CHAPTER 6

SUMMARY AND CONCLUSIONS

Prediction of service life of concrete using OPC and blended cements in low and medium strength concretes was carried out under two exposure conditions such as macro cell corrosion test and salt spray test. Field exposure studies also carried out by exposing the specimens in natural sea water. The sulphate resistance of blended cements was evaluated both under laboratory as well as field conditions. The pore structure refinement of PPC and PSC concretes was done by determining the calcium hydrates content and the diameter of the pore. From the data collected, the service life of OPC and blended cement concretes was estimated using corrosion rate model. From the detailed investigation the following conclusions were drawn:

6.1 MACROCELL CORROSION STUDIES

1. The potential-time studies conducted over a period of 1376 days under macro cell corrosion condition indicates that the rebar embedded in OPC concrete is more active than that in PPC and PSC concretes.

2. The galvanic current measurement with time shows that the rebar in OPC concrete measures only anodic current whereas in PPC and PSC concretes it reverses both in anodic and cathodic side. The maximum anodic current measured in 20 MPa-OPC concrete is 130 $\mu$A whereas it is 46 and 29 $\mu$A
in PPC and PSC concretes. Similar trend is observed in 30 and 40 MPa concrete.

3. The rebars in 20 MPa-PPC and PSC concrete show 5 and 10 times more corrosion resistance than that of OPC concrete. It is 14 and 10 times higher in 30 MPa concrete and 7 times higher in 40 MPa concrete. The corrosion resistance of the rebar in the three cements is in the order PSC > PPC > OPC.

4. The apparent diffusion coefficient of chloride (D_a) of PPC and PSC concrete is 38% less than that of OPC concrete in 20 MPa concrete and 70% less than in 30 and 40 MPa concretes.

### 6.2 SALT SPRAY EXPOSURE STUDIES

1. In 0% Cl⁻ added concrete, time taken by the rebar to reach the threshold potential value of -270 mV is delayed by 2.3 to 7.7 times in PPC and PSC concretes compared to that of OPC concrete. In 0.5% and 1% Cl⁻ added concrete, though the rebar in PPC and PSC concrete showed an active potential initially but with time the potential value shifts to a less negative value.

2. Using EIS technique, the kinetics of corrosion process of the rebar such as passive state, initiation of corrosion and active state has been clearly distinguished by the well-defined Nyquist curve. When the rebar is in passive condition, the presence of CPE element deviates the slope of the low frequency arc >-1. The slope varies from -1 to -3.74. At this condition, the R_p value is >130 kΩ -cm². When corrosion
initiated on the rebar, the $R_p$ value is in the range of $<130 \text{ k\Omega-cm}^2 - 80 \text{ k\Omega-cm}^2$. When corrosion spreads uniformly throughout the rebar, the $R_p$ value is $<25 \text{ k\Omega-cm}^2$.

3. In 0% Cl$^-$ added concrete, the $R_p$ value of the rebar in 20 MPa –PPC and PSC concretes is 47 times higher than that of OPC concrete. It decreases to 16 times in 0.5% Cl$^-$ added concrete. In presence of 1% Cl$^-$, compared to OPC concrete, the $R_p$ value is only 10 and 3 times higher in PPC and PSC concrete respectively.

4. Based on the $R_p$ value, the time taken to initiation of corrosion is 3.4 and 7.7 times higher in PPC and PSC concrete compared to that of OPC concrete. It is 3 and 4 times in 30 MPa; 3.5 and 2.3 times in 40 MPa concrete.

5. The $C_{dl}$ is $<100 \mu F/cm^2$ indicates that there is no chloride on the rebar whereas if $>500 \mu F/cm^2$ then there is an adsorption of chlorides on the rebar. Compared to 0% Cl$^-$ added concrete, the $C_{dl}$ values are higher in 0.5% and 1% Cl$^-$ added concrete. The $C_{dl}$ values are much lower in PSC concrete than the other two concretes even in presence of 1% of chloride.

6. After 1765 days of exposure, in 20 MPa - 0% Cl$^-$ added concrete, the corrosion rate of rebar in PPC and PSC concrete is 0.0074 mmpy and 0.0027 mmpy which is 7 and 20 times higher than that of OPC concrete. It is 3 and 73 times higher in 30 MPa concrete. In 40 MPa concrete, the rebar in blended cement concretes behaves as similar to OPC concrete. The similar trend is observed in 0.5% of Cl$^-$ added concrete.
7. In 20 MPa-1% Cl⁻ added concrete, the rebar in PPC and PSC shows 3 and 73 times higher resistance whereas it is 12 and 50 times higher in 30 MPa concrete. In 40 MPa-OPC concrete the rate of corrosion is less as PPC and PSC concrete, the corrosion resistance of rebar in PPC and PSC reduces to 6 and 8 times. The order of corrosion resistance of the rebar at three chloride levels is PSC > PPC > OPC

8. D_{eff} determined using Warburg-Nyquist method agrees very well with the Deff determined using Fick’s second law. Compared to that of OPC concrete, the D_{eff} is less in PPC and PSC concretes. The time dependent characteristics of D_{eff} can be monitored non-destructively using EIS technique.

### 6.3 FIELD EXPOSURE STUDIES

1. After 852 days of exposure in the tidal zone of sea, the potential value of the rebar in OPC concrete is more negative by 86-126 mV than that of PPC and PSC concrete. Electrical resistivity of PPC and PSC concrete is higher compared to that of OPC concrete.

2. Under 40 mm cover, in 20MPa concrete, PPC and PSC shows 10 and 100 times more corrosion resistant than that of OPC concrete. Because of the reduced rate of chloride diffusion all the three cements showed negligible corrosion rate in 30 and 40 MPa concrete. At 40 mm cover, the effect of type of cement on reducing the corrosion rate could not be able to differentiate in field exposed specimens. The deterioration of cover concrete by sulphate ions is more in PSC but it does not accelerate the corrosion of rebar embedded at 40 mm cover.
6.4 SULPHATE ATTACK: LABORATORY STUDIES

1. At the end of 1080 days of exposure in 10% MgSO₄ solution, the percentage of strength deterioration factor is 0, 21 and 51% in 20 MPa; 7.5, 15.7 and 24% in 30 MPa; 9, 13 and 64% in 40 MPa- OPC, PPC and PSC concrete respectively. PSC concrete deteriorates more than the other two concretes. The order of resistance to sulphate attack of three cements is OPC>PPC>PSC.

2. PSC contains more amount of calcium aluminate rich glasses which are more susceptible to sulphate attack than silica aluminate rich glasses in PPC and OPC.

3. The dense pore structure of low w/c ratio concrete has limited pore space to accommodate the expansive products on the other hand concrete with high w/c ratio could accommodate them. Due to this, MgSO₄ attack is more deleterious on the physical properties of low w/c ratio of OPC and blended cements.

4. In blended cements in the absence of Ca(OH)₂ which is consumed by pozzolanic reaction magnesium and sulphate ions react directly with the C-S-H leading to the formation of M-S-H which is non-cementitious. Magnesium and calcium ions react well with each other due to their equal valence and similar radius.

5. DTA analysis showed that initially the ettringite forms along with the gypsum but finally the formation of gypsum is found to be the major expansive product in both OPC and blended cements. The formation of gypsum ends when all Ca(OH)₂
gets reacted with MgSO₄ and thereafter the deterioration is mainly due to the conversion of C-S-H to M-S-H.

6.5 FIELD EXPOSURE STUDIES

1. As observed in laboratory studies, the sea water exposure test also confirms that the PSC concrete deteriorated more than the PPC and OPC concretes. Sulphate attack is mainly manifested by the formation of gypsum and decomposition of C-S-H gel by magnesium ions. Presence of chloride ions does not delay the process of deterioration.

2. The higher replacement of slag in slag cement reduces the availability of Ca(OH)₂, thereby the C-S-H gel gets attacked by magnesium ions very earlier than by other two cements and deteriorated more.

6.6 PORE STRUCTURE CHARACTERIZATION OF BLENDED CEMENT CONCRETES

1. With an increase of hydration time, the Ca(OH)₂ content increases in OPC concrete whereas in PPC and PSC concrete it gets decreased. At the end of 365 days, in PPC it is 1/10th of that of OPC concrete in 20 and 30 MPa concrete and it is 1/3rd in 40 MPa concrete. The reduction is more in 20 MPa-PSC concrete, which is 1/40th that of obtained in OPC concrete. It is 1/11th and 1/7th in 30 and 40 MPa concretes.

2. The formation of additional calcium hydrates in PPC concrete is 20% higher than that of OPC concrete and in PSC it is 48% higher. The increase in hydrates content with an increase in
hydration time is significant up to 90 days and thereafter it is insignificant.

3. The diameter of the interconnected capillary pores determined using impedance technique falls in the range between 1.062-0.198 µm. 20 MPa –PPC concrete has the pore size of 0.153 µm whereas in OPC it is 0.198 µm. Similarly in 30 MPa concrete it is 0.131 and 0.199 µm in PPC and OPC concrete respectively.

### 6.7 PREDICTION OF SERVICE LIFE DUE TO CHLORIDE ATTACK

1. Time taken to initiation of corrosion (T_i) predicted using corrosion rate model under macro cell corrosion test shows that in 20 MPa concrete, it is delayed by 2 times in PPC concrete and 6 times in PSC concrete. T_i is 7 times higher in 30 and 40 MPa concrete. T_i predicted from T_{Deff} is less than the T_{i, ic}.

2. In 20 MPa concrete, Time to failure (T_f) of PPC and PSC concrete is 4.11 and 10.82 yrs, which is 1.7 and 4.4 times higher than that of OPC concrete. Similarly it is 2.8 and 2 times higher in 30 and 40 MPa concrete. T_f predicted using Maaddawy model from macro cell corrosion current overestimates compared to that of T_f predicted from weight-loss method.

3. Under salt spray test, T_f of 20 MPa – 0% Cl\(^{-}\) added concrete, PPC and PSC concrete is 4 and 5 times higher than that of OPC concrete and it is maximum of 12 times in 40 MPa
concrete. Compared to 0% Cl\textsuperscript{−} added concrete, the addition of chloride decreases the $T_f$. In 20 MPa-0.5 and 1% Cl\textsuperscript{−} added concrete, the $T_f$ of PPC and PSC concrete is 5 and 10 times higher than that of OPC concrete. It is 2-7 times higher in 30 and 40 MPa concrete. $T_f$ predicted by the model agrees very well with the $T_f$ from weigh-loss measurement and cracks on the concrete surface.

4. The enhancement of service life of concrete using PSC cement is higher than that of PPC. $T_f$ predicted using $i_{corr}$ from $R_p$ value is more accurate than from $i_{corr}$ from macro cell corrosion measurement.

5. Under marine atmospheric condition (salt spray test) the rebar embedded in 40 MPa PPC and PSC concrete is having the service life of more than 100 yrs but under splash zone condition (macro cell corrosion test) it reduces to 14 and 22 yrs. To enhance the service life of concrete exposed to splash zone condition to 100 yrs, it appears that additional protective measures such as coatings to rebar and on concrete surface, addition of inhibitor etc., could not be unavoidable.

6.8 **SERVICE LIFE DUE TO SULPHATE ATTACK**

1. Service life of PPC and PSC concrete is 2.5 to 3 yrs in 20 and 30 MPa concrete under laboratory condition whereas it is less than 2yrs when exposed to sea. The service life of 40 MPa concrete is 0.75 yrs under laboratory condition and less than 2.5 yrs in field condition. Magnesium oriented type of attack is more operative in blended cements leads to reduction of
service life. But the service life of OPC is more than 2.5 yrs. Under field condition PPC behaves as similar to OPC.

2. The Al₂O₃ content of PPC and PSC increases the corrosion resistance of rebar on the other hand the same is more vulnerable to attack by sulphates. Hence it should be standardized before blending with clinker so as to have both chloride and sulphate resistance.

6.9 CONTRIBUTIONS

1. A non-destructive method of approach for predicting the service life of concrete structures has been proposed based on corrosion rate model. The increase in service life of blended cement concrete in presence of chloride (1%) has been quantitatively estimated.

2. After conducting the long term test under marine atmospheric condition, release of bound chloride does not occur even in presence of 1% of chloride in blended cement concrete has been proved.

3. Determining the time-dependent characteristics of D_{eff} in actual field structures using EIS technique non-destructively has been proposed and it’s reliability is established.

4. A non-destructive in situ method for predicting the average diameter of the interconnected pore in actual field structures has been proposed.
6.10 SCOPE FOR FURTHER RESEARCH

1. Studies on strength and durability characteristics of ternary blended cements containing clinker, fly ash and slag.


3. Design and evaluation of carbonation resistant fly ash, slag incorporated concrete and its evaluation using SCM (supplementary cementitious material) efficiency factor

4. Micro structural studies on ternary blended cements using Mercury Ion Porosimetry (MIP) and SEM (Scanning electron microscope)

5. Studies on strength and durability characteristics of micro silica pellatised cement containing silica fume and clinker.