CHAPTER 4

RESULTS AND DISCUSSION

4.1 GENERAL

Experiment were conducted to evaluate the different durability properties of different types and grades of concretes made with and with out mineral and chemical admixtures. The durability tests conducted were of Rapid Chloride ion Penetration Test (RCPT), Chloride diffusion, Water Permeability, Resistivity and corrosion initiation time, etc. Each durability parameter was co-related with another parameter and for all the properties were inter linked for estimating the service life of Reinforced Cement Concrete (RCC) structures induced particularly with chloride ions. The study focused to estimate the service life of RCC structures for a given durability property.

4.2 DIFFUSION TEST VALUES

4.2.1 Chloride Profile

The chloride concentration determined using volumetric analysis is plotted against time as shown in Figure 4.1. A typical chloride profile for the specimens of Mix-1(M25) concrete with the applied voltage of 12V is represented in Figure 4.1. For a constant supply of voltage, the chloride concentration of the anode Sodium Hydroxide (NaOH-0.25N) solution
increases gradually with time. After few hours, the chloride concentrations were observed to increase linearly from 0 mmol / cm\(^3\) to 10 mmol / cm\(^3\).

![Graph showing chloride concentration over duration](image)

**Figure 4.1 Typical Chloride Profile of M25 Concrete**

The linear chloride penetration is considered as the steady state chloride profile. In the steady state condition, it is observed that the specimen obtained from a concrete cylinder at top portion has got higher chloride concentration when compared to the middle and bottom portions of the same cylinder.

The bottom portion specimen of the cylinder has got lesser chloride concentration due to proper material distribution and impermeability and moreover higher compaction of the bottom specimen lead to dense micro structure with lesser pores than middle or top specimens.

The chloride concentration for M40 grade concrete is shown in Figure 4.2. The migration rate of chloride ion is less in higher grade concrete.
As the grade of concrete increases, the chloride penetration rate is reduced due to reduction of void in the concrete.

![Figure 4.2 Chloride Profile of M40 Grade Concrete](image)

### 4.2.2 Effect of Concrete Grades on Chloride Diffusion

Concrete of different grades have been made to determine the chloride diffusion ($D_c$) values and the test results indicate that the chloride diffusion value for the M25 grade concrete is $7.56 \times 10^{-12} \text{ m}^2/\text{s}$. The chloride diffusion value for the M35 grade concrete was found to be $5.9 \times 10^{-12} \text{ m}^2/\text{s}$. The $D_c$ values for the concrete of M40, M60 and M75 are found to be $3.05 \times 10^{-12} \text{ m}^2/\text{s}$, $2.71 \times 10^{-13} \text{ m}^2/\text{s}$ and $7.24 \times 10^{-14} \text{ m}^2/\text{s}$, respectively.

The chloride diffusion values obtained for the different grade of concrete are presented in Figure 4.3. The results indicate that the chloride
diffusion value is reduced as the grade of concrete is high, indicating the higher grade concrete has got better durability property.

![Graph showing chloride diffusion in different grades of concrete](image)

**Figure 4.3 Effect of Concrete Grades on Chloride Diffusion**

### 4.2.3 Effect of Fly ash on Chloride Diffusion in Different Grades of Concrete

The chloride diffusion value for the different grades of concrete with different replacement level of cement by fly ash were calculated and presented in Figure 4.4. From the figure, it can be seen that the chloride diffusion value for M25 with 18% fly ash is found to be $1.02 \times 10^{12}$ m$^2$/s which is less than the concrete with out fly ash. With the increased amount of fly ash in concrete as partial replacement of cement by 25% and 35%, the diffusivity values observed to be $7.76 \times 10^{14}$ m$^2$/s and $5.21 \times 10^{14}$ m$^2$/s, respectively. Further with the same content of fly ash in M35 grade concrete as partial replacement of cement by fly ash by 18%, 25% and 35%, the chloride diffusion values are found to be $1.26 \times 10^{13}$ m$^2$/s,
2.04 \times 10^{-14} \text{ m}^2/\text{s} \text{ and } 1.70 \times 10^{-14} \text{ m}^2/\text{s}, \text{ respectively. Concretes of M40, M60 and M75 grades also made with 30% fly ash as cement replacement and the chloride diffusion values are found to be } 1.70 \times 10^{-14} \text{ m}^2/\text{s}, 1.55 \times 10^{-14} \text{ m}^2/\text{s} \text{ and } 1.17 \times 10^{-14} \text{ m}^2/\text{s}, \text{ respectively.}

It has been observed that the addition of fly ash in concrete reduces the chloride diffusion value. Further, fly ash with higher grade concrete is shown remarkable reduction in chloride diffusion values and which shows that the fly ash replacement in concrete improves the durability property of concrete. The above value indicates that the diffusion value of concrete was reduced further with increasing amount of fly ash in concrete. The reduction in chloride ion diffusivity can certainly prolong the service life of the structure.

**Figure 4.4** Effect of Fly Ash on Chloride Diffusion in Different Grades of Concretes
4.2.4 Effect of Ground Granulated Blast Furnace Slag (GGBS) on Chloride Diffusion in Different Grades of Concretes

The chloride diffusion value for the concrete with Ground Granulated Blast Furnace Slag (GGBS) has been studied for determining the chloride diffusion value. Concretes of M40, M60 and M75 grades were made with 40 % GGBS as cement replacement and the chloride diffusion values were determined and found to be $1.23 \times 10^{-14}$ m$^2$/s, $2.88 \times 10^{-14}$ m$^2$/s and $3.46 \times 10^{-14}$ m$^2$/s, respectively.

It was noticed that the addition of GGBS in concrete shown drastic reduction of diffusion value. Further the addition of GGBS in higher grade concrete has shown further reduction of chloride diffusion value. The test results are presented in Figure 4.5.

![Figure 4.5](image)

**Figure 4.5** Effects of GGBS on Chloride Diffusion in Different Grades of Concrete
4.2.5 Effect of Corrosion Inhibitors (CI) on Chloride Diffusion in M40 Grade Concrete

Literatures review indicates that Corrosion Inhibitors (CI) in concrete enhances the durability properties of concrete and some of the corrosion inhibitors makes adverse effect on mechanical properties. In this study Corrosion Inhibitors of Calcium Nitrate \([\text{Ca(NO}_3\text{)}_2]\), Sodium Nitrite \([\text{NaNO}_2]\) and Monoethanolamine \([\text{MEA}]\) are selected and used in M40 grade concrete by 1%, 2%, 3% and 4% by mass of cement. Apart from the durability properties, its mechanical properties of these concretes such as compressive strength, split tensile and flexural strength were studied.

4.2.5.1 Compressive Strength

**Calcium Nitrate Inhibitor:** Compressive strength for the control and concrete with different dosage of calcium nitrate were tested at the ages of 3 days, 7 days and 28 days of curing. Figure 4.6 shows the compressive strength of specimens with Calcium Nitrate Inhibitor.

![Compressive Strength of Concrete with Calcium Nitrate Inhibitors and at Different Ages](image)

**Figure 4.6** Compressive strength of Concrete with Calcium Nitrate Inhibitors and at Different Ages
Compressive strength for the control concrete at 28 days was 50.17 MPa. Concrete with addition of calcium nitrate 1%, 2%, 3% and 4%, the compressive strength was found to be 52 MPa, 56 MPa, 58.5 MPa and 61.3 MPa, respectively. The addition of calcium nitrate in concrete did not show any remarkable change in mechanical properties. However, there is slight increase in strength when calcium nitrate was used in concrete.

**Sodium Nitrite Inhibitor:** Compressive strength for the control and concrete with different dosage of Sodium Nitrite were tested at the ages of 3 days, 7 days and 28 days of curing. Figure 4.7 shows the compressive strength of specimens at different curing period.

![Compressive Strength of Concrete with Sodium Nitrite Inhibitors and at Different Ages](image)

**Figure 4.7  Compressive Strength of Concrete with Sodium Nitrite Inhibitors and at Different Ages**

Compressive strength for the control concrete at 28 days was 50.17 MPa. Concrete compressive strength was observed to 48.3 MPa, 47.5 MPa, 46 MPa
and 45.1 MPa when Sodium Nitrite was added in to concrete at 1%, 2%, 3% and 4% dosages, respectively. The addition of Sodium Nitrite in concrete did not show any remarkable change in mechanical properties. However, there is slight decrease in strength when Sodium Nitrite was used in concrete.

**Monoethanolamine Inhibitor:** The concrete with 1% addition of Monoethanolamine showed marginal increase in compressive strength i.e. 50 MPa, however, by the increasing the inhibitor to 2%, 3% and 4%, the compressive strength has been increased to 49 MPa, 48.5 MPa and 48 MPa, respectively. Figure 4.8 shows Compressive Strength at different ages.

![Figure 4.8 Compressive strength of Concrete with Monoethanolamine at Different Ages](image-url)
### Flexural Strength

**Calcium Nitrate Inhibitors:** Flexural strength for the control and with different dosage of calcium nitrate concrete was tested at 28 days of curing. Flexural strength for the control concrete at the age of 28 days is 6.15 MPa. The concrete with 1% addition of calcium nitrate, there is slight reduction in flexural strength i.e. 6.2 MPa, however, by the increasing the inhibitor to 2%, 3% and 4% the flexural strength has been increased to 6.32 MPa, 6.45 MPa and 6.6 MPa, respectively. Figure 4.9 shows the flexural strength of specimens tested at the age of 28 days.

![Figure 4.9](image)

**Sodium Nitrite Inhibitor:** Flexural strength for the control and admixed with different dosage of Sodium Nitrite inhibitors concrete were tested at 28 days of curing. Flexural strength for the control concrete at 28 days is 6.15 MPa. For concrete with 1% addition of Sodium Nitrite, there
is marginal increase in the flexural strength i.e. 5.74 MPa, however, by increasing the inhibitor to 2%, 3% and 4%, the flexure strength has been found to be 5.67 MPa, 5.55 MPa and 5.4 MPa, respectively. Figure 4.10 shows the flexural strength of concrete at 28 days.

![Graph showing flexural strength of concrete with sodium nitrite inhibitors](image)

**Figure 4.10 Flexural Strength of Concrete with Sodium Nitrite at the Age of 28 days**

**Monoethanolamine Inhibitors:** For concrete with 1% addition of Monoethanolamine, there is slight increase in the flexural strength i.e. 6.26 MPa, however, by increasing the inhibitor to 2%, 3% and 4% the flexure strength has been found to be 6.72 MPa, 6.85 MPa and 6.9 MPa, respectively. Figure 4.11 shows the flexure strength of concrete at the age of 28 days.
Split Tensile Strength (MPa)

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<th>Component</th>
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<td>M.E.A-2%</td>
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<td>M.E.A-3%</td>
<td>4.55 MPa</td>
</tr>
<tr>
<td>M.E.A-4%</td>
<td>4.60 MPa</td>
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</table>

**Calcium Nitrate Inhibitor:** Split Tensile strength for the control and with different dosage of calcium nitrate concrete was tested at the age of 28 days of curing. Split tensile strength for the control concrete at 28 days is 3.86 MPa.

The concrete with 1% addition of calcium nitrate, there is slight increase in split tensile strength i.e. 4.10 MPa, however, by the increasing the inhibitor to 2%, 3% and 4% the split tensile strength has been increased to 4.4 MPa, 4.55 MPa and 4.6 MPa, respectively. Figure 4.12 shows the split tensile strength of specimens at different curing periods.
Sodium Nitrite Inhibitor: Split Tensile strength for the control and with different dosage of Sodium Nitrite inhibitors concrete were tested at 28-d of curing. Split tensile strength for the control concrete at the age of 28-d is 3.86 MPa.

The concrete with 1% addition of Sodium Nitrite, there is reduction in split tensile strength i.e. 3.9 MPa, and by the increasing the inhibitor to 2%, 3% and 4%, the split tensile strength has been found to be 4.1 MPa, 4.24 MPa and 4.3 MPa, respectively. Figure 4.13 gives split tensile strength of concrete at the age of 28-d.
Figure 4.13 Split Tensile Strength of Concrete with Sodium Nitrite at the Age of 28-d

Monoethanolamine Inhibitors: The concrete with 1% addition of Monoethanolamine showed there is slight increase in split tensile strength i.e. 4.1 MPa and by the increasing the inhibitor to 2%, 3% and 4%, the split tensile strength has been found to be 4.4 MPa, 4.6 MPa and 4.65 MPa, respectively. Figure 4.14 shows split tensile strength of concrete at the age of 28-d.
<table>
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<th>Split Tensile Strength (MPa)</th>
<th>Control</th>
<th>M.E.A-1%</th>
<th>M.E.A-2%</th>
<th>M.E.A-3%</th>
<th>M.E.A-4%</th>
</tr>
</thead>
</table>

Concretes with Monoethanolamine Inhibitor

Figure 4.14 Split Tensile Strength of Concrete with Monoethanolamine at the Age of 28-d

4.2.6 Effect of Corrosion Inhibitors on Chloride Diffusion

**Calcium Nitrate Inhibitors:** The Chloride diffusion value for control concrete at the age of 28-d was found to be $3.05 \times 10^{-12}$ m$^2$/s. By the addition of 1% Calcium Nitrate, the Chloride diffusion value found to be $5.65 \times 10^{-12}$ m$^2$/s. By increase content of Calcium Nitrate by 2%, 3% and 4%, the Chloride diffusion value was found to be $1.62 \times 10^{-12}$ m$^2$/s, $2.67 \times 10^{-12}$ m$^2$/s and $4.37 \times 10^{-12}$ m$^2$/s, respectively. The chloride diffusion value for the concrete with Calcium Nitrate inhibitors by adding 1 to 4% in concrete is presented in Figure 4.15. The improvement was not at far and more or less close to the control concrete. However, it was observed that the addition of Calcium Nitrate inhibitor in concrete improves the durability property.
Sodium Nitrite Inhibitors: The addition of 1 % Sodium Nitrite, the Chloride diffusion value is found to be $2.67 \times 10^{-12}$ m$^2$/s. By increasing the content of Sodium Nitrite by 2 %, 3 % and 4 %, the Chloride diffusion values was found to be $1.35 \times 10^{-12}$ m$^2$/s, $1.58 \times 10^{-13}$ m$^2$/s and $3.63 \times 10^{-13}$ m$^2$/s., respectively. The chloride diffusion values for the concrete with Sodium Nitrite inhibitors by adding 1 to 4 % in concrete are presented in Figure 4.16. It was observed that the addition of Sodium Nitrite inhibitor in concrete improves the durability property and performed better than that of concrete with Calcium nitrate inhibitor.

Monoethanolamine (MEA) Inhibitors: Addition of 1 % MEA, the Chloride diffusion value is found to be $1.38 \times 10^{-11}$ m$^2$/s. By increasing the content of MEA by 2 %, 3 % and 4 %, the Chloride diffusion values was
found to be $2.45 \times 10^{-12}$ m$^2$/s, $5.62 \times 10^{-12}$ m$^2$/s and $6.88 \times 10^{-12}$ m$^2$/s, respectively. The chloride diffusion values for the concrete with MEA inhibitors by adding 1 to 4 % in concrete are presented in Figure 4.17. It is observed that the addition of MEA inhibitor in concrete have not shown any improvement on the durability property and have shown less resistance towards durability while compared to control concrete.

![Figure 4.16 Effect of Sodium Nitrite Inhibitors in Concrete on Chloride Diffusion](image1)

![Figure 4.17 Effect of Monoethanolamine Inhibitors in Concrete on Chloride Diffusion](image2)
4.2.7 General Observations of Chloride Diffusion Values in Various Concrete Types

The chloride concentration profile was high for lower grade concrete and lower for the higher grade concrete. The chloride concentration profile was still lower for the concrete with mineral admixtures (fly ash and GGBS) and found the lowest for the M75 grade concrete with fly ash. The concrete with corrosion inhibitors performed similar to that of control concrete. Amongst all CI, the Sodium Nitrite added concretes performed better. Diffusion Co-efficient were calculated from the steady-state chloride flux. The Dc was observed to be 10 times less for M75 of OPC when compared to M40 of OPC. Further, the Dc was 20 times less for M75 with fly ash when compared to M40 of OPC. This result indicates that the addition of mineral admixtures influence the concrete durability characteristics.

4.3 RAPID CHLORIDE ION PENETRATION TEST VALUES

4.3.1 Effect of Concrete Grades on RCPT

Concrete of different grades have been made to determine the RCPT (Q) values and the test results indicate that the RCPT value for the M25 grade concrete was 3300 Coulomb. The RCPT value for the M35 grade concrete was found as 2900 Coulomb. The RCPT value for the concrete of M40, M60 and M75 were found to be 2600 Coulomb, 1500 Coulomb and 900 Coulomb, respectively. The RCPT values obtained for the different grade of concrete are presented in Figure 4.18.
Figure 4.18 Effect of Concrete Grades on RCPT

4.3.2 Effect of Fly Ash in Concretes of Different Grades on RCPT

The RCPT value for the concrete with different content of fly ash for different grade was calculated and is presented in Figure 4.19. From the figure, it can be seen that the RCPT value for M25 with 18% fly ash was found to be 2400 Coulomb which is less than the concrete with out fly ash. With the increased amount of fly ash in concrete as partial replacement of cement by 25% and 35%, the RCPT value was observed to be 1200 Coulomb and 750 Coulomb, respectively.

Further with the same content of fly ash in M35 grade concrete as partial replacement of cement by 18%, 25% and 35%, the RCPT value was found to be 1050 Coulomb, 900 Coulomb and 400 Coulomb, respectively. Concretes of M40, M60 and M75 grades also made with 30% fly ash as cement replacement and the RCPT value are found to be
235 Coulomb, 200 Coulomb, and 190 Coulomb, respectively. It has been observed that the addition of fly ash in concrete reduces the RCPT value. Further, fly ash with higher grade of concrete have shown remarkable reduction in RCPT values.

4.3.3 Effect of Ground Granulated Blast Furnace Slag (GGBS) in Concretes of Different Grades on RCPT

The RCPT values for the control concretes of grades M40, M60 and M75 are 2600 coulomb, 1500 coulomb and 900 coulomb, respectively. The RCPT value for the concrete with Ground granulated Blast Furnace Slag (GGBS) has been studied for determining the RCPT value. Concretes of M40, M60 and M75 grades were made with 40 % GGBS as cement replacement and the RCPT value was found to be 450 Coulomb, 230 Coulomb and 290 Coulomb, respectively. It was noticed that the addition of GGBS in concrete shown enormous reduction in RCPT values compared to their respective

![Figure 4.19 Effect of Fly Ash on RCPT in Different Grades of Concrete](image-url)
control concrete. The RCPT value was further reduced when the GGBS was used in higher grade concrete. The test results are presented in Figure 4.20.

![Figure 4.20 Effect of GGBS on RCPT in Different Grades of Concrete](image)

4.3.4 Effect of Corrosion Inhibitors (CI) in Concretes of Different Grades on RCPT

**Calcium Nitrate Inhibitor:** The RCPT values for M40 grade control concrete was found to be 2600 coulombs. By addition of 1 % calcium nitrate, the RCPT value was found to be 2590 coulombs. By increasing the content of calcium nitrate by 2 %, 3 % and 4 %, the RCPT value was found to be 2560 coulombs, 2540 coulombs and 2519 coulombs, respectively. Figure 4.21 shows the RCPT values for concretes with different content of calcium nitrate inhibitor. It has been observed that there was marginal improvement on durability properties by the addition of calcium nitrate. This improvement may due to reduction in pore size by the C-H-S gel formation.
Sodium Nitrite Inhibitor: The RCPT value for M40 grade control concrete at 28-d was found to be 2600 coulombs. By the addition of 1 % Sodium Nitrite, the RCPT value was found to be 2400 coulombs. By increasing the content of Sodium Nitrite by 2 %, 3 % and 4 %, the RCPT value was found to be 1910 coulombs, 1544 coulombs and 1374 coulombs, respectively. The test values obtained at 28-d curing are presented in Figure 4.22.

Monoethanolamine: The RCPT value for control concrete at the age of 28-d is found to be 2600 coulombs. By addition of 1 % Monoethanolamine, the RCPT value was found to be 2700 coulombs. By increasing the content of Monoethanolamine by 2 %, 3 % and 4 %, the RCPT value was found to be 2850 coulombs, 3050 coulombs and 3100 coulombs, respectively. The RCPT values determined for the concrete with different dosages of MEA is presented in Figure 4.23.
Figure 4.22 Effect of Sodium Nitrite on RCPT in Concrete

Figure 4.23 Effect of Monoethanolamine on RCPT in Concrete
4.3.5 General Observations of RCPT Values in Different Concrete Types

It has been observed that the RCPT value was high for lower grade concrete and lower for the higher grade concrete. The RCPT value was still lower for the concrete with mineral admixtures (fly ash and GGBS). The concrete with calcium nitrate and Sodium Nitrite inhibitors have shown less RCPT value. The increase dosage of inhibitors has further reduction in RCPT value. The use of Monoethanolamine in concrete has shown increased RCPT value.

4.4 CONCRETE RESISTIVITY TEST VALUES

4.4.1 Effect of Concrete Grades on Resistivity

Concrete of different grades have been prepared and tested to determine the concrete Resistivity (R) values. The test results indicate that the concrete resistivity value for the M25 grade concrete was 7 kΩ-cm. The resistivity value for the M35 grade concrete was found to be 8 kΩ-cm. The resistivity value for the concrete of M40, M60 and M75 are found to be 9, 13 and 19 kΩ-cm, respectively. The resistivity values obtained for the different grades of concrete are presented in Figure 4.24. The results indicate that the resistivity value is increased as the grade of concrete is high.

4.4.2 Effect of Fly Ash on Resistivity in Different Grades of Concretes

The resistivity values for the concrete with different content of fly ash for different grade was measured are presented in Figure 4.25. From the figure, it can be seen that the resistivity value for M25 with 18% fly ash was found to be 9.0 kΩ-cm which is higher than the concrete with out fly ash.
Figure 4.24 Effect of Concrete Grades on Resistivity

Figure 4.25 Effect of Fly Ash on Resistivity in Different grades of Concrete
With the increased amount of fly ash in concrete as partial replacement of cement by 25% and 35%, the resistivity value was observed to be 16 and 24 kΩ-cm, respectively. Further with the same content of fly ash in M35 grade concrete as partial replacement of cement by 18%, 25% and 35%, the resistivity value was found to be 17, 19 and 43 kΩ-cm, respectively. The resistivity value for concretes of M40, M60 and M75 grades also made with 30% fly ash as cement replacement and was found to be 75, 95 and 101 kΩ-cm, respectively.

It has been observed that the addition of fly ash in concrete increases the resistivity value. Further, fly ash with higher grade concrete has shown remarkable increases in resistivity values and which shows that the fly ash in concrete improves the durability property of concrete. The increases in concrete resistivity can certainly prolong the service life of the structure.

### 4.4.3 Effect of Ground Granulated Blast Furnace Slag (GGBS) on Resistivity in Different Grades of Concretes

The resistivity value for the concrete with Ground granulated Blast Furnace Slag (GGBS) has been studied for determining the resistivity value. The test results are presented in Figure 4.26.

Concretes of M40, M60 and M75 grades were made with 40% GGBS as cement replacement and the resistivity value was determined and found to be 36, 75 and 59 kΩ-cm, respectively. It was noticed that the addition of GGBS in concrete has shown increase in resistivity value.
4.4.4 Effect of Corrosion Inhibitors (CI) on Resistivity in Different Grades of Concretes

**Calcium Nitrate Inhibitor:** This test provides a useful comparative measures of the properties of Concrete resistivity by measuring the electrochemical means. Figure 4.27 shows the resistivity values for concretes with different content of inhibitor.
The resistivity values for control concrete of M40 grade at 28-d was found to be 8.40 kΩ-cm. By the addition of 1% calcium nitrate, the resistivity value was found to be 8.48 k-Ohm-cm. The increase of calcium nitrate by 2%, 3% and 4%, the resistivity value was found to be 8.63, 8.73 and 8.8 kΩ-cm, respectively. It has been observed that there was marginal improvement on durability by the addition of calcium nitrate. This improvement may due to reduction in pore size by the C-H-S gel formation.

**Sodium Nitrite Inhibitor:** It has been observed that the addition of Sodium Nitrite in concrete by 1%, 2%, 3% and 4%, the resistivity value was found to be 8.95, 10.54, 12.28 and 13.39 resistivity and for control concrete of M40 grade at 28-d was found to be 8.40 kΩ-cm. By addition of 1% Sodium Nitrite, the resistivity value was found to be 8.95 kΩ-cm. The test values are presented in Figure 4.28.

![Figure 4.28 Effect of Sodium Nitrite on Resistivity in Concrete](image-url)
By increasing the content of Sodium Nitrite by 2 %, 3 % and 4 %, the resistivity values found to be 11, 12 and 13 kΩ-cm, respectively. From the test results, it was observed that the addition of Sodium Nitrite in concrete improves the concrete resistivity value as compared to calcium nitrate.

**Monoethanolamine:** The resistivity value for control concrete of M40 grade at 28-d was found to be 8.40 kΩ-cm. For the addition of 1 % Monoethanolamine, the resistivity value was found to be 8.30 k-Ohm-cm. The increasing content of Monoethanolamine by 2 %, 3 % and 4 %, the resistivity value was found to be 8.06 kΩ-cm, 7.78 k-Ohm-cm and 7.68 kΩ-cm, respectively. Addition of Monoethanolamine in concrete, the resistivity values was found to be decreasing. The resistivity value determined for the concrete with different dosages of MEA are presented in Figure 4.29. It clearly indicates that by the addition of MEA in concretes, the Resistivity value found to be decreased as compared to control concrete.

![Figure 4.29 Effect of Monoethanolamine on Resistivity in Concrete](image-url)
4.4.5 General Observations of Resistivity Values in Different Concrete Types

The resistivity value was low for the lower grade concretes and high for the higher grade concretes. The concrete resistivity value was further increased when the mineral admixtures such as fly ash and GGBS were added in to the concrete. The concrete with calcium nitrate and Sodium Nitrite inhibitors improve the resistivity value as compared to control concrete. But, the use of Monoethanolamine in concrete reduces the concrete resistivity value. It has been observed that the resistivity value is indirectly proportional to Chloride diffusion values and RCPT values. While RCPT and chloride diffusion values are high, then the Resistivity value is low. Similarly, when the RCPT and chloride diffusion values are low, the Resistivity value is high.

4.5 WATER PERMEABILITY TEST VALUES

4.5.1 Effect of Concrete Grades on Water Permeability

Concrete of different grades have been tested to determine the water permeability (Wp) values. The water permeability values obtained for the different grade of concrete are presented in Figure 4.30.

![Figure 4.30 Effect of Concrete Grades on Water Permeability](image-url)
The water permeability for M25 grade concrete was found to be $8.66 \times 10^{-12}$ m$^2$/s. The results indicate that the water permeability value was reduced as the grade of concrete is high. The water permeability value for M35, M40, M60 and M75 was observed to be $7.8 \times 10^{-12}$ m$^2$/s, $7.2 \times 10^{-12}$ m$^2$/s, $5.0 \times 10^{-12}$ m$^2$/s and $3.8 \times 10^{-12}$ m$^2$/s. Further, it has been observed that the water permeability was low, the RCPT and Chloride diffusion values were also found to be low.

4.5.2 Effect of Fly Ash on Water Permeability in Different Grades of Concretes

The water permeability value for the concrete with different content of fly ash of different grades was calculated and is presented in Figure 4.31. From the figure, it can be seen that the water permeability value for M25 with 18% fly ash is found to be $6.71 \times 10^{-12}$ m$^2$/s which is less than the concrete with out fly ash. With the increased amount of fly ash in concrete as partial replacement of cement by 25% and 35%, the water permeability value was observed to be $4.27 \times 10^{-12}$ m$^2$/s and $3.66 \times 10^{-12}$ m$^2$/s, respectively. Further with the same content of fly ash in M35 grade concrete as partial replacement of cement by 18%, 25% and 35%, the water permeability value was found to be $4.2 \times 10^{-12}$ m$^2$/s, $3.8 \times 10^{-12}$ m$^2$/s and $2.71 \times 10^{-12}$ m$^2$/s, respectively. Concretes of M40, M60 and M75 grades also made with 30% fly ash as cement replacement and the water permeability value was found to be $2.48 \times 10^{-12}$ m$^2$/s, $2.40 \times 10^{-12}$ m$^2$/s and $2.38 \times 10^{-12}$ m$^2$/s, respectively. It has been observed that the addition of fly ash in concrete reduces the water permeability characteristics. The water permeability value reduces in concrete with the addition of fly ash. It shows that the fly ash admixing in concrete improves the durability property of concrete.
Figure 4.31 Effect of Fly Ash on Water Permeability in Different Grades of Concrete

4.5.3 Effect of Ground Granulated Blast Furnace Slag (GGBS) on Water Permeability in Different Grades of Concretes

The water permeability characteristics for the concrete with Ground Granulated Blast Furnace Slag (GGBS) have been studied. Concretes of M40, M60 and M75 grades were made with 40% GGBS as cement replacement and the water permeability value was determined and found to be $2.9 \times 10^{-12}$ m$^2$/s, $2.30 \times 10^{-12}$ m$^2$/s and $2.71 \times 10^{-12}$ m$^2$/s, respectively. It was observed that the addition of GGBS in concrete decrease the water permeability value. The test results are presented in Figure 4.32.
4.5.4 Effect of Corrosion Inhibitors on Water Permeability

**Calcium Nitrate Inhibitors:** The water permeability value for control concrete of M40 grade at the age 28-d was found to be $7.20 \times 10^{-12}$ m$^2$/s. The water permeability value was found to be $7.76 \times 10^{-12}$ m$^2$/s, $7.49 \times 10^{-12}$ m$^2$/s, $7.08 \times 10^{-12}$ m$^2$/s and $7.15 \times 10^{-12}$ m$^2$/s for the addition of calcium nitrate by 1%, 2%, 3% and 4%, respectively. The water permeability values for the concrete with calcium nitrate inhibitor are presented in Figure 4.33. It has been observed that there was no significant improvement on water permeability value by addition of calcium nitrate inhibitor in concrete.
Sodium Nitrite Inhibitor: By the addition of 1 % Sodium Nitrite in M40 grade concrete, the water permeability value at the age of 28-d was found to be $7.08 \times 10^{-12}$ m$^2$/s. By increasing the content of Sodium Nitrite by 2 %, 3 % and 4 %, the water permeability value was found to be $5.71 \times 10^{-12}$ m$^2$/s, $4.91 \times 10^{-12}$ m$^2$/s and $4.62 \times 10^{-12}$ m$^2$/s, respectively. The water permeability values for the concrete with Sodium Nitrite inhibitor by adding 1 to 4 % in concrete are presented in Figure 4.34. It has been observed that the admixing of Sodium Nitrite inhibitor in concrete improves the durability property and performed better than that of concrete with Calcium nitrate inhibitor.
Figure 4.34  Effect of Sodium Nitrite Inhibitor on Water Permeability in Concrete

**Monoethanolamine (MEA) Inhibitor:** The water permeability values for the concrete with MEA inhibitors by adding 1 to 4% in concrete are presented in Figure 4.35. It has been observed that the addition of MEA inhibitor in concrete did not improve the durability property.

Figure 4.35  Effect of Monoethanolamine Inhibitor on Water Permeability in Concrete
4.5.5 General Observations of Water Permeability Values in Different Types of Concrete

The water permeability value was high for the lower grade concretes and lower for the higher grade concretes. The water permeability value was reduced for the concrete with mineral admixtures (fly ash and GGBS). The concrete with calcium nitrate and Sodium Nitrite corrosion inhibitors performed slightly better than that of control concrete. The Monoethanolamine addition in concrete increases the water permeability value. It has been observed that the water permeability value was directly proportional to Chloride diffusion values and RCPT values.

4.6 ACCELERATED CORROSION TEST

4.6.1 Effect of Concrete Grades on Rebar Corrosion

Effect of concrete grades on re-bar corrosion behaviour has been studied. Figure 4.36 shows the current Vs time for the concrete with M25 and M35 grades concrete.

![Figure 4.36 Current intensity for Concrete of M25 and M35 (29.5 mm cover thickness) Under Accelerated Corrosion Test](image-url)
The corrosion initiation time was observed and found that the corrosion initiation time has been enhanced for M35 grade concrete ($T_i$ – Corrosion initiation period, $T_p$ – Corrosion propagation period).

Figure 4.37 shows the corrosion initiation time for the concretes of different grades with out mineral admixtures. The corrosion initiation was observed for the M25 grade concrete at 6 days and 7 days for the M35 grade concrete. The corrosion initiation period for M40, M60 and M75 was found at 8, 14 and 26 days, respectively. It has been seen clearly from the figure that as the grade of concrete increases, the corrosion initiation time is extended. Corrosion initiation time for M75 grade concrete was 26.20 days which was 4.60 times that of concrete of M25.

![Figure 4.37 Effects of Concrete Grades on Corrosion Initiation Time]

**Figure 4.37 Effects of Concrete Grades on Corrosion Initiation Time**
4.6.2 Effect of Fly Ash on Rebar Corrosion in Different Grades of Concrete

Effect of fly ash in different grades of concrete on corrosion behavior has been studied. The current intensity was monitored with respect to time. Typical figure 4.38 shows the current Vs time for the concrete of M25 and M40 grades with 18% addition fly ash.

![Figure 4.38](image)

**Figure 4.38** Current Intensity of Concrete of M25 and M35 with Fly Ash as CRM (29.5 mm cover thickness) Under Accelerated Corrosion Test

Figure 4.39 shows the corrosion initiation time for the concretes with fly ash of different grades of concretes. The corrosion initiation time for M25 grade concrete with 18% fly ash was observed at 8 days and at 22 days for the M25 grade concrete with 25% fly ash. The corrosion initiation time for M75 grade concrete was 160 days and which was 20 times that of concrete of M25 grade concrete with fly ash. The delay in corrosion initiation time with
fly ash addition in concrete may be due to its internal arrangement of pore structure and its concentration in mineralogical composition.

![Figure 4.39 Effect of Fly Ash on Corrosion Initiation Time in Different Grades of Concrete](image)

4.6.3 Effect of Ground Granulated Blast Furnace Slag (GGBS) on Rebar Corrosion in Different Grades of Concrete

The current intensity was monitored with respect to time. Figure 4.40 shows the current Vs time for the concrete of M40 and M60 grades concrete with 40 % GGBS cement replacement by mass. The current intensity was observed and found less in M60 that of M40.
Figure 4.40  Current Intensity of Concrete of M40 and M60 with 40% GGBS as CRM (29.5 mm cover thickness) Under Accelerated Corrosion Test

Figure 4.41 shows the corrosion initiation time for the different grades of concretes with 40% GGBS as CRM. The corrosion initiation time for the M40 grade concrete with GGBS is observed to be 59 days and 110 days for the M60 grade concrete with GGBS as CRM. The corrosion initiation time for M60 grade concrete with 40% GGBS as CRM is 4.2 times that of concrete of M40 grade concrete with GGBS.

4.6.4 Effect of Corrosion Inhibitors in Concrete on Rebar Corrosion

Experimental studies have been carried out on rebar corrosion in concrete with different dosage of inhibitors by mass of cement such as 1%, 2%, 3% and 4%. It has been observed that the corrosion initiation time has been more or less same, while using the calcium nitrate and Monoethanolamine inhibitor in concretes, but the improvements are observed in Sodium Nitrite addition.
Figure 4.41 Effect of Ground Granulated Blast Furnace Slag on Corrosion Initiation Time in Different Grades of Concrete

**Effect of Calcium Nitrate Inhibitor in Concrete on Corrosion Initiation Period:** Figure 4.42 shows corrosion initiation time of concrete with different dosage of calcium nitrate. It has been observed that all the concrete specimens with different dosage of calcium nitrate inhibitor was found to be almost similar corrosion initiation period to that of control concrete.

Figure 4.42 Effect of Calcium Nitrate on Corrosion Initiation Time in Concrete
Effect of Sodium Nitrite Inhibitor in Concrete on Corrosion Initiation Period: Effect of Sodium Nitrite in concrete on corrosion behavior has been studied. The current intensity was monitored with respect to time. Figure 4.43 show the corrosion initiation time of concretes with 1%, 2%, 3% and 4% addition of Sodium Nitrite inhibitor. The corrosion initiation time was found to be 6, 13, 14, and 14 days for concrete with 1%, 2%, 3% and 4% addition of Sodium Nitrite inhibitor. It has been observed that the corrosion initiation time was enhanced with Sodium Nitrite to that of control concrete.

![Figure 4.43 Effect of Sodium Nitrite on Corrosion Initiation Time in Concrete](image)

**Figure 4.43 Effect of Sodium Nitrite on Corrosion Initiation Time in Concrete**

Effect of Monoethanolamine in Concrete on Corrosion Initiation Period: Corrosion initiation time was measured for the concrete with different content of Monoethanolamine.

With the addition of 1% of Monoethanolamine the corrosion initiation time was found to be 6 days. The increasing content of Monoethanolamine in
concrete by 2%, 3%, and 4%, the corrosion initiation time was found to be 6.3 days, 7 days and 6.2 days, respectively. It has been observed that the corrosion initiation time was early by addition of Monoethanolamine to that of control concrete.

![Figure 4.44](image)

**Figure 4.44  Effect of Monoethanolamine on Corrosion Initiation Time in Concrete**

**4.6.5  Effect of Concrete Surface Coatings on Corrosion Initiation Period**

The Corrosion initiation time for the concrete specimen of M30 grade with coating has been studied. The study has been conducted with thee types of coating materials of epoxy type. Fig.4.45 shows the condition of un-coated specimen at the end of corrosion initiation period. Figure 4.46 shows the un-coated specimens continued till the coated specimen to crack under polarization study. Figure 4.47 shows the condition of coated specimens at the end of corrosion initiation period.
Figure 4.45 Condition of Un-Coated Specimens at the End of Corrosion Initiation Period

Figure 4.46 Condition of Un-Coated Specimens Continued Till the Coated Specimens to Reach the End of Corrosion Initiation Period

Figure 4.47 Condition of Coated Specimens at the End of Corrosion Initiation Period
Figures 4.48 shows current Vs time for specimens of coated and uncoated specimens. The corrosion initiation period for un-coated specimen was found to be 6 days. The specimens with coat (A), Coat (B) and coat (C) was found to be 40 days, 80 days and 70 days, respectively. Coat (A) and Coat (B) are epoxy types, but the consumption of coat (B) was two times that of coat (A). Due to this, the specimen coat with (B) type materials performed better. The (C) type materials were zinc based and performed best among other coating materials. Figure 4.49 shows the corrosion initiation period for the coated and uncoated specimens.

![Figure 4.48 Current Vs Time for Coated and Un-coated Specimens](image)

**Figure 4.48  Current Vs Time for Coated and Un-coated Specimens**

In general, it was observed that the corrosion initiation period has been enhanced for the concrete specimens by the application of surface coating materials. The efficiency factor of coating with respect to delay the corrosion initiation time was found to 4 times, 8 times and 7.6 times less for coat (A), coat (B), and coat (C), respectively to that of un-coated specimen.
As discussed in materials and Method chapter, Ordinary Portland cement, river sand, coarse aggregate, high strength deformed bars (TMT) of 8, 10, 16, 20 and 32 mm diameters were used. The specimens were cast with M25 concrete using cylinders of size 75 mm dia × 150 mm height, 100 mm dia × 200 mm height and 150 mm dia. × 300 mm height to achieve an equal concrete cover of 29.5, 40, 46, 59 and 70 mm all around and also at bottom and top of the cylinder. Figure 4.50 shows the effect of concrete cover thickness on corrosion initiation time. It has been observed that the corrosion initiation time has been enhanced for the specimens having increased cover thickness. While increasing the cover thickness, the conductivity of the concrete reduces and resistance towards the corrosion activity is increased and thereby the corrosion initiation time is increased for the increased cover thickness.
Figure 4.50  Effect of Concrete Cover Thickness on Corrosion Initiation Time [Mix-1C(25)]

Similar test has been carried out for concretes of different grades with various cover thickness. Figure 4.51 shows the effect of concrete grades and cover thickness on corrosion initiation time.

Figure 4.51  Effect of Concrete Cover Thickness on Corrosion Initiation Time in Different Grades
Corrosion initiation time has been increased by using higher grade and increased cover thickness.

4.6.7 Effect of Fly Ash, Cover Thickness and Grades of Concrete on Corrosion Initiation Time

Figure 4.52 shows typically the effect of concrete cover thickness on corrosion initiation time of M25 concrete with fly ash. It has been observed that the corrosion initiation time has been enhanced for the specimens having increased cover thickness.

Figure 4.52 Effect of Fly Ash and Concrete Cover Thickness on Corrosion Initiation Time [Mix-6F-18%(25)]

Different grades of concretes using fly ash also have been studied and with equal cover thickness of 29.5, 40, 46, 59 and 70 mm. Figure 4.53 shows the effect of fly ash, grades and cover thickness on corrosion initiation time.
Figure 4.53  Effect of Fly Ash on Corrosion Initiation Time in Different Grades of Concrete and Cover Thickness

4.6.8 Effect of Ground Granulated Blast Furnace Slag (GGBS), Cover Thickness and Grades of Concrete on Corrosion Initiation Time

Figure 4.54 shows the effect of concrete cover thickness on corrosion initiation time of M40 grade with Ground Granulated Blast Furnace Slag (GGBS).

Figure 4.54  Effect of GGBS and Concrete Cover Thickness on Corrosion Initiation Time [Mix-15GGBS-40\%(40)]
Concretes of M40, M60 and M75 with Ground Granulated Blast Furnace Slag (GGBS) have been cast using cylindrical moulds with reinforcement to obtain equal cover thickness 29.5, 40, 46, 59 and 70 mm all around and also at bottom and top of the cylinder.

Figure 4.55 shows the effect of GGBS and cover thickness on corrosion initiation time. This test results show the enhanced corrosion initiation period for higher cover thickness. The high performance Concretes have shown better resistance from corrosion and its performance is almost seven times better than the control concretes.

Figure 4.55 Effect of GGBS Corrosion Initiation Time in Different Grades of Concrete and Cover thickness
4.6.9 Effect of Corrosion Inhibitor, Cover Thickness and Grades of Concrete on Corrosion Initiation Time

Figure 4.56 shows the effect of concrete cover thickness on corrosion initiation time of concrete with 1\% of calcium nitrate inhibitor of M40 grade.

Figure 4.56 Effect of Corrosion Inhibitor and Concrete Cover Thickness on Corrosion Initiation Time [Mix-18CI(40)]

Figure 4.57 shows the effect of various Corrosion Inhibitors in Concrete with variation of cover thickness on corrosion initiation time.

Figure 4.57 Effect of Various Corrosion Inhibitors in M40 Grade Concrete and Cover Thickness on Corrosion Initiation Time
4.7 DEPTH OF CHLORIDE ION PENETRATION IN DIFFERENT GRADES OF CONCRETE AT MARINE ENVIRONMENT

Ten different types of concrete cylindrical specimens of size 100 mm dia. and 200 mm length having the RCPT values ranging from 195 Coulombs to 3500 coulombs were placed in Tidal zone to study the chloride ion penetration depth. About 300 specimens were placed and 30 specimens in each type. These specimens from each types were brought to the laboratory after 50, 100, 200, 340 and 460 days exposure in the actual marine environment and determined the depth of chloride ion penetration. The depth of chloride ion was determined for the specimens having the RCPT value of 3500, 2200, 1595, 1300, 929, 650, 451, 290, 250, 195 coulombs and is reported in Table 4.1 and Figure 4.58.

**Table 4.1 Depth of Chloride Ion Penetration in Concretes of Different Types Exposed to Marine Environment**

<table>
<thead>
<tr>
<th>Sl. No</th>
<th>Details of Mixes</th>
<th>RCPT</th>
<th>Chloride Penetration Depth (mm)</th>
<th>Period of Exposure (Days)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>50</td>
</tr>
<tr>
<td>1</td>
<td>Mix-1C(25)</td>
<td>3300</td>
<td>15.00</td>
<td>22.00</td>
</tr>
<tr>
<td>2</td>
<td>Mix-6F-18%(25)</td>
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<td>8.34</td>
<td>10.74</td>
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<tr>
<td>3</td>
<td>Mix-4C(60)</td>
<td>1500</td>
<td>6.70</td>
<td>8.00</td>
</tr>
<tr>
<td>4</td>
<td>Mix-7F-25%(25)</td>
<td>1200</td>
<td>6.00</td>
<td>7.00</td>
</tr>
<tr>
<td>5</td>
<td>Mix-10F-25%(35)</td>
<td>900</td>
<td>5.50</td>
<td>6.31</td>
</tr>
<tr>
<td>6</td>
<td>Mix-8F-35%(25)</td>
<td>750</td>
<td>5.00</td>
<td>5.80</td>
</tr>
<tr>
<td>7</td>
<td>Mix-15GGBS-40%(40)</td>
<td>450</td>
<td>4.90</td>
<td>5.51</td>
</tr>
<tr>
<td>8</td>
<td>Mix-16GGBS-40%(75)</td>
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<td>4.80</td>
<td>5.30</td>
</tr>
<tr>
<td>9</td>
<td>Mix-12F-30%(40)</td>
<td>235</td>
<td>4.70</td>
<td>5.10</td>
</tr>
<tr>
<td>10</td>
<td>Mix-14F-30%(75)</td>
<td>190</td>
<td>4.60</td>
<td>5.10</td>
</tr>
</tbody>
</table>
It has been observed that the rate of chloride ion was found very high in the case of concrete of high RCPT values and it was found low in the case of concrete with low RCPT values. Similarly, the depth of chloride ion penetration is found more in concrete with high RCPT values over the period of time and less in concrete with less RCPT values.

![Figure 4.58 Chloride Ion Penetration Depth of Concretes placed in Tidal Zones](image)

The chloride diffusion based on marine exposure is calculated and compared to accelerated test condition and presented in Figure 4.59.
Durability properties such as RCPT and diffusivity values were found to be decreased when the strength of concrete increases. From the Fick’s second law of diffusion, the corrosion initiation period extended when the diffusivity of concrete decreases. The polarization test results show that the corrosion initiation period is directly proportional to the concrete grade and cover thickness. The corrosion initiation time has been enhanced for the coated specimens. It was observed that the service life of concrete structures against rebar corrosion may be extended by using higher grade of concrete, larger cover thickness and concrete surface coating.

Table 4.2 Shows the durability properties of different grades of concrete with mineral admixtures such as Fly Ash, Ground Granulated Blast Furnace Slag (GGBS), Corrosion Inhibitors and Cover Thickness. It has been observed that the RCPT plays a vital role to control the durability parameter of these
concretes. It has been observed from the specimens placed in tidal zone, that the rate of chloride ion was found very high in the case of concrete of high RCPT values and it was found low in the case of concrete with low RCPT values.

In general, it was observed that when the RCPT value was high, the chloride diffusion and water permeability rates were also high. At the same time, the concrete resistivity and corrosion initiation period were less. Similarly, when the RCPT value was less, the rate of chloride diffusion and water permeability values were also less, and the concrete resistivity and corrosion initiation period were high. The chloride diffusion and water permeability values were directly proportional to RCPT value. The concrete resistivity and corrosion initiation time values were indirectly proportional to RCPT value.
Table 4.2 Durability Properties of Concretes of Various Grades with Fly Ash, Ground Granulated Blast Furnace Slag (GGBS) and Corrosion Inhibitors

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<tr>
<th>S.No</th>
<th>Mix Details</th>
<th>RCPT (Coulombs)</th>
<th>Chloride Diffusion, m²/s</th>
<th>Concrete Resistivity (k-Ohm-cm)</th>
<th>Water Permeability (m²/s)</th>
<th>Concrete Cover Thickness (mm)</th>
<th>Corrosion Initiation Time (Days)</th>
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