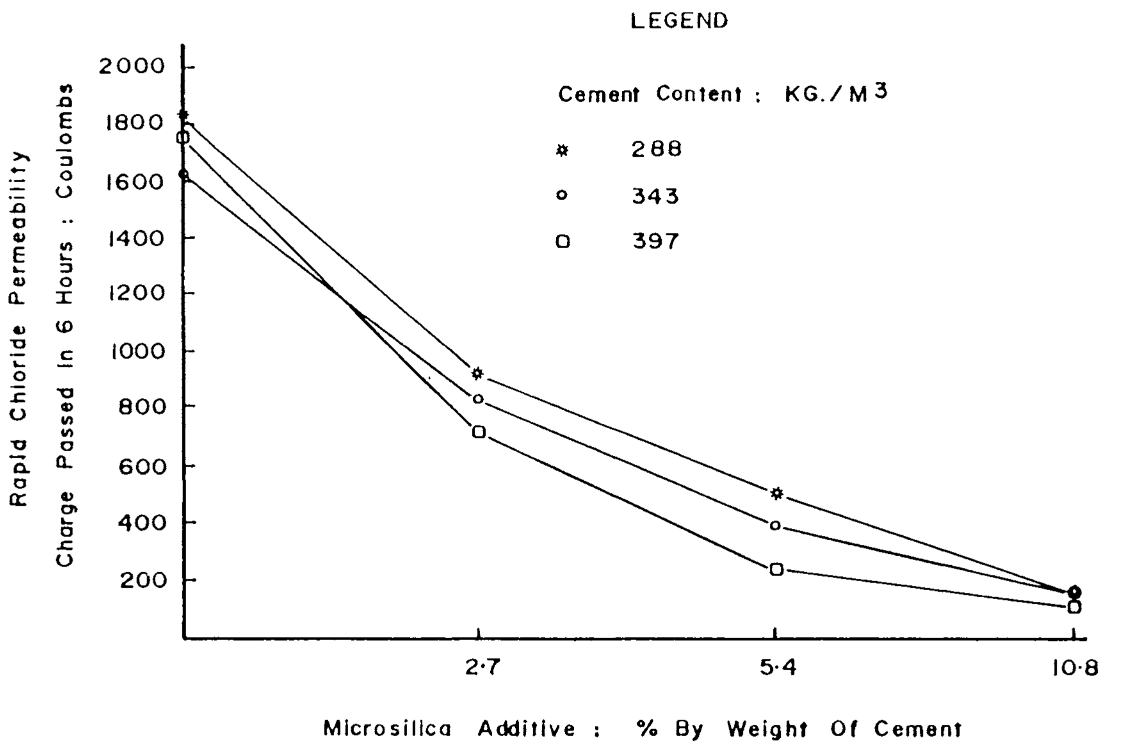

Fig. 3--Effect of silica on chloride diffusion rate
(from Bickley, Reference 2)