CHAPTER 4

DETAILS OF EXPERIMENTAL PROGRAMME

4.1 GENERAL

The detail of the experimental investigations carried out on test specimens to study the strength and durability properties of high-performance concrete (HPC) using fly ash, silica fume and rice husk ash are discussed below. In order to produce HPC using fly ash, silica fume and rice husk ash as an admixture for cement, it is essential that the fly ash, silica fume should satisfy the requirements of physical and chemical characteristics as given in IS 3812, ASTM C – 618 – 949 and ASTM C – 1240 – 93, respectively. Test specimens of cement mortar and different grades of concrete with combination of supplementary cementitious materials were cast to assess the properties such as flow value, pozzolanic activity index, compressive strength, flexural strength, water absorption, water permeability, drying shrinkage, chloride permeability and electrical resistivity.

4.2 FLOW TABLE TEST

Flow table test were used to select a suitable super plasticizer (SP) and determine the dosage of Sp to obtain a flow of 180mm. Two SPs, CONPLAST 430, RHEOBUILD 1100 were considered for the study. The cement mortar was prepared as per proportion (Table 4.1). It is placed in mould of flow table as 3 layers. Each layer was compacted well. After that the top surface of the mould was leveled, the flow table was given 25 drops. After
that the spread dimension was measured in 3 directions and average value was taken. The value of base diameter is equal to 100mm, which is constant. From this data the percentage of flow was calculated by using the following formula

\[
\text{Percentage of flow} = \frac{\text{Spread diameter} - \text{Base diameter}}{\text{Base diameter}} \times 100 \quad (4.1)
\]

### Table 4.1 Mix Proportions of Cement Mixer for Flow Table Test

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Cement</th>
<th>Fly ash</th>
<th>Silica Fume</th>
<th>Rice Husk ash</th>
<th>Sand</th>
<th>Water/Binder</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.00</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.5</td>
<td>0.30</td>
</tr>
<tr>
<td>2</td>
<td>1.00</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>2.0</td>
<td>0.35</td>
</tr>
<tr>
<td>3</td>
<td>0.925</td>
<td>-</td>
<td>0.075</td>
<td>-</td>
<td>1.5</td>
<td>0.30</td>
</tr>
<tr>
<td>4</td>
<td>0.875</td>
<td>-</td>
<td>0.125</td>
<td>-</td>
<td>1.5</td>
<td>0.30</td>
</tr>
<tr>
<td>5</td>
<td>0.925</td>
<td>-</td>
<td>0.075</td>
<td>-</td>
<td>1.5</td>
<td>0.30</td>
</tr>
<tr>
<td>6</td>
<td>0.875</td>
<td>-</td>
<td>0.125</td>
<td>-</td>
<td>1.5</td>
<td>0.30</td>
</tr>
<tr>
<td>7</td>
<td>0.750</td>
<td>0.25</td>
<td>-</td>
<td>-</td>
<td>1.5</td>
<td>0.30</td>
</tr>
<tr>
<td>8</td>
<td>0.700</td>
<td>0.25</td>
<td>0.050</td>
<td>-</td>
<td>1.5</td>
<td>0.30</td>
</tr>
<tr>
<td>9</td>
<td>0.675</td>
<td>0.25</td>
<td>0.075</td>
<td>-</td>
<td>1.5</td>
<td>0.30</td>
</tr>
<tr>
<td>10</td>
<td>0.500</td>
<td>0.50</td>
<td>-</td>
<td>-</td>
<td>1.5</td>
<td>0.30</td>
</tr>
<tr>
<td>11</td>
<td>0.500</td>
<td>0.50</td>
<td>-</td>
<td>-</td>
<td>2.0</td>
<td>0.35</td>
</tr>
<tr>
<td>12</td>
<td>0.450</td>
<td>0.50</td>
<td>0.050</td>
<td>-</td>
<td>1.5</td>
<td>0.30</td>
</tr>
<tr>
<td>13</td>
<td>0.450</td>
<td>0.50</td>
<td>0.050</td>
<td>-</td>
<td>2.0</td>
<td>0.35</td>
</tr>
<tr>
<td>14</td>
<td>0.800</td>
<td>0.20</td>
<td>-</td>
<td>-</td>
<td>3.0</td>
<td>0.40</td>
</tr>
<tr>
<td>15</td>
<td>0.800</td>
<td>0.20</td>
<td>-</td>
<td>-</td>
<td>3.0</td>
<td>0.40</td>
</tr>
<tr>
<td>16</td>
<td>0.950</td>
<td>-</td>
<td>-</td>
<td>0.05</td>
<td>1.5</td>
<td>0.30</td>
</tr>
<tr>
<td>17</td>
<td>0.950</td>
<td>-</td>
<td>-</td>
<td>0.05</td>
<td>1.5</td>
<td>0.30</td>
</tr>
<tr>
<td>18</td>
<td>0.990</td>
<td>-</td>
<td>-</td>
<td>0.01</td>
<td>1.5</td>
<td>0.30</td>
</tr>
</tbody>
</table>

### 4.3 POZZOLANIC ACTIVITY INDEX TEST (ASTM C 311 – 94A)

In this test the pozzolanic activity of fly ash, silica fume, rice husk ash with cement was tested. For this the mortar cubes were prepared with the mix proportions. The fresh mortar was placed in cube mould of size of
70.2mm. It was placed in three layers. Each layer was well vibrated. It was
demoulded and placed in a curing tank. Three identical cubes were tested at
the ages of 3 days, 7 days and 28 days. These specimens were tested using
compression testing machine of 10t capacity. The loading was continued till
the cube reaches its ultimate load. From the ultimate load the compressive
strength was calculated. The ultimate load divided by the cross sectional area
of the specimen is equal to the cube compressive strength. From the
compressive strength test results the pozzolanic activity index was calculated
using the following formula.

\[
Pozzolanic \text{ activity index} = \frac{(A/B) \times 100}{(4.2)}
\]

where,

\[
A = \text{Average compressive strength of test mixture cubes at}
\text{any age (MPa)}
\]

\[
B = \text{Average compressive strength of control mix cubes at the}
\text{same age (MPa)}
\]

**Table 4.2 Mix Proportions of Cement Mixer for Pozzolanic Index Test**

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Cement</th>
<th>Fly ash</th>
<th>Silica Fume</th>
<th>Rice Husk ash</th>
<th>Sand</th>
<th>Water/Binder</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.00</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.5</td>
<td>0.30</td>
</tr>
<tr>
<td>2</td>
<td>0.750</td>
<td>0.25</td>
<td>-</td>
<td>-</td>
<td>1.5</td>
<td>0.30</td>
</tr>
<tr>
<td>3</td>
<td>0.925</td>
<td>-</td>
<td>0.075</td>
<td>-</td>
<td>1.5</td>
<td>0.30</td>
</tr>
<tr>
<td>4</td>
<td>0.675</td>
<td>0.25</td>
<td>0.075</td>
<td>-</td>
<td>1.5</td>
<td>0.30</td>
</tr>
<tr>
<td>5</td>
<td>0.500</td>
<td>0.50</td>
<td>-</td>
<td>-</td>
<td>1.5</td>
<td>0.30</td>
</tr>
<tr>
<td>6</td>
<td>0.425</td>
<td>0.50</td>
<td>0.075</td>
<td>-</td>
<td>1.5</td>
<td>0.30</td>
</tr>
<tr>
<td>7</td>
<td>0.990</td>
<td>-</td>
<td>-</td>
<td>0.01</td>
<td>1.5</td>
<td>0.30</td>
</tr>
<tr>
<td>8</td>
<td>1.00</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>2.0</td>
<td>0.35</td>
</tr>
<tr>
<td>9</td>
<td>0.750</td>
<td>0.25</td>
<td>-</td>
<td>-</td>
<td>2.0</td>
<td>0.35</td>
</tr>
<tr>
<td>10</td>
<td>0.925</td>
<td>-</td>
<td>0.075</td>
<td>-</td>
<td>2.0</td>
<td>0.35</td>
</tr>
<tr>
<td>11</td>
<td>0.675</td>
<td>0.25</td>
<td>0.075</td>
<td>-</td>
<td>2.0</td>
<td>0.35</td>
</tr>
<tr>
<td>12</td>
<td>0.500</td>
<td>0.50</td>
<td>-</td>
<td>-</td>
<td>2.0</td>
<td>0.35</td>
</tr>
<tr>
<td>13</td>
<td>0.425</td>
<td>0.50</td>
<td>0.075</td>
<td>-</td>
<td>2.0</td>
<td>0.35</td>
</tr>
<tr>
<td>14</td>
<td>1.00</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>3.0</td>
<td>0.40</td>
</tr>
<tr>
<td>15</td>
<td>0.750</td>
<td>0.25</td>
<td>-</td>
<td>-</td>
<td>3.0</td>
<td>0.40</td>
</tr>
</tbody>
</table>
4.4 PREPARATION OF TEST SPECIMENS

The test specimens were cast in cast iron steel moulds. The inside of the mould was applied with oil to facilitate the easy removal of specimens. The raw material was weighed to an accuracy of two grams. The concrete mixtures with fly ash and Rice husk ash, the ingredients were placed in concrete pan mixer machine and mixed thoroughly in dry condition. Initially, 75% of the water was added to the dry mix and mixed thoroughly. After that the superplasticizer and silica fume was mixed with the remaining 25% of water and then added to the mix.

In all the above mixtures, the mixing was continued till a uniform colour was obtained. Fresh concrete was placed in the mould in three layers and each layer was vibrated. The details of the number of concrete specimens cast for the ten HPC mixtures are as follows.

- 100mm cube – 168 Nos.
- 100mm × 100mm × 500mm prism – 42 Nos.
- 25mm × 25mm × 250mm prism – 60 Nos.
- 100mm dia. × 200mm height cylindrical – 28 Nos.
- 150mm cube – 42 Nos.

After 24 hours the test specimens were demoulded and placed in a curing tank, till the age of test. The details of the specimen for the various tests are given in Table 4.3.
### Table 4.3 Type of Tests and Specimen Sizes

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Type of Test</th>
<th>Properties Studied</th>
<th>Specimen Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Concrete Strength related properties</td>
<td>Cube compression strength at 3, 7 and 28 days</td>
<td>100 mm size cube</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Flexural strength at 28 days</td>
<td>Prism of size 100 x 100 x 500mm</td>
</tr>
<tr>
<td>2.</td>
<td>Concrete durability related properties</td>
<td>Water permeability after 28 days</td>
<td>150 mm size cube</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Water absorption after 28 days</td>
<td>100 mm size cube</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Free drying shrinkage</td>
<td>25mm x 25mm x 250mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Chloride permeability after 28 days</td>
<td>Cylindrical specimen of size 100mm dia and 50mm height</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Electrical resistivity at 1, 3, 7, 14, 21, 28 and 56 days</td>
<td>70 mm size cube</td>
</tr>
</tbody>
</table>

#### 4.5 STRENGTH RELATED PROPERTIES

The specimens were subjected for the following tests.

1. Cube Compression Test
2. Flexural Strength Test

#### 4.5.1 Cube Compression Test

For cube compression testing of concrete, 100mm cubes were used. All the cubes were tested in saturated surface dried condition. For each mix combination, three cubes were tested at the ages of 3, 7, 28 and 56 days using maps.
compression testing machine of 100 tonne capacity. The tests were carried out at a uniform stress rate after the specimen was centered in the testing machine. The loading was continued till the specimen reaches its ultimate load. The ultimate load divided by the cross sectional area of the specimen is equal to the ultimate compressive strength.

4.5.2 Flexural Strength Test

Flexural strength test were carried out at the age of 28 days on the 100mm × 100mm × 500mm prism using a universal testing machine of 100t capacity with two point load. All the specimens were tested after removal from moist storage. Loading was applied continuously and without shock at a constant rate to the breaking point. From this load the modulus of rupture was calculated using the following formula. If the fracture initiates in the tension surface within the middle third of the span length,

\[ R_m = \frac{PL}{bd^2} \]  \hspace{1cm} (4.3)

where,

- \( R_m \) = Modulus of rupture (MPa)
- \( P \) = Maximum applied load indicated by the testing machine (N)
- \( L \) = Span length (mm)
- \( b \) = Average width of specimen at the fracture (mm)
- \( d \) = Average depth of specimen at the fracture (mm)

4.6 DURABILITY RELATED PROPERTIES

The specimens were tested for the following test for to check the durability of concrete specimens prepared from the different mixtures.
1. Water absorption test
2. Water permeability Test
3. Free drying shrinkage Test
4. Rapid Chloride permeability Test
5. Electrical Resistivity Test

4.6.1 Water Absorption (ASTM C 642-97)

Water absorption tests were carried out on 100mm cubes. This test was done after 28 days curing. The specimens were kept inside an oven for not less than 24 hours at a temperature of 100 to 110°C. After that, the specimens were removed from the oven, allowed to cool in dry air to a room temperature. The dry weight of the each specimen was taken (A). Then the specimens were immersed in to water. The weight of each specimen (B) was taken a time intervals of 30 minutes for the first 2.5 hours, after that every 1 hour up to 4 hour, then after, 24 hours, 48 hours and 72 hours are tabulated. Using this value the water absorption was calculated by using the following formula.

$$\text{Water Absorption (\%)} = \frac{(B-A)}{A} \times 100$$  \hspace{1cm} (4.4)

where,

A = Mass of oven-dried sample in air (g)
B = Mass of surface dry sample in air after immersion (g)
4.6.2 **Water Permeability**

Water permeability test was done after 28 days of curing. In this test, the 150mm cube was used. The test was carried out using German permeability apparatus. This apparatus was fixed on top surface of 150mm cubes. Water was filled in to the compression chamber and the pressure inside of the compression chamber was fixed at 4 bars. All air locks were removed. Due to water infiltration the pressure tended to reduce. A constant head was maintained by the inward movement of screw that accounts for the depleted volume of water. A micrometer attached to the screw gives the measure of infiltration. The readings of micrometer were noted at every two minutes up to 30 minutes. From this, value the permeability at different time intervals was calculated by using the following formula:

\[
\text{Water permeability (m/s)} = P_w = \left( \frac{a \pi L_p r^2}{\pi R_c^2 t h} \right)
\]  

(4.5)

where,

- \( r \) = Radius of movable shaft of micro meter (m)
- \( a \) = Distance moved by the shaft to maintain constant pressure (m)
- \( R_c \) = Radius of the compression chamber (m)
- \( t \) = Time during which the pressure is held on inside the compression chamber (s)
- \( L_p \) = Depth of penetration (m)
- \( h \) = Pressure head (m)

**4.6.3 Free Drying Shrinkage Test**

Free Drying shrinkage test is done as per ASTM C 596-89. Free drying shrinkage is defined as the decrease in concrete volume with time due
to moisture loss. A prism of size 25mm × 25mm × 285mm with an effective gauge length of 250mm were used as mould for casting. Four test specimens were made from a single batch of mortar. The specimens are removed from mould and cured for 48 hrs. At the age of 72 ± ½ hr, the specimen is removed from water, wiped with a damp cloth and immediately the length comparator reading is obtained for each specimen. Then the specimens are placed in air for 25 days. The length comparator reading was taken for each specimen after 7, 14, 21, 28, 56 days of air storage. The linear shrinkage of each specimen is calculated at each age by subtracting the initial comparator reading.

\[
\text{Length Change} = \left( \frac{(L_x - L_i)}{G} \right) \times 100
\]  

(4.6)

where,

\begin{align*}
L_x &= \text{Comparator reading of specimen at x age minus comparator reading of the specimen bar at x age}, \\
L_i &= \text{Initial comparator reading of specimen minus comparator reading of reference bar at that same time}, \\
G &= \text{Nominal gauge length 250mm}, \\
L &= \text{Change in length at x age, in %}
\end{align*}

4.6.4 Rapid Chloride Permeability Test (RCPT)

The Rapid Chloride penetration test is based on the principle that the process of transport of chloride through a concrete specimen is under a gradient and could be accelerated by the application of an electric field and total migration of chloride ions over certain duration of time is reflected in the corresponding cumulative current conducted over that duration. In this test, an electrical potential of 60 volts is applied across a 100mm diameter x 50mm thick concrete specimen, which is fitted between two transparent plastic cells
after the specimen is saturated with water. The end faces of the concrete disc are mounted with copper mesh electrodes and the cells are sealed with rubber gasket and suitable sealant to prevent any leakage. One of the cell is filled with 3% NaCl solution, while the other is filled with 0.3M NaOH solution. The copper mesh electrode is connected to 60V external DC power source and the current conducted is recorded at every 30 minutes interval. The total charge carried over a period of 6 hours is computed by using the formula given below

\[ Q = 900 (I_0 + 2I_1 + 2I_2 + \cdots + 2I_{n-1} + I_n) \]  

(4.7)

where,

- \( Q \) = Charge passed (Coulombs)
- \( I_0 \) = Current (amperes) immediately after voltage is applied
- \( I_t \) = Current (amperes) at \( t \) hours after voltage is applied

If the specimen diameter is other than 95mm, the value for total charge passed calculated must be adjusted. The adjustment was made by using the following formula,

\[ Q_s = Q_X \times \left( \frac{95}{X} \right)^2 \]  

(4.8)

where,

- \( Q_s \) = Charge passed (Coulombs) through a 95mm diameter specimen
- \( Q_X \) = Charge passed (Coulombs) through a \( X \)mm diameter specimen
- \( X \) = Diameter (mm) of the nonstandard
Table 4.4 RCPT Ratings (As per ASTM C 1202)

<table>
<thead>
<tr>
<th>Charge passed (Coulombs)</th>
<th>Chloride ion permeability</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 4,000</td>
<td>High</td>
</tr>
<tr>
<td>2,000 – 4,000</td>
<td>Moderate</td>
</tr>
<tr>
<td>1,000 – 2,000</td>
<td>Low</td>
</tr>
<tr>
<td>100 – 1,000</td>
<td>Very Low</td>
</tr>
<tr>
<td>&lt; 100</td>
<td>Negligible</td>
</tr>
</tbody>
</table>

4.6.5 Methods to find out Diffusion Co – Efficient
Non – Steady State Method

The non – steady state method involves applying a potential of 60 V across a specimen of 50mm thick for duration of 6 hours. It is similar to that of RCPT test but the theoretical formulations and calculations are based on the equations which are based on Tang Luping model (i.e. the non –
steady state can be done by using the same set up of RCPT). After finishing of Rapid Chloride Permeability Test (RCPT), the specimens were taken out from the cells. Then the disks were split into two splices along their longitudinal axis. A 0.1N silver nitrate solution was sprayed on the split surfaces of the cylinder disk specimens. Silver nitrate solution reacts with chloride wherever it has penetrated and the color change boundary becomes clearly discernible due to formation of silver chloride which is whitish in color, while in the area not penetrated by Cl\(^{-}\), it reacts with OH\(^{-}\) ions to form silver oxide which appears on the surface as a brownish deposit. The specimens were allowed to dry and the average penetration depth was measured by taking averages of depth penetrated surfaces.

From the Ficks law (Tong and Gjorv 2001), as per Tang Luping for Non-Steady-State condition, the diffusion coefficient is calculated by the following equation

\[
D = \frac{RT}{zFE} \frac{x_d - \alpha \sqrt{x_d}}{t} \tag{4.9}
\]

where, \(\alpha\) can be taken as laboratory constant

\[
\alpha = 2 \sqrt{\frac{RT}{zFE}} \operatorname{erf}^{-1} \left( 1 - \frac{2C_d}{C_0} \right) \tag{4.10}
\]

where,

\[
a = \frac{z \times FE}{RT} \tag{4.11}
\]

Therefore,

\[
\alpha = 2 \sqrt{\frac{1}{a}} \operatorname{erf}^{-1} \left( 1 - \frac{2C_a}{C_0} \right) \tag{4.12}
\]
where,

\[
\begin{align*}
    z &= \text{Valence of chloride ions} \\
    F &= \text{Faraday constant} \\
    E &= \text{Potential difference} \\
    R &= \text{Gas constant} \\
    T &= \text{Absolute temperature} \\
    L &= \text{Length} \\
    C &= \text{Concentration of chloride} \\
    C_d &= \text{Chloride concentration at which the color changes using a volumetric titration} \\
    C_0 &= \text{Initial chloride concentration in percentage} \\
    A_e &= \text{Area of exposure (specimen)} \\
    I &= \text{Current} \\
    n &= \text{No. of ions} \\
    t_n &= \text{Transport number}
\end{align*}
\]

**Steady state Method**

A concrete specimen exposed to chloride contamination for a long time, evidently acquire a 100% penetration and further ingress occurs at a constant rate. Steady state method must, therefore, be considered in order to determine chloride diffusivity.

The greatest difference between the steady state and non–steady state method is that in the former the chloride ions must pass through the specimen and the flow rate be measured until steady state flow is reached.

\[
\text{Flux} = \text{Diffusion + Migration + Convection} \quad (4.13)
\]
\[ J = D \frac{dc}{dx_1} + z_i F \frac{dE}{dx_1} + DC \frac{dE}{dx_1} + CV_e \]  

(4.14)

where,

\[ J = \text{Mass flux (g/m}^2\text{s)} \]
\[ D = \text{Diffusion Coefficient (m}^2\text{/s)} \]
\[ C = \text{Concentration (g/m}^3\text{)} \]
\[ x_1 = \text{Distance (m)} \]
\[ z_1 = \text{Electrical charge} \]
\[ F = \text{Faraday constant (J/V mol)} \]
\[ R = \text{Gas constant (J/mol.k)} \]
\[ T = \text{Absolute temperature (K)} \]
\[ E = \text{Electrical Potential (V)} \]
\[ V_e = \text{Velocity of solution (m}^2\text{/s)} \]

Assuming a stationary flow of ions and provided there is no convection of ions due to electrolyte movements, the equation allows the calculation of the diffusion coefficient, D. A direct application of this equation to concrete is difficult because the pore solution is poly electrolyte of high ionic strength.

However, if only an approximate or average value is enough, the introduction of some simplifying assumptions will allow the calculation of the ion diffusivity D,

The main simplifying assumptions needed are two:

- No convection is produced inside the concrete
- Diffusion is negligible compared with migration when the external electrical field is applied is higher than 10 V.
Thus in such cases, the Nerst – Planck equation can be condensed to:

\[ J = D_j C_j \frac{z F}{R T} \frac{\Delta E}{x_1} \]  

(4.15)

For Steady- State condition an effective value of ‘D’, ‘D_{eff}’ is obtained; this equation for Steady – State condition may be written as;

\[ D_{eff} = \frac{RTt_nL}{nF^2EA_xC} \]  

(4.16)

4.6.6 Electrical Resistivity

Electrodes can be of various types. Brass is the commonly used material, but steel is also used. They can be meshes or plates. Note that the amount of force used to hold the electrodes in place can influence the results obtained. The resistance normally decreases with the amount of force used, because the contact progressively eliminates air gaps between the electrode and concrete surfaces. This increases the effective solid area of contact, lowering resistance. The wires for the electrodes are soldered with the plate of size 50mm × 50mm square before casting. While casting of concrete specimens for resistivity test the electrode plates was placed 20mm from top and bottom of the cube. The current was applied through the specimens at the age of 5 hours, 1, 2, 3, 7, 14, 21, 28, 56 and 90 days. By using constant voltage source and multimeter, the voltage was measured and the resistivity was calculated. In the case of frequency generator source measurements, the voltage and current was measured with the different frequencies viz. 1, 100, 1000, 10000, 100000 Hz. Then the resistivity was calculated by using the formula.
\[ \rho = R \left( \frac{A_i}{L} \right) \text{ and } R_s = \frac{V}{I} \quad (4.17) \]

where,

- \( \rho \) = Resistivity (ohm.cm),
- \( V \) = DC Voltage (Volts),
- \( I \) = Current (Amperes),
- \( R_s \) = Resistance (ohm),
- \( L \) = Length (cm),
- \( A_i \) = Area of Electrochemical Impedance is normally measured using a small AC signal (cm\(^2\)).