

**ASSESSMENT OF DAMAGE DUE TO REINFORCEMENT
CORROSION USING OPTICAL FIBER SENSOR-BASED DATA**

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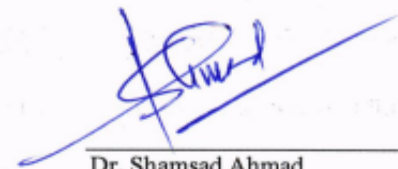
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To my late Father, Muhammad Subhan Roghani and My Mom

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LIST OF ABBREVIATIONS

FBG	:	Fiber Bragg Grating
FOS	:	Fiber Optic Sensor
H₂SO₄	:	Hydrogen Sulfate
LPR	:	Linear Polarization Resistance
SP	:	Surface Potential
OCP	:	Open Circuit Potential
SHM	:	Structural Health Monitoring
ECI	:	Embedded Corrosion Instrument
PRC	:	Parallel Resonant Circuit
UPV	:	Ultrasonic Pulse Velocity
UGW	:	Ultrasonic Guided Wave
GPR	:	Ground Penetrating Radar
RCC	:	Reinforced Cement Concrete

ABSTRACT

Full Name : Laiq Jamal Roghani

Thesis Title : **Assessment Of Damage Due To Reinforcement Corrosion Using Optical Fiber
Sensor-based Data**

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In reinforced concrete the effect of corrosion over the steel is one of the major issue for durability of concrete throughout the world. Where the service life of each types of buildings structures are hardly damage by reinforcement corrosion which results in (billions of dollars annually) in repair and maintenance. Therefore, evaluating the corrosion of steel rebar's embedded in reinforced concrete in terms of safety and maintenance is the main theme of this study. Although the reinforcing bars embedded in concrete initially possess passivity due to high alkalinity of concrete, however, the passivity is lost due to penetration of chloride ions, deicing salt or due to destruction of alkalinity by carbonation leads to the steel bars corrosion. Where the cross section or diameter of steel bars in reinforcement concrete losing dimension, loss of bond between steel rebar's with concrete, and inducing of rust layer on the surface of steel rebar's. The rust layer initiated on steel bars causes expansion and concrete cracking of cover due to swelling pressure (tensile stress) inside concrete, where the loss of bond and cross-section results into the loss or destruction of load sustaining and defraying capacity of the corroding structural members.

In the initiation of corrosion, time of cracking of cover concrete and rate of reinforcement corrosion are needed to be evaluated and determined in order to assess the corrosion damage and to predict or estimate the remaining services life of a reinforced concrete subjected to reinforcement corrosion. Conventionally, electrochemical and gravimetric tests are conducted to estimate corrosion rate that is essentially required for the assessment and diagnosing of damaging due to corrosion. However, the measured values of corrosion rate using such techniques having lack of accuracy due to many factors, which lead to inaccurate assessment of the corrosion damage and inaccurate prediction of remaining service life.

Therefore, there is a need for a reliable inspection technique that can be employed to collect the data required for estimating the reinforcement corrosion rate accurately. Here in this work the proposed work is related to use Fiber Bragg grating (FBG) sensors-based technique where (FBG) sensor will play an

important role to identify both cracking position and time. Where we can say in other words (i) to monitor the hoop strain due to increase in diameter of corroding steel bars embedded in concrete and (ii) to record the time of cracking of cover concrete due to corrosion. In propose work we reached to a point that install FBG sensors at close locations along the length of the corroding embedded steel bars to record hoop strain by the impact of increasing of bar diameter owing to the corrosion. In order to record the time of cracking, sensors will also be installed on the surface of concrete. The recorded hoop strain will be used to determine the increase in diameter with time due to rust formation. This information will be used to estimate the reinforcement corrosion rate, which will be compared with the reinforcement corrosion rate obtained for similar specimens tested using electrochemical and gravimetric methods. Finally, a methodology to the evaluation of corrosion damage and the life prediction of further surviving service will be developed according to the recorded values of corrosion cracking time and increase in the diameter due to rust formation. Using this technique based on FBG sensors is highly predictable for accuracy and determination of both parameters.

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الاسم الكامل: لايق جمال روغاني

عنوان الرسالة: تقييم الأضرار الناجمة عن التآكل المعزز باستخدام البيانات القائمة على مستشعر الألياف البصرية

مجال التخصص: الهندسة الكهربائية

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يعد تأثير التآكل على الفولاذ في الخرسانة المسلحة أحد المشاكل الرئيسية لمتانة الخرسانة في جميع أنحاء العالم. حيث أن العمر التشغيلي للأكل ينمو من أنواع هياكل المرافق، كما لا يتصور مستوى تآكل التعزيز الذي ينتج عنه

INTRODUCTION

1.1 Motivation

The existing world are most probably dependent on concrete structures where we have mega projects in residential and commercial setup, like high rise residential buildings, shopping malls, bridges, tunnels and dams to name a few. Therefore, to monitor the health of these structures is of paramount importance for ensuring the durability of such structures'. All of these civil structures deteriorate and age with the passage of time. Such deterioration having multiple reasons while mainly it's due to aging of the materials, extreme weather conditions, delayed maintenance and non-availability of appropriate inspection techniques. These issues contribute to the structural degradation shortening the service life. Sometimes a non-reversible and permanent structural damage or a catastrophe occur. Reinforcement corrosion is one of the most severe deterioration problems in concrete structures exposed to the aggressive conditions. The exposure conditions, which cause reinforcement corrosion include deicing salts, ocean spray, use of chloride contaminated aggregates, and carbonation. Most of the region having humidity where the high relative humidity and temperature with their wide fluctuations, such as those prevailing in the Arabian Gulf, corroborate the effects of the aggressive species responsible for initiating and propagating reinforcement corrosion. Depending on the quality of cover concrete and the exposure conditions, the initiation of reinforcement corrosion takes place sooner or later. However, once reinforcement corrosion is initiated after the passivity of the bar is lost, the first thing, which happens, is the deposition of rust products that expands the surrounding concrete causing the development of cracking and delamination of concrete. Besides cracking and delamination of concrete, the loss of bond between steel bars and concrete and the loss of diameter of the steel rebar also occur that cause a severe loss of the load-bearing capacity of the corroding structural member, reducing the service life. Therefore, the timely detection of the state and extent of reinforcement corrosion is of great importance.

If detected early, it may be possible to make remaining service life prediction and to apply palliative mitigations to arrest the damage at a relatively low-cost. Therefore, to ensure the safety of concrete structures against reinforcement corrosion, the structural members should be equipped with smart structural health monitoring (SHM) systems that would provide continuous monitoring and damage detection. A real time SHM system is found helpful for detecting various defects; e.g. cracking on the concrete surface, corrosion of the rebar inside the concrete and hoop strain, so that timely repair and maintenance of the structure can be carried out. A SHM system consists of a sensing system, a data acquisition system, a transmission system and finally a storage system. Different types of sensing systems are reported in the literature. That include, piezoelectric sensors, fiber reinforced structural composites and fiber optic sensors. These sensors have the ability to sense various physical and chemical properties related to health of the structures'. Fiber optic sensors are lightweight with small footprint and therefore do not affect the performance of the structural member on which it is mounted or embedded. The fiber optic cables are immune to electromagnetic interference and thus not affected by the nearby electric cables. A single fiber optic cable can effectively monitor the structural degradation at different locations by utilizing the distributed fiber Bragg grating (FBG) technology. Considering the advantages offered by the fiber optic based sensors for the sake of structural health monitoring, attempts have been made to develop an optical fiber sensor based technique for monitoring damage due to reinforcement corrosion.

In this proposed research, the distributed fiber Bragg grating sensors (FBGs) will be placed on the surface of bar's embedded inside concrete to measure the hoop strain due to increase in diameter of corroding steel bars. Further, the FBGs will also be placed around the surface of concrete to monitor the development of cracks on concrete surface. This will enable to record the time of cracking of cover concrete due to corrosion. The FBGs will be installed at close locations along the length of the embedded steel bars to record hoop strain due to the increase in the diameter of the bar due to corrosion. In order to record the time of cracking, sensors will be wrapped around the surface of concrete. The recorded hoop strain will be used to determine the increase in diameter with time due to rust formation. This information will be used to estimate the reinforcement corrosion rate, which will be compared with the reinforcement corrosion rate obtained for similar specimens tested using electrochemical and gravimetric methods. Finally, a methodology for assessment of corrosion damage and determination of remaining service life will be developed based on the recorded values of corrosion cracking time and increase in the diameter due to rust formation using fiber FBGs-based technique.

1.2 Thesis Objective

The main objective of the proposed research work is to develop a methodology for assessment of damage caused by reinforcement corrosion utilizing the data recorded using FBG sensors- based technique.

The unique objectives of the proposed research are as follows:

1. To generate reinforcement corrosion data through an experimental design considering the key factors such as concrete quality (different concrete mixtures using different supplementary cementations materials and different mixture proportions), chloride exposure conditions, cover thickness, different grades of steel and diameter of steel bar.
2. To propose a novel method for assessment of damage due to reinforcement corrosion.
3. To publish the research findings in top tier international journals.
4. To develop a purpose-built set-up for monitoring hoop strain of corroding steel bars and recording cracking time using FBG sensors.

1.3 Thesis Overview

The Overview of this study according to work done on optical detection techniques following chapter 1 for introduction. Where Chapter 2 having brief explanation of literature review by different ways of corrosion detections including FBG sensors detection theoretical and technical background to use in this research. Chapter 3 is a concept and practical implementation of research work to implement practical fundamental preparation in order to minimize the failure in actual experimental work. Chapter 4 contain the entire experimental work and showing design, circuit integration setup and results of optical sensor (BG) to adopt corrosion detection in reinforcement concrete. At the end chapter 5 presenting the conclusion and future work to proceed.

CHAPTER 2

Literature Review

Here we have to review the entire theoretical background of corrosion causes, appearance and basic principles in reinforcement concrete. As well as we have to discuss all associated theory related to FBG sensor used for corrosion detection over a steel bar in reinforced concrete with the help of mechanism in concrete setup and basic principle of fiber optic sensor.

2.1 Corrosion

Corrosion is a gradual process of destruction in metals objects which is caused by most probably environmental effect leading to chemical reactions on metal surface, which is accurately known by electrochemical oxidation with oxygen as oxidant. Iron oxide formation can be considered as a best example of this phenomenon to identify rusting. At the same time, we have to know that corrosion can take place on non-metallic surfaces or material like polymers or ceramics. To explain corrosion theory, we will consider four fundamental components.

2.1.1 Anode

2.1.2 Cathode

2.1.3 Connectivity in-between anode and cathode for the flow of electrons

2.1.4 Electrolyte for ionic moment.

The typical electrochemical process having battery characteristics, exposed atoms of metal to an environment having water or containing water will produce electron. As a metallic bar or iron element (Fe) having an atomic number 26 in periodic table surface are normally coated with a thin film of oxide layer as shown in Fig: 2.1a. Because of some environmental effects, this thin film oxide layer will get disturbed to develop anode and cathode on steel bar as shown in Fig: 2.1b. Here the electron released from iron molecule forming iron ion as shown in Fig: 2.1c. After breaking of this layer, the released electron ($2e^-$) will move from anode to cathode due to environmental effect where Oxygen O_2 and H_2O already exist as shown in Fig: 2.1d which developed $(2OH^-)$. Now the electron reacts with the dissolved oxygen of atmosphere to form hydroxyl ion. This reaction will form a corrosion in the form of $Fe(OH)_2$ as shown in Fig: 2.1f. This confined corrosion losing the bond between steel rebar and concrete degrading and deteriorating the structure.

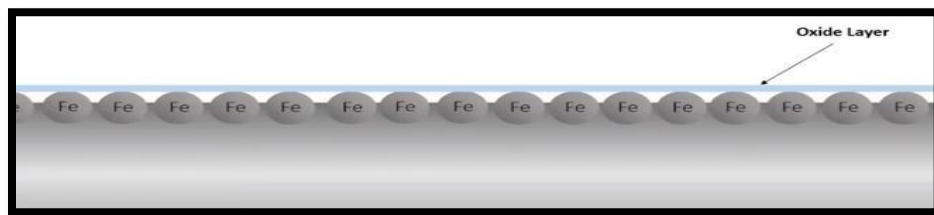


Figure 2. 1: Iron oxide film over the surface of steel inside in concrete.

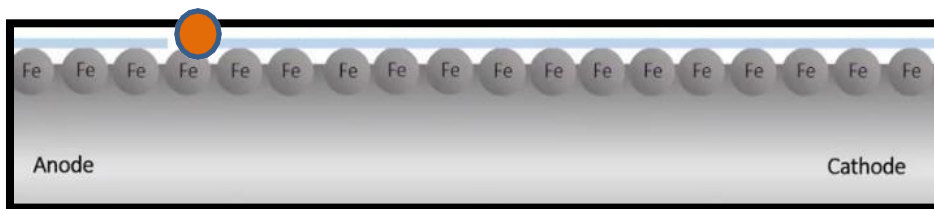


Figure 2.1b: Anode and cathode on iron film due to environmental disturbance.

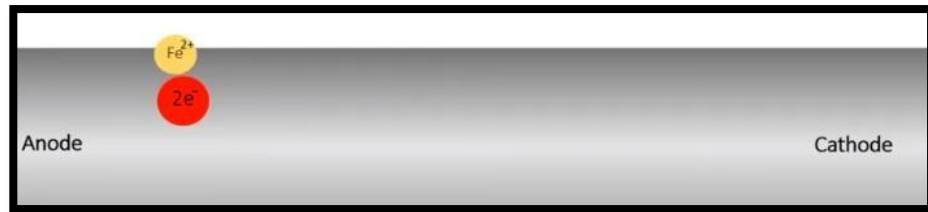


Figure 2.1c: Electron released from iron molecule

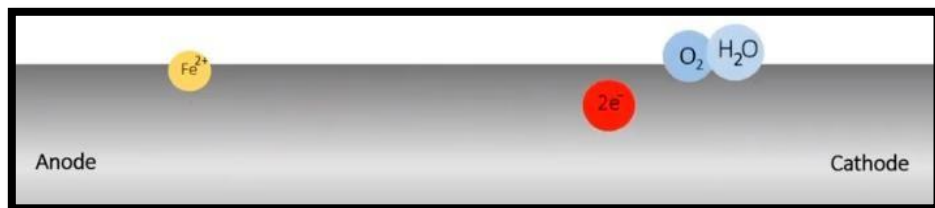


Figure 2.1d: Moving of electron ($2e^-$) from anode to cathode due to environmental effect



Figure 2.1e: Developed ($2OH^-$)

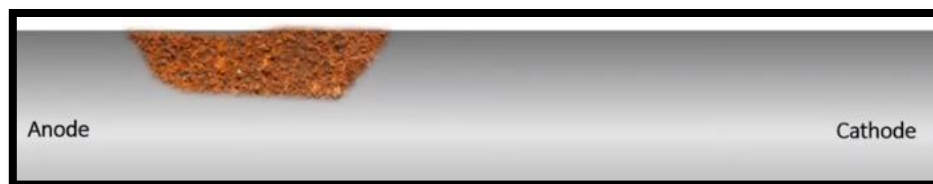


Figure 2.1f: Practical form of corrosion as $Fe(OH)_2$

This condition of steel bar in reinforced concrete structure is well understood to the need of expensive repairing. The reason of corrosion like carbonation or chloride induced corrosion takes much more important place in chloride exposed structures (deicing salt, a marine climate, salt contaminated aggregates). To understand more about corrosion process and influencing the rate of corrosion will be discussed in following section, the mechanism of chloride and water transport in concrete.

2.2 Corrosion basics in reinforcement concrete.

Generally, the high alkalinity of the concrete (pH over 12.50) forming a passive layer over the steel bar to maximize protection against corrosion attack. The corrosion will not occur unless the passive layer is sustained over the steel bar. There are two processes to disturb or break the passive layer and cause the corrosion.

- Carbonation of concrete
- Chloride attack

2.3 Corrosion as an electrochemical process.

There are electrochemical reactions on concrete reinforced steel bar which causes the corrosion. These reactions are demonstrated by Fig 2.2 and explained by equations 2.1.

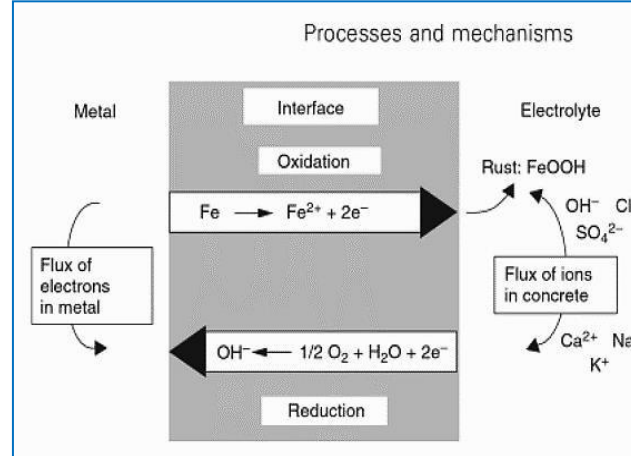
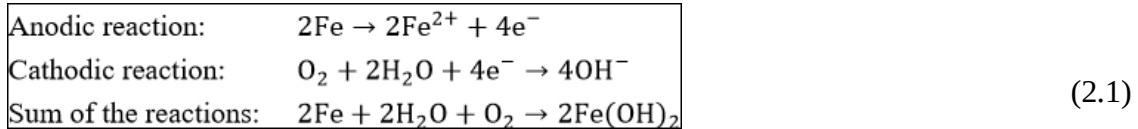


Figure 2. 2: Corrosion as electrochemical process. [4]



The dissolution of metal caused by anodic reaction where the flux of electron and ions taking place for corrosion rate, which can be counted as a mass lost per unit of time and area. This process leading to the reduction of thickness per unit of time, where the current density is measured as current per unit area. The current density leading to the reduction in the rebar diameter per year is shown in 2.2 [4].

$$\begin{aligned} \text{Iron/steel} &= 1\text{mA/cm}^2 \approx 11.6 \text{ mm/year} \approx 250 \text{ g/m}^2\text{-day} \\ &1\mu\text{A/cm}^2 \approx 12\mu\text{m/year} \approx 0.25 \text{ g/m}^2\text{-day} \end{aligned} \quad (2.2)$$

2.3.1 Corrosion Potential

Corrosion potential for a metal in a different electrolyte having specific characteristic values, where some are tabulated in Table 2.1. For stainless steel, normal steel, galvanized steel and copper concrete.

Table 2. 1: Corrosion potential of different metals in concrete. [4]

Electrode/Metal	Corrosion potential, mV _{CSE}		
Reinforcing steel bar in:			
saturated Ca(OH) ₂ solution			-1.1
O ₂ -free, water-saturated concrete			≥-1.1
humid, Cl ⁻ -containing concrete			≥-0.6
humid, Cl ⁻ -free concrete	+0.1	to	-0.1
humid, carbonated concrete	+0.1	to	-0.3
dry, carbonated concrete	+0.2	to	0
dry concrete	+0.2	to	0
Stainless steel in humid concrete	+0.1	to	-0.2
Copper in humid concrete	+0.1	to	-0.2
Zinc coated steel in:			
wet concrete			≥-1.1
humid, Cl ⁻ -containing concrete			≥-0.8
humid concrete	similar to reinforcing steel		
humid, carbonated concrete	+0.2	to	-0.1
dry, carbonated concrete	similar to reinforcing steel		
dry concrete	similar to reinforcing steel		

2.3.2 Corrosion Initiation and Propagation.

A very known and classified statement that reinforcement in fresh or young concrete structure is possibly protected. Where the pH of pore water is maximum while less quantity of chloride ions in the concrete. Whereas no chloride contaminated component been used for concrete productions. For given types of concrete quality, the corrosion rate after initiation and propagation of corrosion depend on the factors as shown in Fig 2.3.

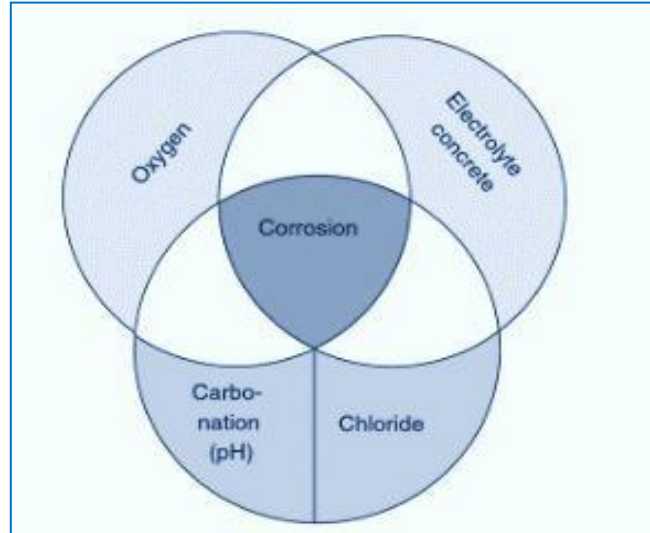


Figure 2. 3: Corrosion conditions of steel in concrete. [4]

During carbonation the macro element that appears as chlorides attacks the steel rebar locally to initiate corrosion when the pH is lower than 11.5 [4]. This element between anode and cathode is the area that is locally attacked by corrosion shown in Fig 2.4.

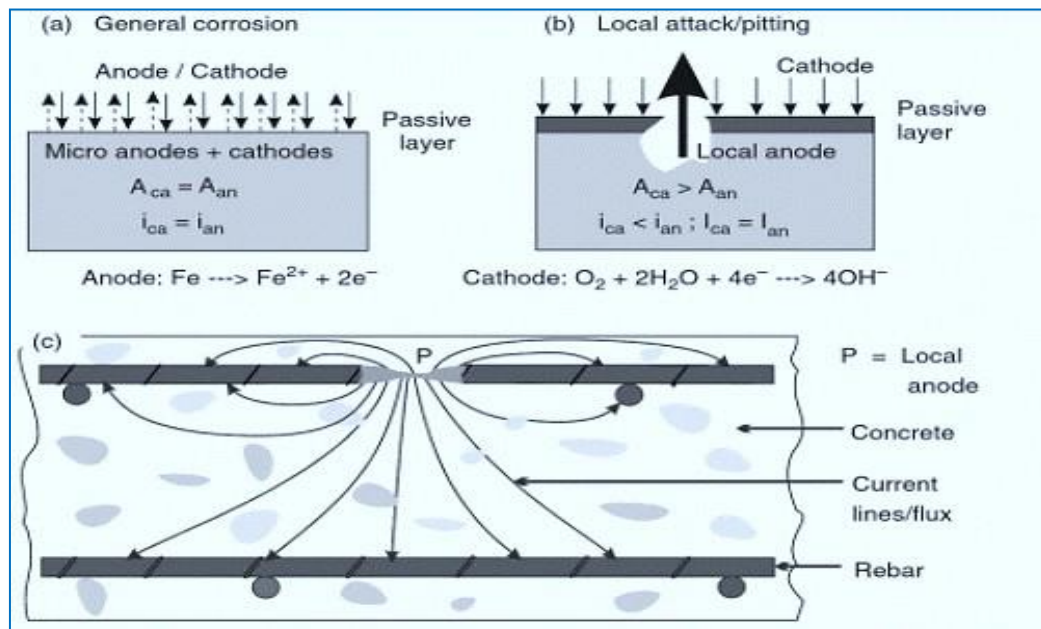


Figure 2. 4: General corrosion, localized attack, pitting corrosion in concrete. [4]

This macro element is denoted by i_{corr}^0 , is normally leading or affecting the localized attack on steel bar. This effect can be calculated by i_{corr} as shown in equation 2.3. Regardless of any influences of i_{corr}^0 macro element compared to the value of i_{corr} will be doubled, which accounts for the area of anode (A_{an}) and the area of cathode (A_{ca}).

$$i_{\text{corr}} = i_{\text{corr}}^0 \left(1 + \frac{A_{\text{ca}}}{A_{\text{an}}} \right) \quad (2.3)$$

According to this practice cathodic area is much larger than anodic area whereas initially both have same dimensions. To compare the value of macro element, i_{corr}^0 with corrosion rate, i_{corr} is doubled. The high ratios of $A_{\text{ca}}/A_{\text{na}}$ increases I_{corr} . This is because of electrochemical resistance in anodic and cathodic reactions which limits the current flux as well.

The study about i_{corr} in [4] have very good estimation of driving force of macro element potential difference (ΔU) of both anode and cathode with electrochemical resistance shown in equation 2.4.

$$i_{\text{corr}} = \frac{I_{\text{corr}}}{A_{\text{an}}} = \left(\frac{\Delta U}{R_{\text{an}} + R_{\text{ca}} + R_{\text{E}}} \right) \frac{1}{A_{\text{an}}} = \frac{U_{\text{corr,ca}} - U_{\text{corr,an}}}{r_{\text{an}} + \frac{r_{\text{ca}} A_{\text{an}}}{A_{\text{ca}}} + \frac{\rho_{\text{c}} A_{\text{an}}}{L}} \quad (2.4)$$

Where

I_{corr} = Corrosion Current (A)

i_{corr} = Corrosion Current density (A/m²)

ΔU = Driving Force (Corrosion Potential difference, V)

R_{an} = Resistance of Anode (Ω)

R_{ca} = Resistance of Cathode (Ω)

R_E = Electrolyte, concrete resistance (Ω)

$U_{corr, an}$ = Corrosion Potential of Anode (V)

$U_{corr, ca}$ = Corrosion Potential of Cathode (V)

A_{an} = Area of anode (m^2)

A_{ca} = Area of cathode (m^2)

r_{an} = Specific anodic electrochemical resistance (Ωm^2)

r_{ca} = Specific cathodic electrochemical resistance (Ωm^2)

ρ_c = Specific resistivity or electrical resistance of concrete (Ωm)

L = Characteristic length (m)

For defined macro element characteristic length L , is dependent upon concrete volume over the rebar thickness, anodic and cathodic area, current path (distance between cathode and anode) and resistivity of concrete. The electrochemical resistance depends on current density, cathodic area and macro element driving force of concrete resistivity. Some well-defined results of experimental practice in laboratory were conducted under Hunkeler 1994.

- Driving force decreasing while concrete resistivity increasing with decrease of moisture content.
- Electrochemical resistance and ohmic resistance are increasing with decrease of moisture contents.
- Cathodic resistance grows faster with decreasing moisture contents. In wet concrete the r_{ca}/r_{na} ratio is 10 while dry concrete having greater than 100.
- Cathodic area increasing with decreasing moisture content.

- The anodic resistance r_{an} depends on the size of anode which become smaller, if anode area is getting increased.
- Galvanic current of macro element increasing with moisture content of concrete get increased.
- Galvanic current of macro element increasing with increase of corroding site area with constant ration of A_{an}/A_{ca}
- Increasing the ratio of A_{an}/A_{ca} will increase the temperature.

2.4 Corrosion Identifications and measurement techniques.

The quality control and maintenance of infrastructure required planning for maintaining and restoration of these structures with the help of non-destructive techniques to inspect and monitor the level of corrosion at earlier stage. The corrosion have mega impact on concrete structures which consumes a huge budget of countries in terms of infrastructures restorations or reconstructions. To encounter these difficulties of corrosion deterioration in infrastructures large number of investigations and measurements [Table 2] are used to secure these structures [5] [32-34].

Table 2. 2: Corrosion Identifications and measurements techniques

No.	Corrosion Identifications and measurements techniques		
1.	Open circuit potential (OCP) measurements	11.	Vibrating wire and electrical strain gauges
2.	Surface potential (SP) measurements	12.	Cover thickness measurements
3.	Concrete resistivity measurement	13.	Ultrasonic pulse velocity technique
4.	Linear polarization resistance (LPR) measurement	14.	X-ray, Gamma radiography measurement
5.	Tafel extrapolation	15.	Infrared thermograph Electrochemical
6.	Galvan static pulse transient method	16.	Visual inspection
7.	Electrochemical impedance spectroscopy (EIS)	17.	UGW Based Techniques for Corrosion Monitoring of RC
8.	Harmonic analysis	18.	Ground penetrating radar
9.	Noise Analysis	19.	Optical fiber sensors
10.	Embeddable corrosion monitoring sensor		

2.4.1 Open circuit potential (OCP) measurements.

The environmental effect or reaction to any metal in reinforcement concrete is indicated by the potential which develops from environmental contacts. The concrete in concrete structures acts as electrolytes while reinforcement bar develops a potential which is dependent upon the environment and may vary accordingly. The schematic or configuration diagram for OCP measurement is shown in Fig. 2.5. In this procedure or techniques having potential difference of rebar with reference electrode made of either copper sulfate electrode (CSE), silverchloride electrode (SCE) or saturated calomel electrode [35].

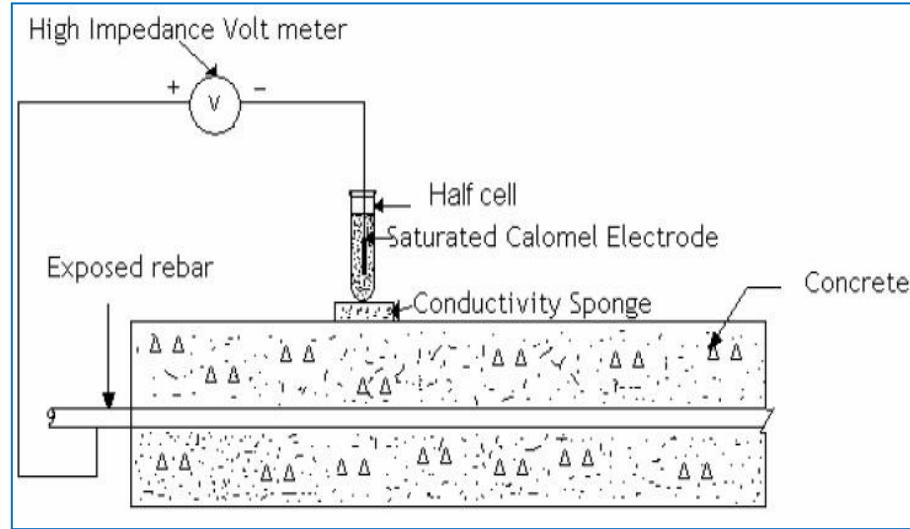


Figure 2. 5: Schematic diagram of (OCP) measurement. [35]

The results of OCP technique are calculated and shown in table 2.3.

Table 2. 3: Half Cell Potential (HCP) measurements correlated with corrosion conditions. [35]

Open circuit Potential value		Corrosion Condition
mV vs SCE	mV vs CSE	
< -426	< -500	Severe corrosion
< -276	< -350	High risk (<90) of corrosion
-126 to -275	-350 to -200	Intermediate corrosion risk
> -125	> -200	Low risk (10%) of corrosion

Various methods and techniques are used for corrosion detection in concrete structures. But no proper consensus have been made over any of these calculations to diagnose corrosion level in reinforcement concrete. To find the level of corrosion which has been explained in [36] following several electrochemical techniques. Where the OCP has been found to be the most sustainable techniques in routine inspections of concrete infrastructures.

The more negative value of -276mV showing 90% probability of corrosion on reinforcement concrete steel bar. This test is a nondestructive test of any type of common or large concrete structural area to collect enormous quantity of data to diagnose the corrosion risk or probability of corrosion risk in reinforced concrete [37-38]. Moreover, the reliable relation between open circuit potential and corrosion rate is highly predictable in laboratory test to define well established conditions [39] [40]. In these studies, many authors indicated that HCP techniques can detect the corrosion rate while OCP cannot detect the rate of corrosion [41-45] only providing the information about corrosion probability [46].

2.4.2 Surface Potential (SP) Measurements.

The setup for the surface potential (SP) is demonstrated in Fig 2.6 having two different reference electrodes named as fixed reference electrode and movable reference electrode. The electric current flowing between anode and cathode through concrete during corrosion process where the potential drop will be considered the flow of current in the concrete. Hence this nondestructive testing technique for corrosion are used to identify the area of anodic and cathodic regions in concrete which are indirectly detecting the corrosion of rebar in concrete structures. As shown in Fig 2.6 no external electrical source is connected with reference electrode or rebar except high impedance volt meter. The fixed electrode is kept on symmetrical point on concrete structure while movable electrode moved along the structure of nodal points of the grid. The movable electrode potential will measure against fixed electrode by high impedance voltmeter when movable electrode placed on a nodal point. The high positive potential in anodic area will represent possible corrosion on rebar. The higher value of potential difference in-between cathodic and anodic area showing maximum probability of corrosion.

These techniques are known by non-destructive assessment of corrosion in concrete infrastructures. Multiple surveys and assessments have been done by using surface potential measurements techniques [47].

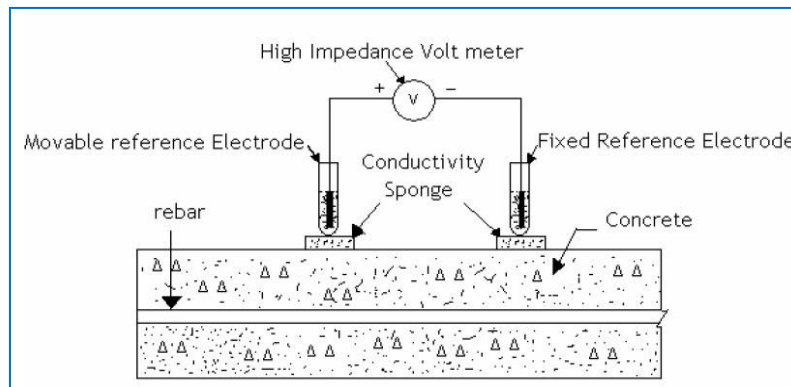


Figure 2. 6: Schematic diagram of surface potential measurement (SP) [47]

2.4.3 Concrete Resistivity Measurements

To determine the intensity of corrosion or corrosion initiation by concrete resistivity method, depends on the electrical resistivity of the concrete. Actually, the higher electrical resistivity of concrete has slow corrosion process compared to low resistive concrete, leading to flow of high current between anode and cathode. Concrete resistivity measurements techniques are based on two different methods, named as AC and DC measurements. In both techniques the probes which are embedded applied on surface where constant electric field will calculate between two embedded electrodes and resulting current as voltage drop over resistivity meter to accomplish DC measurements.

AC measurement will be conducted along four pins or four probes methods. In AC method the current will pass through outer electrodes while the potential will be between inner electrodes. This technique based on four probes method is shown in Fig 2.7.

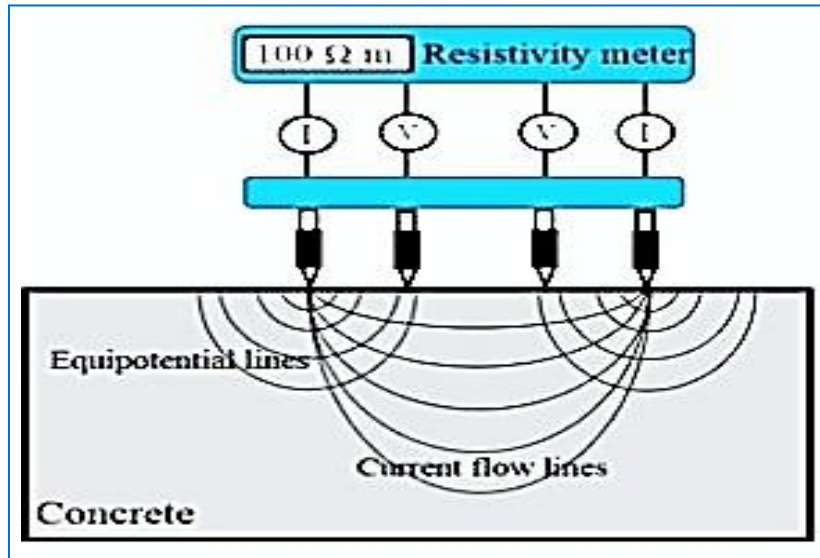


Figure 2. 7: Circuit connectivity of concrete resistivity measurements. [51]

The current (I) is calculated through outer probes while the voltage (V) is taken from inner probes. The resistance is represented by V/I and the concrete resistivity by $\rho = 2 \pi a R$

In the above relation “a” represents the distance of inner electrode in centimeter and “R” is the resistance measured in ohms. The electrical resistivity is more precise parameter to be measured carefully using different techniques. This electrical resistivity is being used indirectly to define or evaluate characteristics of concrete, such as degree of concrete saturation, chloride ion diffusivity [48] [49]. These information and parameters may help to provide some meaningful information related to rebar corrosion performance inside concrete [50].

This is also indicated in [51] that corrosion rate having inversely proportional relation with electrical resistivity of concrete which is supported by G. Glass et al in [52]. This relation affecting rebar corrosion with strong dependency of environmental humidity. The electrical resistivity has been proposed as an effective parameter towards assessment of risk evaluation in reinforcing steel corrosion, specifically, when corrosion is induced from chloride attack [53]. Some authors made relationship of corrosion and resistivity [54] [55] as elaborated in Table 2.4.

Table 2. 3: Corrosion risk from resistivity [51].

Resistivity (Ohm.cm.)	Corrosion risk
Greater than 20,000	Negligible
10,000 to 20,000	Low
5,000 to 10,000	High
Less than 5,000	Very high

2.4.4 Linear polarization resistance (LPR) measurements.

For the measurement of reinforcement steel corrosion rate in concrete, LPR is a well- established technique due to immediate response and non-intrusive. Only localized damage of concrete cover is required for enabling electrical connection with reinforced steel. LPR technique are using to collect the data for valuable assessment and influences to instantaneous corrosion rate of reinforcement steel. LPR technique to measure the reinforcing steel corrosion by a small amount of its equilibrium potential. It will be completed potentiostatically by vary fixed amount of potential “ ΔE ” of reinforcing steel bar with monitoring current decay “ ΔI ” after a citrine fixed time.

The polarization resistance R_p of steel can be calculated from equation as below. Hence we can also calculate the corrosion rate “ I_{corr} ” in equation 2.5.

$$R_p = \Delta E / \Delta L$$

$$I_{corr} = B / R_p \quad (2.5)$$

Where “B” indicate Stern-Geary constant having value of 25mV for active steel and 50mV for passive steel [57]. However the corrosion current density “ i_{corr} ” can be determined to divide corrosion rate by surface area “A” of steel as shown in equation 2.6.

$$i_{corr} = I_{corr} / A \quad (2.6)$$

In conventional LPR test we can present the residual strength and remaining services of the structure. In this techniques the perturbation is applying from auxiliary electrode on concrete surface as shown in fig 2.8. The surface area of steel bar supposed to be polarized that laying directly beneath the auxiliary electrode.

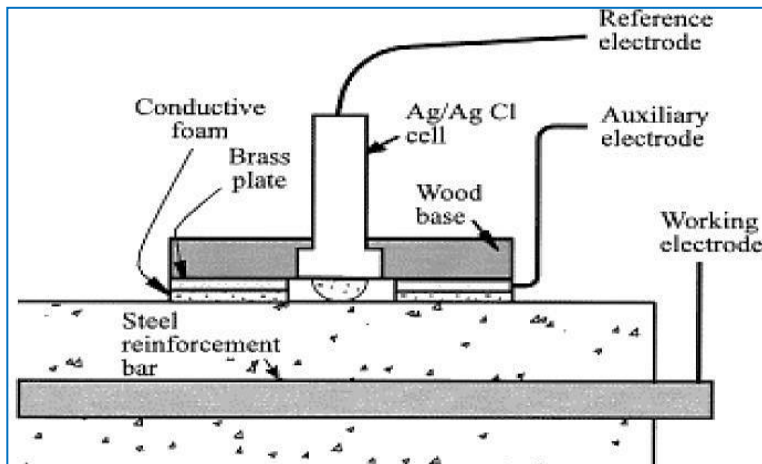


Figure 2. 8: Linear polarization resistance measurements [57]

In conventional LPR test some author predict [58-59] the error of corrosion current density due to unconfined current flowing from auxiliary electrode and can spread over a large area of steel. In order to mitigate or overcome this issue of confining current to a predetermine area. Second auxiliary electrode techniques developed, which making ring shape guard surrounding the inner auxiliary electrode [60-65] shown in figure 2.9. This solution of second auxiliary electrode will maintain confinement current to prevent perturbation current spreading in unknown area during LPR measurements. This technique relies on potential response of guard ring using Galvanostatic control system.

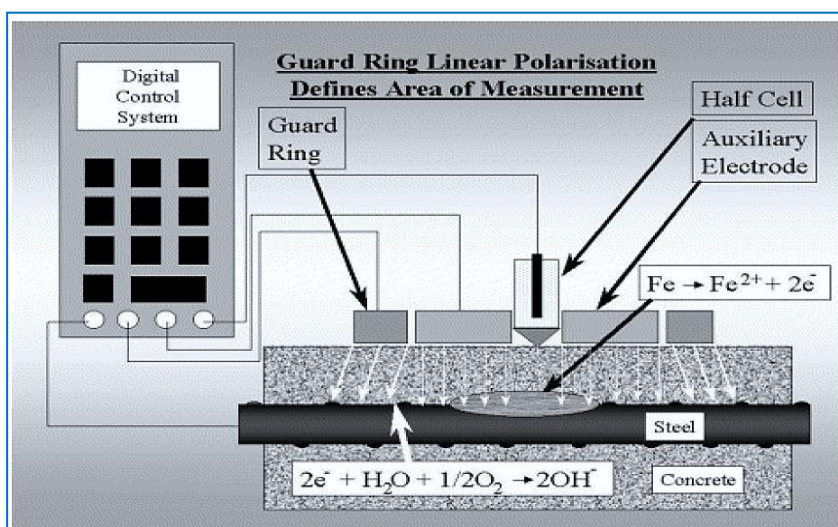


Figure 2. 9: Linear polarization resistance measurements with guard ring test set-up [57].

To become more appropriate level of confinement current, two more sensor electrode between the inner auxiliary electrode and outer auxiliary electrodes can be placed. The change in potential will monitor by digital control system between those sensors electrodes while confinement current will maintain this potential change or difference over sensors electrode throughout LPRtest [66].

After using second auxiliary electrode as guard ring the performance improved comparatively over a single electrode to detect accurate corrosion rate. For more accuracy and enhancement embeddable linear polarization sensor techniques are developed for new constructions. It is shown in Figure 2.10. Here the measurement will take with embedded half-cell against mild steel “working electrode” according to single or more than single stainless steel auxiliary electrode. Mild steel is actually representative of reinforced steel which must be representing the accurate value of corrosion rate around it.

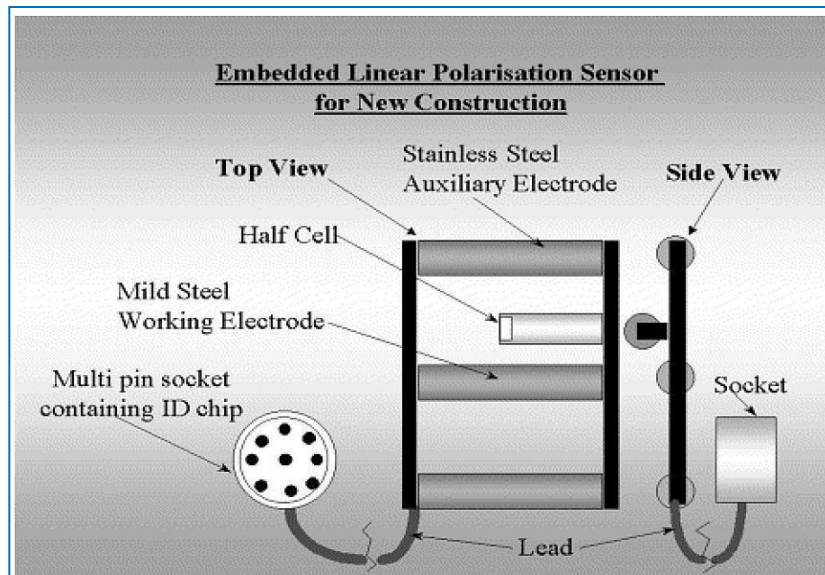


Figure 2. 10: Embedded linear polarization sensor for new construction.

Above mention criteria have been developed from laboratory to the field investigation with sensor controlled guard ring device. The results are showed in table 2.5 where the measurements are effected by temperature and humidity. That's why the measurement must be accurate to within a factor of two. This work has been concluded with the correlating I_{corr} to section loss and end of service [67].

Table 2. 4: Corrosion current against condition of the rebar. [67]

Corrosion current (I_{corr})	Condition of the rebar
$I_{corr} < 0.1 \mu A/cm^2$	Passive condition
$I_{corr} 0.1 - 0.5 \mu A/cm^2$	Low to moderate corrosion
$I_{corr} 0.5 - 1.0 \mu A/cm^2$	Moderate to high corrosion
$I_{corr} > 1.0 \mu A/cm^2$	High corrosion rate
The device without sensor control has the following recommended interpretation.	
$I_{corr} < 0.2 \mu A/cm^2$	No corrosion expected
$I_{corr} 0.2 - 1.0 \mu A/cm^2$	Corrosion possible in 10 -15 years
$I_{corr} 1.0 - 10 \mu A/cm^2$	Corrosion expected in 2-10 years
$I_{corr} > 10 \mu A/cm^2$	Corrosion expected in 2 years or less

2.4.5 Tafel Extrapolation.

The tafel extrapolation (TP) techniques is another types of electrochemical process for calculating corrosion rate. This techniques are based on corrosion current I_{corr} intensity and tafel slopes. As well as the tafel slope is possible to use for corrosion rate calculation with LPR techniques [68-71]. Here we have to summarize both techniques LPR and TP base on application of following monitoring of potential (Galvanostatic) or followed the by (Potentio static) monitoring of the current.

The change of potential is the main deference of both techniques, where the changed in potential must be less than ± 25 mV for the LPR while in TP the potential can reach up to ± 250 mV. Whether the interpretation of testing results having another difference of both LPR and TP techniques.

The calculation of corrosion rate in TP is just straight forward, which is direct substitution of slope value (β_a and β_c) to get the corrosion current. It is shown in equation (2.7) whether calculating corrosion rate shown in equation (2.8).

$$i = i_{\text{corr}} \{ \exp [S1 (E - E_{\text{corr}})] - \exp [-S2 (E - E_{\text{corr}})] \} \quad (2.7)$$

$$\text{Corrosion rate } (\mu\text{m/yr}) = \frac{0.129 I_{\text{corr}} E.W_s}{dA} \quad (2.8)$$

The corrosion current intensity I_{corr} in A/cm^2 is the surface area of reinforcing steel in cm^2 in equation 2.9. However “E.W” is the equivalent weight of steel which is the atomic weight of an element that having same combining capacity of given weight of other element and “d” is the reinforcing steel density in g/cm^3 whether “A” is exposed surface area of steel bar.

$$I_{\text{corr}} = \frac{\beta_a \beta_c}{2.3 R_p (\beta_a \beta_c)} \quad (2.9)$$

Using equation 2.9 to calculate corrosion intensity I_{corr} by LPR method, which having relationship of stern-Geary. After that using equation 2.8 to calculate corrosion rate.

Further I_{corr} can be calculated in [72, 73] in detail. Where R_p is polarization resistance in $\text{k}\Omega\text{cm}^2$ and (β_a, β_c) are constants taking from Tafel plot. Another techniques used by some researchers [74-78] shows in equation (2.10) where the constant value $B=26\text{mV}$.

$$I_{\text{corr}} = B/R_p \quad (2.10)$$

This equation offer some significant advantages.

1. In ideal condition, the Tafel extrapolation accuracy is = equal or > greater than weight loss method.
2. With this method extremely low corrosion rate measurement is possible.
3. Tafel plots can elaborate corrosion current measurements directly

2.4.6 Galvanostatic Pulse Transient Method

Galvanostatic pulse transient method is a transient polarization time domain techniques. Which is shown in figure 2.11. Anodic current pulse are applying on reinforced bar galvanostatically from counter or reference electrode. The reference electrode is normally placed on the surface of concrete. The applied current usually taking in the range of 10 to 200uA with 10 seconds duration of typical pulse. Where the reinforced bar get polarized in anodic direction according to its free corrosion potential. This typical potential transient response shown in figure 2.12. Which is recorded in the center of counter electrode as functionality of time named polarization time.

Polarization of rebar approaching slightly after ohmic potential increased. When constant current I_{app} applied in the system, the transient behavior of rebar along the reinforcement potential $V_t(t)$ can be express as below in equation 2.11 [79].

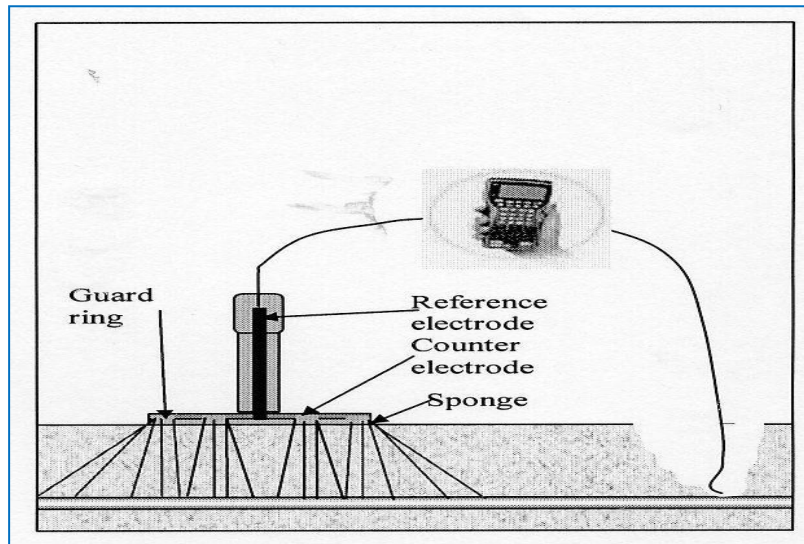


Figure 2. 11: Galvanostatic pulse technique set-up. [51]

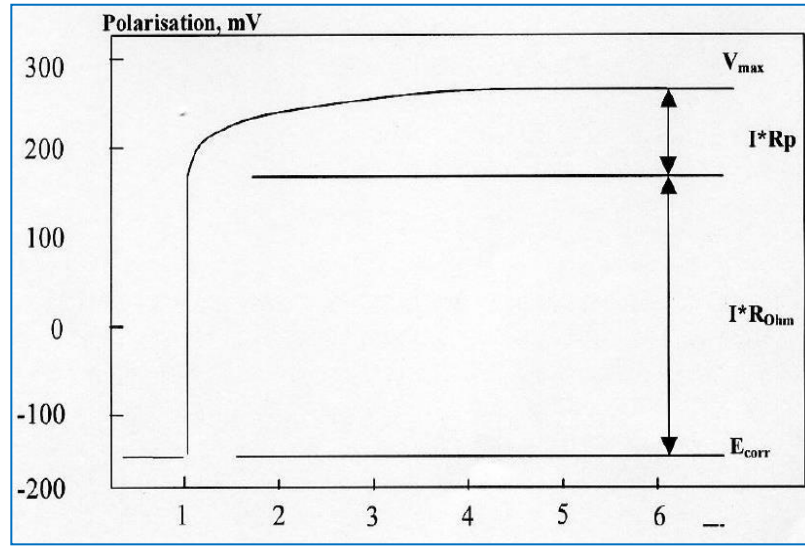


Figure 2. 12: Potential time curve the response to a Galvano static pulse [51].

$$V_t(t) = I_{app} [R_p [1 - \exp(-t / R_p C_{dl})]] + R_{\Omega} \quad (2.11)$$

R_p is the polarization resistance C_{dl} is the double layer capacitance R is ohmic resistance

To obtain the values of C_{dl} , R_p and the R_{Ω} ohmic resistance will be evaluated further based on experimental output. For this purpose two different methods are proposed. Linearization [80] and exponential curve fitting [81]. For the first method of linearization we are using equation 2.12.

$$\ln(V_{max} - V_t(t)) = \ln(I_{app} R_p) - t / (R_p C_{dl}) \quad (2.12)$$

After long polarization the final steady potential V_{max} reaching to its max, it's known in experimental process. Where "t" is the time $t=0$ of straight line in linear aggression analysis. $\ln(I_{app} R_p)$ corresponding with slope of $1/(R_p C_{dl})$ while ohmic voltage drop corresponds to $I_{app} R_{\Omega}$

2.4.7 Electrochemical Impedance Spectroscopy (EIS)

In recent years a very useful nondestructive techniques A.C impedance spectroscopy been experimented for corrosion quantifying of embedded steel bars in concrete structures. Where “Z” is the impedance, the ration of A.C voltage to current. Further from 10mV to 20mV AC voltage will applied on steel bar whether the current and phase angle will measure against various frequencies. In result a complex impedance with real and imaginary capacitive or inductive component Z' and Z'' are shown in Fig 2.13.

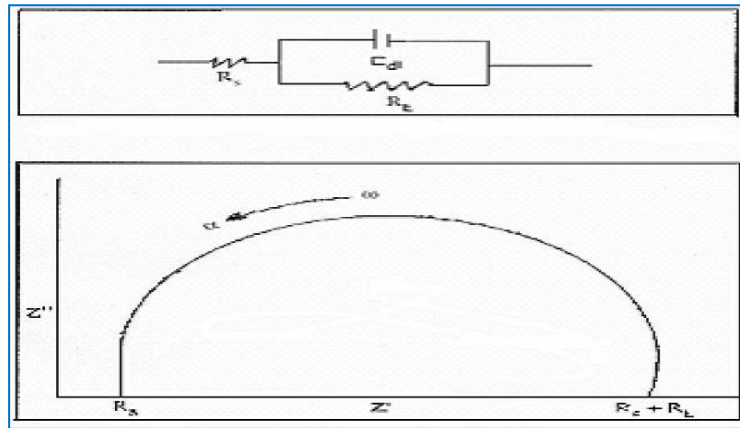


Figure 2. 13: Nyquist Plot for steel in concrete [51]

The equivalent electrical circuit has to be determined with variation of impedance across frequency. To plot imaginary impedance gives a semicircle against real impedance with R_t diameter. Which is taking from origin R_s known by ohmic resistance of the concrete.

The frequency “f” can be determine over the highest point of semicircle where the double layer capacitance value is shown in equation 2.13.

$$C_{dl} = 1/2\pi R_t f \quad (2.13)$$

The combination of different semicircles correspond to different parallel components of RC will response to AC impedance. Where the value of C_{dl} is very useful to use in corrosion process. That’s why AC

impedance considered as more informative method than DC LPR techniques. But there is major disadvantage of this techniques which is high time consuming process [82]. The use of various frequencies in wide range will reflect with detail information about the mechanism and electrochemical reaction of kinetics. These are related to corrosion rate with the help of Stern-Geary formula. Many researcher have focus and concentrated on impedance spectroscopy for the corrosion behavior characterization on embedded steel bar in concrete [83-87]. With the advantage of EIS techniques of small excitation amplitude in the range of 5mV to 10mV as a peak to peak minimally disturb the steel. The corrosion product or absorbed species during testing [88].

2.4.8 Harmonic Analysis

Actually this is the extension method of Electrochemical Impedance Spectroscopy (EIS). It is more straightforward than that electrochemical impedance process, which carrying quick results. The same process are here to apply AC voltage perturbation “V₀” on a single frequency while taking AC current density i_1 to measure next two harmonic i_2 and i_3 analysis.

Because it is define and fact that corroding interface act as a rectifier. So the second harmonic current reflection will not linear about free corrosion potential [89]. Where the corrosion rate I_{corr} can be calculated [90] in this method shown in equation 2.14. In this method we have one more advantage to calculate Tafel constant as shown in equation 2.15. In other have Tafel constant can be calculated from equation 2.16.

$$I_{corr} = \frac{i_1^2}{\sqrt{48} \sqrt{2i_1i_3 - i_2^2}} \quad (2.14)$$

$$1/\beta_a \text{ Or } 1/\beta_c = 1/2 V_0(i_1/i_{corr} + 4i_2/i_1) \quad (2.15)$$

$$B = \beta_a\beta_c/2.3(\beta_a+\beta_c) \quad (2.16)$$

Same like electrochemical impedance method, a sinusoidal voltage of 10mV will applied to perturbate which is working by reference electrode with a single frequency. Where the current response is measured as fundamental first and second harmonic. It is going to enable the Tafel slope (β_a and β_c) calculation directly during test. The harmonic analysis are going to performed in very narrow frequency range which provide a quick and rapid rebar corrosion rate results.

2.4.9 Electrochemical Noise Analysis

This is one of the emerging technique [91] for corrosion monitoring in reinforced concrete structures. In this techniques potential fluctuations will record as a noise data in the form of power spectra to measure corrosion rate by low amplitude variation. The noise source has to be located on corroding area. Where a sufficient interval of time will record to monitor in the frequency range (10 μ Hz to 10Hz). Noise signal from corroded bar in time domain will transfer to frequency domain to displayed on fast Fourier transform or max entropy techniques. This techniques will take 2-10 seconds interval depending on frequency. Which is showing the spontaneous random fluctuations in current flow in-between two identical. The steel bars are electronically isolated in concrete coupled through poor or zero resistance, the potential fluctuations are measure against reference electrode. In this way the polarization resistance shown in equation 2.17.

$$R_p = \sigma_E / \sigma_I \quad (2.17)$$

The corrosion rate can be determine from polarization resistance R_p . In addition the current variation coefficient indicating the type of corrosion [92]. Further the more modern techniques like electrochemical nose (EN) of macro-cell current also measured. The EN comprise on voltage and current fluctuations, that spontaneously produced by corrosion reactions [93-95]. Multiple studies claimed that this method has high attention to use for characterization of corrosion types like uniform corrosion, metastable pitting corrosion, stress-corrosion cracking and pitting and crevice corrosion [96-98].

2.4.10 Embeddable Corrosion Monitoring Sensor

In this techniques we are using embedded system to detect corrosion or warn for early conditions of concrete damages. The embedded device or sensor known by ECI embedded corrosion instrument which is electronic corrosion sensor to detect corrosion and warn the condition of damage in concrete infrastructure. ECI system monitoring by five key factors and communicating with a digital network. Which provide comprehensive and real time information of structural conditions. Which helps to averts crises and save money. Without physical inspection of inspector and cutting samples or interrupting structures ECI monitoring system having 5 key factors in corrosion detection.

- i. Linear polarization resistance (LPR)
- ii. Open circuit potential
- iii. Resistivity
- iv. Chloride ion concentration
- v. Temperature.

These information or more than enough and comprehensive data to monitor corrosion. It is known by (NDE) none destructive evolution device having the ability to detect causes among correlation sign of corrosion. An embedded sensor of ECI processing electronically and connected with digital communication system to maintain or secure from electromagnetic interference of power line or radio waves. ECI system of full cover package shown in Fig 2.14. It has corrosion sensor incorporates of 5 sensors to a small rugged package that need to install or place in during coasting of concrete. This process has much application commercial maintenance of civil structures [99].



Figure 2. 14: During operation ECI sensor [57]

2.4.11 Vibrating wire and electrical strain gauges

Vibrating wire strain gauges system or technique need to be embed in concrete to determine strain due to stress variation shown in figure 2.15. A conventional devices of vibrating wire and electrical strain gauges are used to demonstrate or measure strain in concrete structures. Long term reliability for exact strain measurement and frequent transmission of signal over long distance are the main advantages of this vibrating wire technique. Actually it is detecting the formation of internal craze delamination in concrete. Whether electrical strain gauges on other side are not suited for internal cracks monitoring and propagation. In that way the formation of cracks intersects across these foil sensor. As well as electrical strain gauge need a bonding surface, therefore cannot be embedded in concrete mixture for delamination and crack detection.



Figure 2. 15: Installation of VW strain gauge [57]

2.4.12 Cover Thickness Measurement

For this technique we are using converter or profometer to measure the concrete cover. With the help of this solution we can measure the rebar size, position and the direction based on damping of PRC parallel resonant circuit. Here the alternating current AC with a specific frequency flowing through probe coil that creating electromagnetic field. In the range of this electromagnetic field, metal object alter coil voltage will count as a function of cover and bar diameter. There are two unites. The probe and indicator unit in electronic system. The indicator unit are placed on indicator joint front panel. Different diameter of bars from 8 to 34mm has to be set in a rotary selector switch. While the maximum cover thickness can be measure up to 120mm.

The bright light and loud audio signal on detection head showing a warning of low concrete cover. In figure 2.16 it is shown about concrete cover thickness and diameter with steel size measuring tool or meter.



Figure 2. 16: Cover meter [57]

By moving the instrument over concrete surface will accomplished the location of primary and secondary reinforcing bars. The needle of the meter will indicate the maximum deflection, in case the instrument axis is parallel and directly over a reinforcing bar or multiple bars. This investigation revealed at least 40mm which is necessary for marine exposure with 50mm cover will be optimum [100]. Furthermore the higher thickness of 70mm and 100mm are also recommended for marine environment [101, 102].

2.4.13 Ultrasonic Pulse Velocity Measurement

The (UPV) is nondestructive solution for corrosion measurement. This technique measuring speed of sound in materials to predict material strength, as well as detecting the presence of concrete internal flaws like cracking, honeycomb, decay and other damages [103- 105]. This solution is also applicable for undesirable testing if destructive test is not suitable to concrete stone and timber. The main theme or strength of this solution is determine general changes in concrete structure or part of structure. But this UPV not practicable and not matching in testing sound concrete, as well as it is ineffective to investigate the crack depth in the form of water to fill the crack. In other hand the performance is quite poor for rough surface. A sound energy of ultrasonic frequency is define above than audible frequency of 16 KHz. This frequency is actually propagating through materials in the form of mechanical energy as a stress wave and intimate mass contact regardless of physical moment of the material. Longitudinal pulses of stress wave been generated by electro acoustical transducer that posting directly for test with the surface of concrete. After traveling or propagating across the concrete pulses converted to electrical energy over a second transducer. Most of the standard categorized three arrangements of transducers as below.

1. Direct Transmission. When the transducers are located directly opposite to each other
2. Diagonal transmission. When the transducers are located diagonally to each other across the corners.
3. Indirect transmission. When the transducers are attached to the same surface and separated by define distance

In this procedure pulses emitting from transducer and transmitting through the material to receive by other transducer located by “L” distance from first transmitting transducer. The first pulse time are measured by electronic mean in microsecond with respect to time “T” arriving at the receiver. While pulse velocity can be calculated as follows by equation 2.18

$$\text{Pulse Velocity, } V = L / T \quad (2.18)$$

The interpretation or determination of data is quite difficult due to handling large number of factors and effecting the velocity of pulse [106]. The relation between concrete quality and ultrasonic pulse velocity is given in table 2.6.

Table 2. 5: Concrete quality Vs Longitudinal pulse velocity [106]

Longitudinal pulse velocity (Km/sec.)	Approximate compressive strength (N/mm²)	Quality of concrete
Below 2.0	---	Very poor
2.0 to 3.0	4	Poor
3.0 to 3.5	Up to 10	Fairly good
3.5 to 4.0	Up to 25	Good
4.0 to 4.5	Up to 40	Very good
Above 4.5	Up to 40	Excellent

There are many testing techniques in under this method like pulse transmission, impact- echo, pulse-echo and resonance techniques. Each of them have different tools for use with different features of pros and cons.

2.4.14 X-ray /Gamma Radiography

This technique are known by radiography. This technique providing concrete quality and damages in reinforcement concrete via nondestructive procedures. Radioactive isotopes are using for concrete testing to employ γ radiography studies. This techniques considered as reliable method of identifying internal crack with location, as well as variation in density of the concrete. Radiography techniques are known by two names. The first techniques using x-rays while the second one are using gamma γ -rays. These both rays are electromagnetic radiation in invisible range. Which are easily penetrating in traveling in concrete in straight line. The effect of rays attenuating due to nature of the concrete along the thickness and density. The photonic emission by the radiation generator are transformed in visible light by fluometallic converter to attain max energy. In this way producing photograph of reinforcement concrete to show the cracks or other defects.

2.4.15 Infrared Thermograph Electrochemical

This is a new procedure to attain information of chloride content. This system having a near-infrared irradiation equipment, near-infrared multi spectrum camera and imaging spectroscope. A dispersed transmitted signal of near-infrared rays through spectroscope receiving in each wavelength over light sensitive element on multispectral camera as shown in figure 2.17, which showing the results according to [107]. This techniques are very effective in order of correlation between apparent diffusion coefficient and heat dissipation characteristics of concrete.



Figure 2. 17: Measurement and result of multi-spectrum camera [106]

2.4.16 Visual Inspection

Visual inspection elaborated by the name that a person has to perform physical inspection to check or inspect the structure by person visually. Usually the visual inspection taking once in a month, year or quarterly. Time period of inspection depend often the time after structure completion. This might be destructive or nondestructive but some time a sonic inspection carried by using the hammer to assess the sound of concrete. Visual inspection also depend on the inspector personality and expertise. The periodic inspection supposed to cover the information regarding cracks, quality of concrete, rust stains, spalled concrete and exposed reinforcement etc.

2.4.17 UGW Based Techniques for Corrosion Monitoring of RC

Using ultrasonic guided wave technique, some important characters are very useful to utilize. Normally the testing structure close to signal transmitter where the wave goes to disperse in the medium are known by guided wave. Which propagating in isotropic medium of concrete and steel rebar.

Three major types of propagating waves in cylindrical waveguide. Longitudinal, torsional, and flexural waves due to complex and imaginary properties of boundaries. As well as having frequency dependent characteristics with notational of $L(m, n)$, $T(m, n)$ and $F(m, n)$ [108-110]. UGW having capability of long distance testing with greater sensitivity in multilayered structures. Furthermore the frequency tuning and mode tuning will be utilized for different type's deterioration or damage evaluation. Due to mentioned properties UGW techniques been found very efficient and effective for damage detection in civil structures with various assessment. The mechanism of corrosion extraction will elaborate before explaining concrete alkalinity. The presence of $(Ca(OH)_2, KOH, \text{ and } NaOH)$ hydroxide of calcium, potassium, and sodium. With high concrete alkalinity the reinforcement steel bars are passivated of iron oxide film that create protection of steel bar.

Gradually the approaching of Oxygen, water molecule or ions steel bar are going to depassivated mode and start corrosion. Later on the corrosion depend on different parameters, but low to medium chlorides lead to uniform attack of corrosion. While high to low or medium to low chlorides are leading to localize attack of corrosion. Under guide wave corrosion detection the most prominent mechanisms are used. (i). Initiated corrosion makes roughness on the surface of the reinforcement steel bar which effect the guided wave propagation and character. (ii). A severe pitting corrosion create discontinuity of reinforcement steel rebar that changes the guided wave propagations characteristics. (3). Huge corrosion eventually approach to separation or delamination of reinforcement steel bar within the concrete which effecting the guided wave propagation characteristics.

To use above three mechanism UGW based techniques are more ever categorized in four groups.

- (1). Induced deboning corrosion monitoring
- (2). Pitting corrosion Monitoring
- (3). Monitoring corrosion induced interface roughness
- (4). Monitoring combined effects in actual corrosion.

In next section we will cover a short introduction of above mentioned four groups of UGW monitoring techniques.

(1). Induced deboning corrosion monitoring: This mechanism explained by Miller in [111]. Author said that two types of energy profiles are reported inside in the bar. Where the wave energy traveled from (T) transmitter toward (R) receiver showing in figure 2.18 as a mode A and mode B.

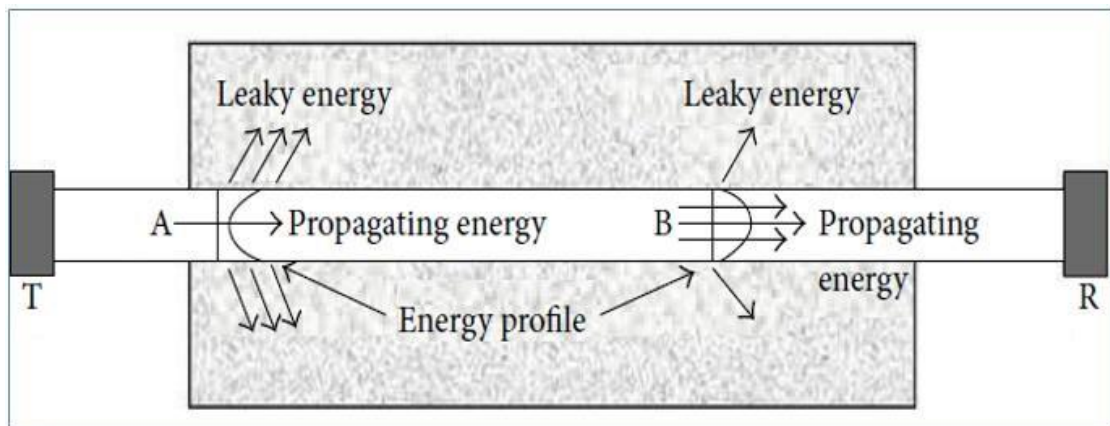


Figure 2. 18: Guided wave mode with two types (A, B), both can propagate from transmitter to receiver end [111]

In mode “A” it’s representing that most of the energy propagating in near area or circumference of steel rod. This core seeking energy detecting pitting corrosion.

(2). Pitting corrosion Monitoring: The best elaboration of this mechanism done by Markov chain models to simulate pitting corrosion, where the author described in first model “Time evolution of pit depth”. Whether the second model accumulate the “maximum pit depth”. Both model using experimental data to validate corrosion detection [113].

The wave propagating between transducers with respecting of time and group velocity of longitudinal wave mode along the steel bar or in the steel bar where defected location can be calculated by $D = Vt/2$.

Here the “D” showing the distance of defective area from transducer while “V” used for the group velocity of excited mode. However “t” is known by flight time.

(3). Monitoring corrosion induced interface roughness: This mechanism explained by Milleret al [113] on different corroded steel bar to differentiate the level of induced corrosion by simulating general corrosion concept. This experimental results are highly impressed by [113- 114] with different types of steel bar and different dimensions.

(4). Monitoring combined effects in actual corrosion: This mechanism explained by Mukerjee and Sharma in [115]. The author studied multiple modes of guided wave on embedded steel rebar. The dispersion curve indicating the L(0, 1) at low frequency around 100KHz. And it is the significant or efficient amount of axial displacement at structural interface of steel or concrete. This is known by surface-seeking mode which is also showing the L(0, 7) mode at higher frequency around 1MHz, it will lead to the central core of rebar. Hence it is known by core seeking mode which more suitable for pitting corrosion detection.

2.4.18 Ground Penetrating Radar.

GPR technique are known by electromagnetic investigation procedure. An electromagnetic signal emitted from antenna on concrete surface into the structure shown in Fig 2.19. The reflected signal from structure make some changes in transmitted signals which indicate the structure condition and corrosion over embedded bar. GPR techniques considered as a potential techniques for concrete structure periodic inspection [116-118]. As GPR having capability of localization and estimation of rebar, cracking, and corrosion detection. However the corrosion detection is a laboratory output which need more advance study. Moreover to describe GPR is scanning process of concrete structures via electromagnetic way to get 3D image and data for corrosion detection.

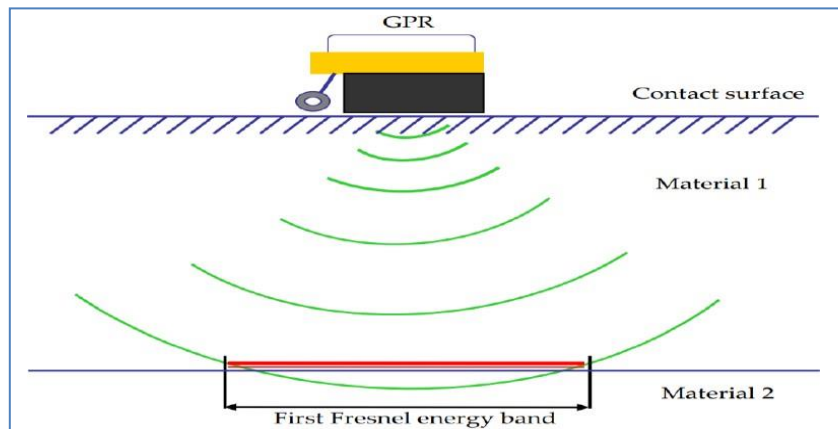


Figure 2. 19: Energy Wave Band of First Fresnel [111]

GPR technology contain multiple solution like medium position, shape, thickness and size etc to detect with the help of waveform variations of EM signals. The transmitted signal will reflect back through the medium to determine structure characteristics by using the reflecting power, resistivity /impedance of the medium interface.

The receiver operating characteristics (ROC) curve [119] used to obtain to threshold values. This analysis need numerical assessment and approach to identify the structure condition as shown infigure 2.20.



Figure 2. 20: Numerical process or assessment of concrete structures. [119]

2.4.19 Optical Fiber Sensor

In 21 century optical fiber sensor technology opened a broad area of research. These fiberoptic sensor are mainly using for physical and chemical variations like strain, water salinity, temperature, vibration, pH values, Oil and gas pipeline etc. Fiber optic sensor took dominant position in sensing area due to high capabilities, special characteristics and benefits of high bandwidth, ability of prosper in harsh environments (high temp, toxic and pressure), immune to electromagnetic interference, disturbing to sensing capability, remote monitoring and access to unale areas etc. In addition the faster response, light weight, low cost fabrication, high sensitivity are adding more importance to fiber optic sensors in different applications. Fiber optic sensors are actually the development of optical fiber core structure in specific dimensions to propagate and reflect the signal in required wavelength according to the specifications. A normal fiber optic cable consist on glass or plastic core to prophage the light and cladding to cover total internal reflection at core-cladding interface to maintain the light propagation in core. Moreover the physical protection are providing on requirement and uses based, which is knownby outer jacket. General structure

of fiber optic cable is identified in figure 2.21.

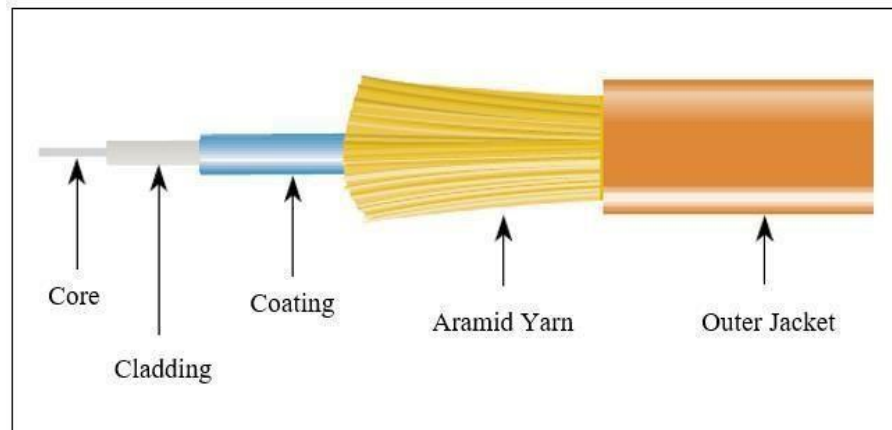


Figure 2. 21: Optical fiber cable structure [122]

Usually an optical fiber is classified by two types of single mode fiber or multimode fiber. Where a single mode fiber propagating a single mode of light having narrow core of 8 to 12 μm diameter. A multimode fiber propagating multimode of light with 50-200 μm diameter. There is big advantage of single mode fiber sensors against multimode fiber sensors due to absence of intermodal dispersion which is more suitable for incorporating sensors.

i. Fiber Optic Sensor Principle and Classification

A system for fiber optic sensor consist on optical source like laser, fiber optic cable and light signal detection component (optical spectrum analyzer). Since the light properties like frequency, phase and intensity can be altered. Therefore the optical sensor effectiveness depends on light signal parameters variations. Fiber optic sensor (FOS) classification is based on sensing position, application, working principle, topology, wavelength modulated sensors and working positions [120-122] shown in table 2.7.

Table 2. 6: Classifications of Fiber optic sensor [120]

Category	Types
Application	Chemical sensor
	Physical sensor
Operating principle	Intensity
	Phase
	Polarization
	Frequency
Topology	Wavelength modulated sensor
	Single-point sensor
	Quasi-distributed sensor

To detect any types of environmental effect or variations through fiber optic sensor are classified in above categories. After sensing these environmental effects through fiber optic sensor need to convert and transmit over fiber optic network into a server room or visualized form for define appropriate application. For defining application and required measurements, the important and main objective is sensorselection to have close comfortability with determined scope. A simple and easy configuration are shown in figure 2.22 to provide a light signal form laser source trough optical cable and detect the reflection of that light signal with optical detector.

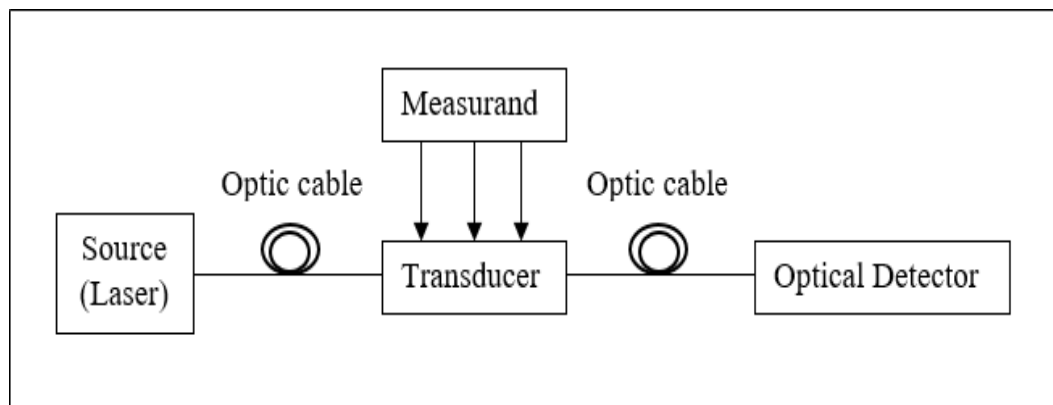


Figure 2. 22: Basic component of a fiber optic sensor [123]

ii. Fiber Bragg Grating (FBG) Sensor

In 1978 Hill et.al discovered a wavelength modulated sensor [123-125]. This sensor was named by fiber Bragg grating. It's discovered in the result of nonlinear properties of germanium dopes fiber research, where the continuous argon ion laser was pumper into a dopes fiber. That observed increases in reflected wavelength of light. And few year later a tremendous output investigated in term of fiber refractivity due to grating formation and that concept implemented for developing fiber Bragg grating (FBG) sensor. Initially it has been used in telecommunication applications while gradually its move to other industrial applications for different purposes, because of multiple specifications like light weight, highly sensitive and used under harsh condition. This FBG manufacturing process is known or define by recurring contradistinction of core refractive index through ion implantation, chemical etching, and ultraviolet irritation [126]. The propagating light in the core will be reflected at a specific wavelength due to interruption or discontinuity of grating interface, whether remaining passing wavelength will be unperturbed or transmit in the core toward next level as shown in figure 2.23. The reflected wave are caused by satisfying the Bragg condition as below equation 2.19.

$$\lambda_B = 2n_{eff}\Lambda \quad (2.19)$$

Where the Bragg grating wavelength, effective refractive index and grating period are define as below.

λ_B : Bragg wavelength,

n_{eff} : Effective refractive index

Λ : grating period.

To vary the grating period will engineered toward application objectives by Bragg wavelength. Whether non uniform shapes of grating plus lengths can produce different grating chirped, tilted and superstructure. To use a single optical fiber cable have to made gratings at different length across the fiber to achieve multi-sensing applications targets.

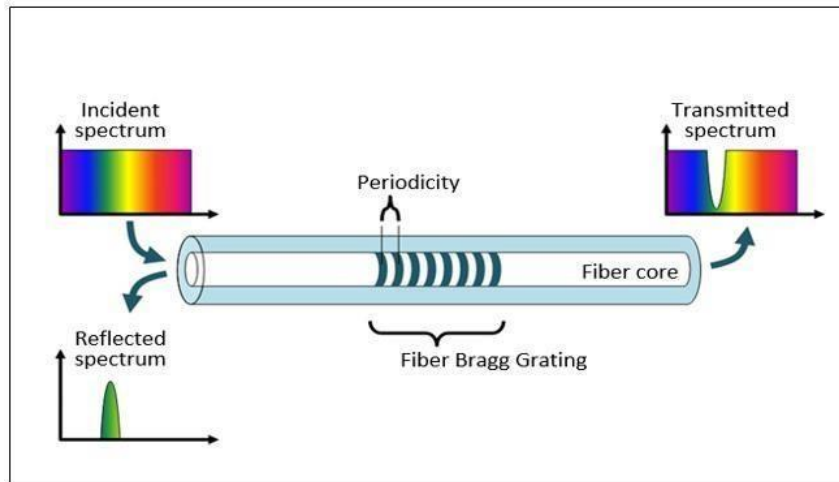


Figure 2. 23: Working principle of FBG [126]

Ideally FBGs are designed to sense external behaviors of mechanical strain, pressure and thermal perturbations [127]. This phenomenon having expansion and compression logics over FBGs sensors. As the strain exerted on FBG sensor, the expansion or compression changes its grating period due to the strain optic effect. Same thermal effect changing FBG thermal expansion coefficient of fiber optic and FBG response as a shift in Bragg wavelength.

iii. Types of Fiber Bragg Grating (FBG) Sensor.

On structure based we have four types of FBG sensors, which are actually the structure of grating. These structures are named below in figure 2.24.

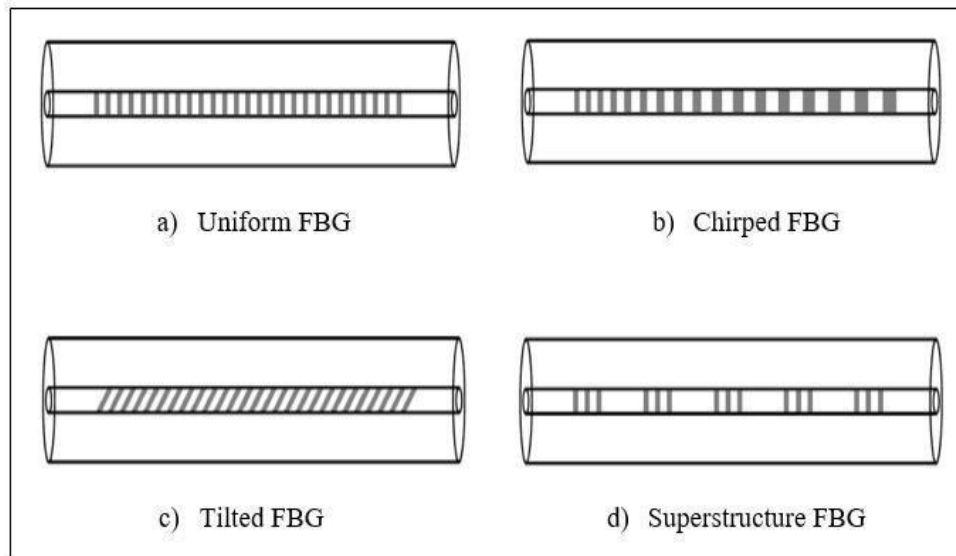


Figure 2. 24: Typical fiber Bragg grating design [127]

In these FBG sensor the structures are varying via refractive index or grating period [128]. There are two fundamental characteristics of refractive index. The offset and refractive index profile which typically approach to positive or zero and uniform or apodized simultaneously. With this concept it leads to six common structures for FBGs.

1. Uniform positive-only index change, 2. Gaussian apodized, 3. Raised-cosine apodized,
4. Chirped 5. Discrete phase shift, and 6. Superstructure

iv. Criteria for selecting sensors

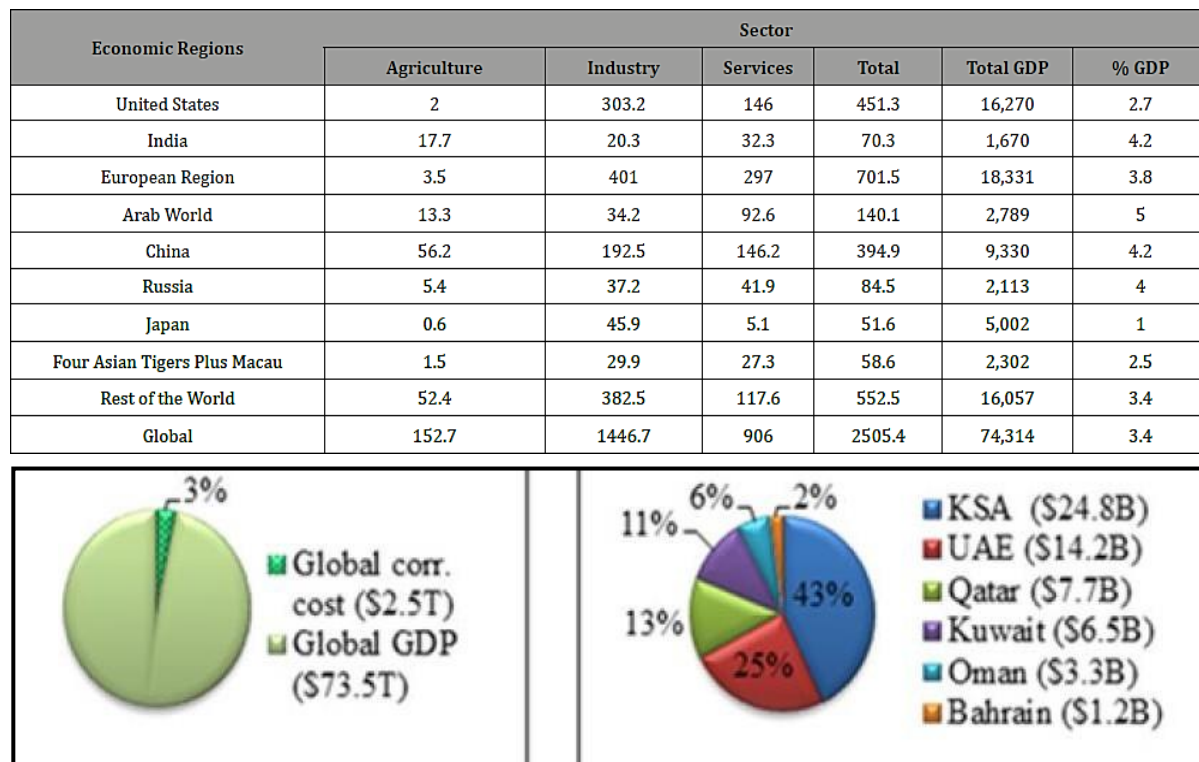
For the selection of FBG sensor according to application requirements, one needs to consider and test its accountability and suitability. Based on application requirements, we have to select an FBG sensor from the mentioned criteria [128] as below.

- I. Non-intrusive design.
- II. The complexity of sensor output data.
- III. Frequency or optical response.
- IV. Ruggedness

2.5 Damages caused in RCC due to corrosion

Corrosion of embedded steel rebar in concrete structures is a worldwide problem. Majority structures are tested and found corroded. Most of the tested structures have billions of dollars need to be spent for their repairs. Table 2.8 shows some tested structure detail for estimates of loss due to corrosion of steel rebar in concrete structures. These damage and economic loss due to corrosion of steel recorded worldwide in different state of different countries.

Figure 2. 25: Damage and economic loss due to corrosion of steel. [129]



Chapter 3

Materials and Experiments

This chapter discusses the basic experimental work that was planned and recommended for corrosion detection of steel rebar through FBG based sensors. The experiments start from civil structure response to normal fiber optic cable, as there is high probability of fiber optic cable being damaged during installation and concrete casting. High sensitivity measurements were taken for optical fiber installation in concrete structures while further observing the experimental output for concrete response against normal fiber optic cable in order to accumulate concrete compression and expansion during curing time. To evaluate these parameters some fundamental experiments are discussed in this chapter. These first few basic experiments paved way for our later successful experiments for corrosion detection in steel rebar's in concrete.

3.1 Fiber optic cable embedding in concrete

In the very early stage of experimental work, our goal was to check the optical fiber behavior inside in the concrete. The challenge was to secure the optical fiber cable attached with the steel rebar inside the concrete during the casting and curing process. The initial dimensions of concrete specimen were taken to be $300 \times 150 \times 50 \text{ mm}^3$, where the quantity of concrete materials was calculated as discussed in the next section.

3.1.1 Steel bar dimensions of sample 0:

The following are the steel rebar dimensions used in the preliminary experiments. Length=300mm, Width =150mm, Height =50mm, Steel bar length= 320mm

3.1.2 Concrete's constituents' parameters

Volume of the specimen = $L \times W \times H$

Volume of the specimen = $300 \times 150 \times 50 = 2250000 \text{ mm}^3 = 2.25 \times 10^{-3} \text{ m}^3$

To find concrete density we need to multiply by 2200 with volume density.

$2.25 \times 10^{-3} \times 2200 = 4.95 \text{ kgs.}$

Multiply concrete density (4.95 kg) with 1.2 as a standard constant. $4.95 \times 1.2 = 5.94$ which is approximately 6 kgs.

So total weight will be counted as 0.5:1:2:3

0.5. Water: 1. Cement: 2. Sand: 3. Aggregate

Cement: $6/6 = 1\text{kgs}$

Sand: 2 kgs

Aggregate: 3 kgs

Water: 500 ml

3.2 Fiber optic continuity for sample#1:

It is very important to check fiber optic cable before casting concrete in the specimen as there are chances that fiber could be damaged during concrete casting or before concrete casting which might create high ambiguities for remaining process. For this specimen we attached one single mode optical fiber cable along the steel rebar with a tape. Then we used a light source to couple the light into the optical fiber and see the continuity of the fiber through the steel rebar. An optical power meter was used at the other end of the fiber to detect the received light signal through the concrete sample. The test was done successfully as shown in the Figure 3.1 (a,b,c). Figure 3.1 shows the rebar with the attached optical fiber cable.

Figure 3.1b shows the light source emitting at 1530 nm being used for this test and Figure 3.1c shows the optical power meter to measure the received power. After this test we are ready to execute next step of integration of steel rebar in frame for concrete casting.

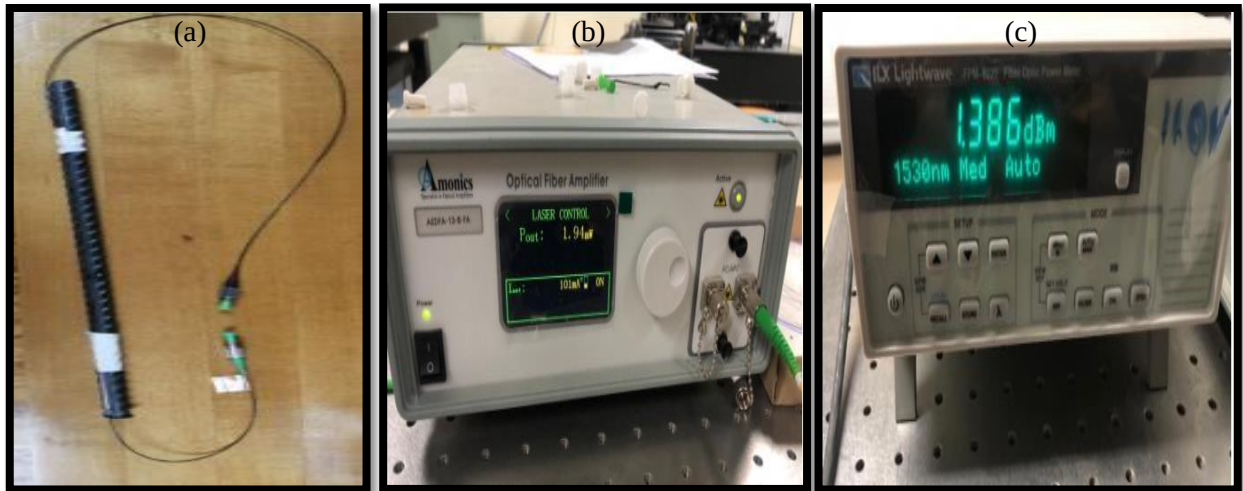


Figure 3. 1: **(a)** Fiber attached with steel rebar **(b)** Light source **(c)** Optical power meter

After casting and curing we found that the fiber optic cable got damaged as it was not transmitting the light from the light source to the optical detector as shown in figure 3.2. It shows that we could not transmit the light from optical fiber which is embedded along the steel bar in the concrete specimen. At this stage we realized that the fiber optic might be damaged during installation or during curing period. The reason for breakage of the fiber optic cable inside the concrete specimen was the splicing point which happened to be inside the specimen. Therefore, we concluded that to avoid the breakage of the fiber inside the specimen, the splicing region of the fiber and the connector should be outside the specimen. Also, during the casting process the concrete mixture should be used in a very gentle manner to avoid optical fiber damaging. To avoid these issues, we planned to analyze this sample before moving to next specimen. In this analysis we identified some of the possible causes of fiber breakage as explained below.

- i. Fiber optic cable was damaged during splicing with connectors.
- ii. Fiber optic cable damaged during fiber installation along steel rebar.
- iii. Fiber optic cable damaged due to steel bar installation in frame.
- iv. Fiber optic cable damaged during concrete casting in frame.
- v. Fiber optic cable damaged during curing period.

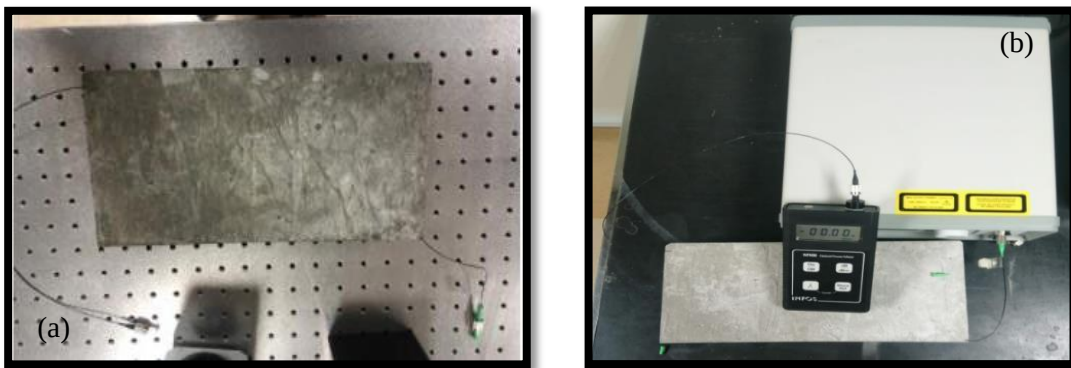


Figure 3. 2: **(a)** Concrete specimen with embedded fiber **(b)** Damaged fiber optic cable during the curing process

After a detailed analysis of the first specimen a proper plan was developed to ensure that the embedded fiber optic cable survives inside the concrete sample.

3.3 Fiber optic continuity test for sample #2:

Based on our experience from test on sample#1 we identified possible reasons for its failure and devised a new strategy for sample #2. Here we are going to apply step by step laser test to ensure fiber continuity in the embedded concrete structures. To proceed with this test we considered a random dimensions of length $L=150\text{mm}$, width $W=50\text{mm}$, height $H=50\text{mm}$, where the length of Steel bar = 190 mm. For these dimensions of specimen concrete items are calculated as below.

Aggregate= 600g, Sand=400g, Cement= 200g, Water =110 ml

To facilitate the testing of the sample#2, we utilized a handheld laser source to check the fiber continuity in the concrete specimen during the live activities randomly at any stage of casting, and curing. Before casting concrete in frame, a fiber optic cable was laid along the steel bar and fixed by epoxy tape. At this stage we checked the continuity of the fiber optic cable by passing the light and checking it at the other side of the fiber optic cable. Next, the steel rebar along with the attached fiber optic cable was placed inside a wooden frame as shown in Fig. 3.3 (a). To control harsh bending of fiber optic cable we covered the steel rebar by soft epoxy tape to avoid sharpness and damaging of fiber optic cable with concrete. Before casting the concrete mixture, the fiber optic cable continuity was again conducted with the handheld laser source. The Helium Neon laser light passed successfully through the fiber optic cable as shown in blue circles of figure 3.3(a). The next step was to cast concrete mixture in the wooden frame as shown in figure 3.3(b). Again, the continuity test was conducted successfully as shown in blue circle of figure 3.3(b). It is important to mention that the vibration of concrete was performed where the fiber still passed the continuity test.



Figure 3. 3: **(a)** Fiber optic test before concrete casting **(b)** Fiber optic test after concrete casting

After casting was completed, the curing process was divided into two stages whereby, during the first stage was kept at room temperature in the laboratory for 24 hours. During the next stage the sample was immersed in a water container to ensure a uniform chemical reaction involving, sand, cement, and gravel. The optical fiber continuity test was conducted between the two stages as shown in Figure 3.4 as well after the completion of the complete curing process as shown in figure 3.5.



Figure 3. 4: Fiber optic test after 24 hours of concrete casting



Figure 3. 5: Fiber optic test after removing the specimen from the frame

3.3 Sensor placement in a concrete sample

In this section we will discuss about the placement of fiber optic-based sensors in concrete samples. By this stage of research, we have mastered the placement technique of fiber optic cable inside the concrete samples. Now the next step is to place the fiber optic-based sensors inside the concrete for corrosion sensing of steel rebar. It will be our first attempt of placing fiber Bragg gratings (FBGs) based optical sensors along the steel rebar inside the concrete specimens. The FBG sensors are very sensitive to the applied pressure which will serve as our sensing parameter. As discussed previously in chapter 2 the most important parameters of the FBG based sensors are its wavelength, bandwidth and reflectivity. The first experiment with the FBG placement in the concrete along the length of the steel rebar was conducted and is explain below. The FBG sensor used for this experiment has a center wavelength of 1545.4532nm, 3 dB bandwidth of 0.196, with a reflectivity in the range 90%<R>89%. This FBG sensor specifications are compatible with the lab equipment like the interrogator and broadband laser light source.

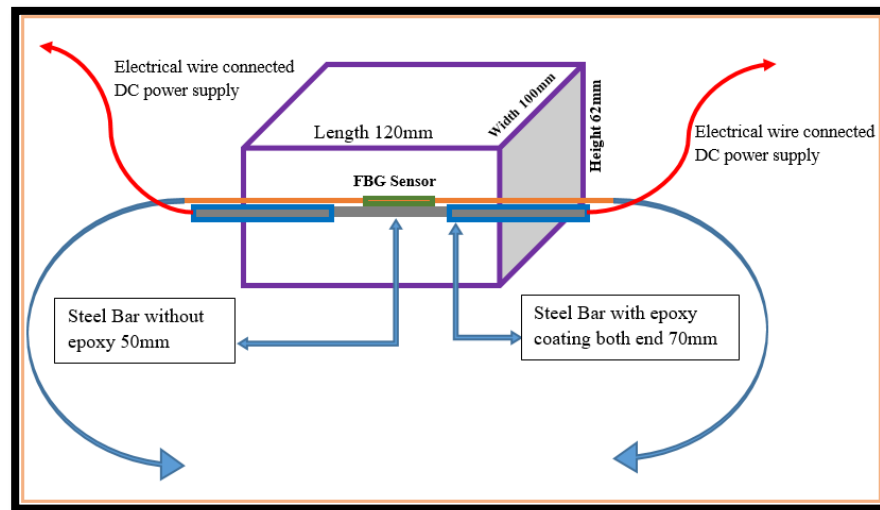


Figure 3. 6: Proposed diagram of FBG integration along embedded steel bar.

Figure 3.6 shows the three major parts i.e., Steel Bar, FBG Sensor and concrete structure to visualize the concrete the specimen. To safely embed the optical fiber sensor inside the specimen the optical fiber and steel rebar should be properly aligned. For this specimen we have the following dimensions (L=120mm, Width=100mm, H=62mm) while the length of steel bar is divided into two parts. i. Epoxy coated. ii. None-coated. The total length of the steel bar is 190mm, where the both ends up to 70mm of the steel rebar are epoxy painted, while the center 50 mm of steel bar is kept non-painted to detect the corrosion by placing the FBG sensor in that region. Embedded steel bar having electrical connectivity of copper wire with DC power source for accelerated corrosion purposes is shown in figure 3.6. Before casting concrete specimen, the FBG sensor was attached over the defined area in the middle of steel bar as shown in figure 3.7.

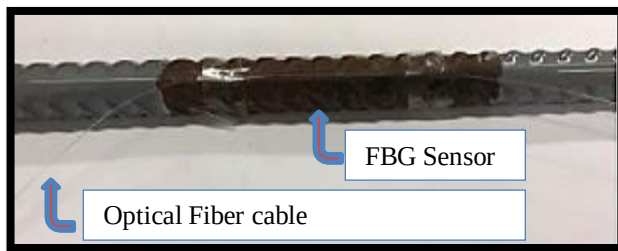


Figure 3. 7: FBG sensor over Steel bar before casting Concrete.

Next the steel rebar with the FBG sensors needs to be placed in the concrete frame as shown in figure 3.8. The frame has the following dimensions. Specimen Length=120mm, Width=100mm, Height=62mm. Steel bar Length = 190mm

The concrete items consist of the following components with their portion in the mixture as stated below:

Cement= 500g, Sand = 500g, Aggregate = 1000g Water = 500 ml



Figure 3. 8: Before casting concrete, embedded Steel bar along FBG sensor.

Electrical copper wire was soldered on left side of the steel rebar for connecting to the counter electrode before setting in the frame. After casting the concrete, the specimen was taken to civil engineering lab for 10 days for curing in order to complete cementation chemical process. After complete curing process and curing period the specimen was shifted to optical fiber lab for further tests for corrosion detection. For this purpose, we have to connect embedded FBG sensor with laser light source and an interrogator at the other end, while the steel rebar has to be connected with DC power supply source. The experimental setup to complete these tests is shown in Fig. 3.9.

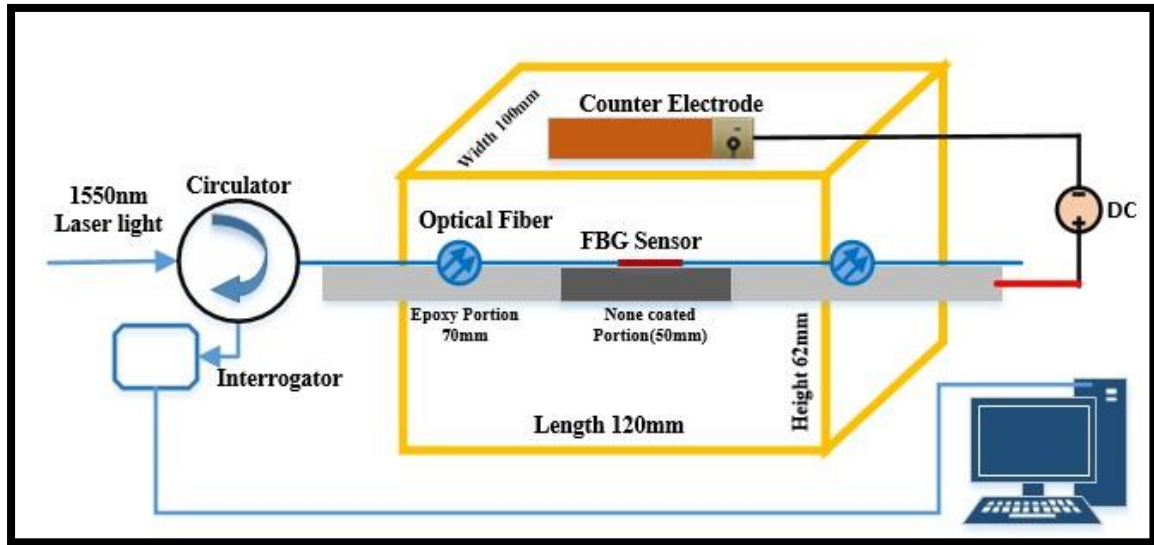


Figure 3. 9: Experimental setup for FBG integration along embedded steel bar.

A DC power source and computer system are connected across optical circulator and IMON interrogator. In this system we are using counter electrode and DC power source for accelerated corrosion. The broadband light source is connected to the port 1 of circulator to pass light signal to the FBG sensor. The FBG sensor attached to the steel bar will detect this corrosion by reflected wavelength through circulator and interrogator using IMON software. Figure 3.10 shows the working experimental setup used in the lab for corrosion detection.



Figure 3. 10: Practical implementation of complete setup.

In order to detect corrosion of embedded steel rebar in concrete structure we need to accelerate corrosion process. Multiple authors have done excellent work for accelerating the corrosion process by using different techniques in reinforcement concrete structures over embedded steel rebar. Electrochemical corrosion acceleration techniques [124] are most effective in order to corrode steel rebar in reinforcement concrete. In this techniques DC current applied on embedded steel to make anodic and cathodic circuitry. A steel plate on concrete surface is called counter electrode and works as a cathode to complete the circuit with embedded steel bar working as an anode. Embedded steel bar in reinforcement concrete is connected with +ve terminal of DC power supply while counter electrode is connected to negative terminal of power supply.

In this experiment we have applied a DC current of 0.1 mA/cm² to accelerate the corrosion process. The total current applied on the steel rebar is calculated based on its exposed surface area of 50 mm where we have attached the FBG sensor.

Exposed length of steel rebar (l_{corr}): 50 mm = 5cm

Diameter of steel rebar: 16mm = 1.6cm

Area of the steel bar: $A_{\text{corr}}: \pi dl/\text{cm}^2 \Rightarrow \pi * 1.6 \times 5 = 25.1328 \text{cm}^2$

Applied current (I): 0.1mA/cm²

Applied current density: $0.1 \times 25.1328 = 2.51 \text{mA}$

Applying 2.51 mA DC current to the specimen will uniformly corrode the embedded steel rebar to make ensure that we detect the corrosion as shown in figure 3.11. At the end of every 12 hours wavelength variation was recorded using the IMON interrogator. Initially the wavelength of the FBG sensor was 1529.8803 nm.

After applying a DC current of 2.5mA the wavelength shifted to 1530.3661nm at the end of 24 hours. Such sudden red shift in wavelength shows concrete compression and pressure on the sensor. We maintained the value of DC current at the same level for the next 20 days for corrosion acceleration. After 21 days (504 hours) a sudden drop in wavelength up to 1530.1943nm was observed which created some ambiguity. Based on previous studies the wavelength shift is directly proportional to the applied pressure. If pressure increases on the FBG sensor the wavelength will red shift. But unfortunately, in our experiment we got uncertainty after 21 days (504 hours). However, the current was kept constant for 72 days (1728 hours) and there was still no observable corrosion on the steel rebar. The entire detail of wavelength shift of 72 days is shown in figure 3.12.



Figure 3. 11: DC current applied on specimen showing counter electrode.

After 72 days (1728 hours) of experimental work we decided to check the electrical connections of the DC power supply with steel rebar and the counter electrode. To our surprise we found that the counter electrode was connected to the opposite polarity of the DC power supply.

Changing of DC polarity create cathodic protection for embedded steel bar while corroding counter electrode as shown in figure 3.13.

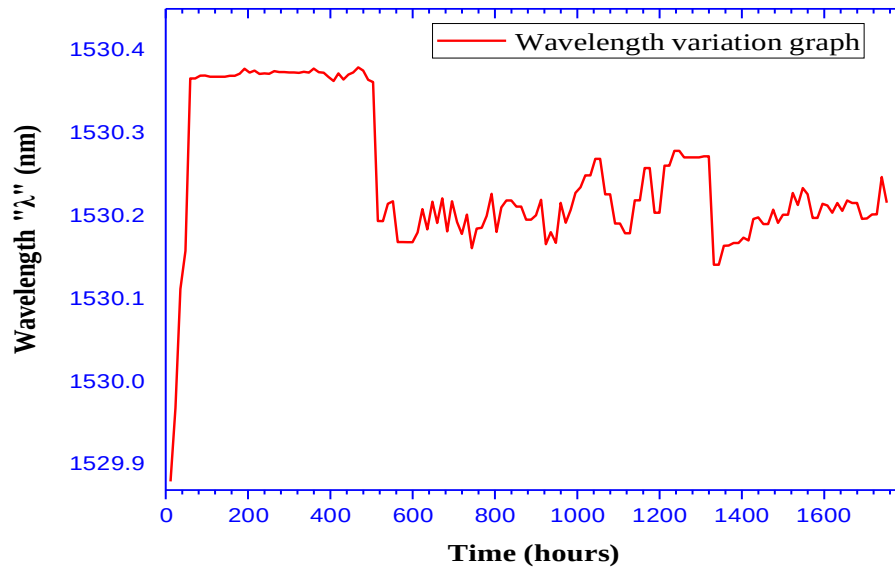


Figure 3. 12: Daily reading of the specimen showing wavelength shift in hours.



Figure 3. 13: Cathodic protection of embedded steel bar result counter electrode corrosion.

The failure of this specimen or experiment gives us a clear direction to maintain the correct polarity of DC current to corrode embedded steel bar only. We decided to consider this specimen as specimen zero and started to build new specimens for corrosion detection experiments as elaborated in the chapter 4.

Chapter 4

Experimental work and results

Introduction

The main focus of this chapter is to use optical sensors (FBG) in concrete structures to determine the entire behavior of corrosion over embedded steel rebar. For this analysis we have casted multiple specimens to determine the exact response of FBG against corrosion in concrete structures.

4.1 Experimental Setup and procedure.

Extensive experiments on multiple specimens were planned and recommended for corrosion detection through FBG sensors. A complete experimental setup for corrosion detection in embedded rebar is illustrated in Fig 4.1. The setup consists of a broadband light source, a circulator, a DC power supply, ampere meter, counter electrode placed on the surface of concrete specimen, and an interrogator connected to a computer.

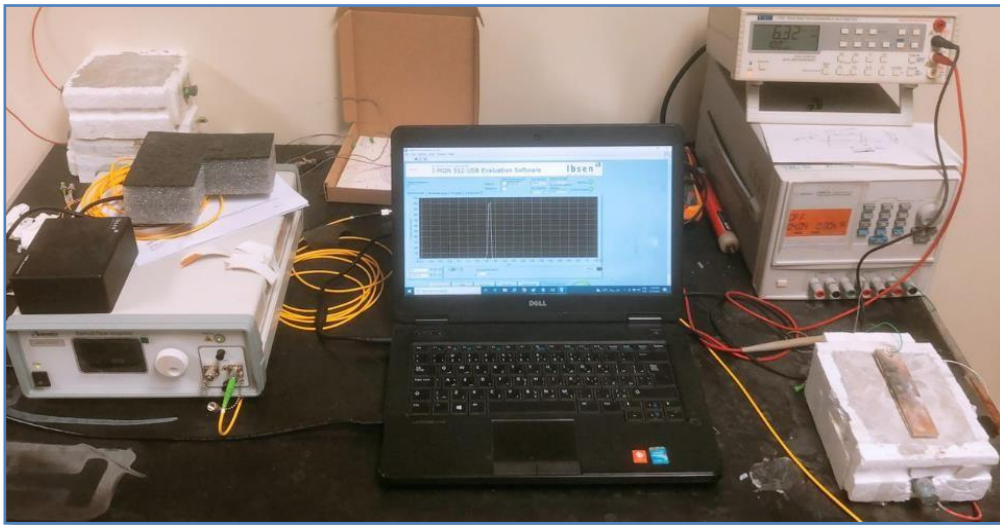


Figure 4. 1: Experimental setup for corrosion detection in steel rebar

To elaborate the working of the experimental setup, we have divided it into optical and electrical connections. The accelerated corrosion is controlled through the electrical connections while the optical connections are used to observe the corrosion through the wavelength shift of the FBG based sensors. The DC power supply provides current for accelerated corrosion as increase in current would accelerate the corrosion rate. The DC ampere meter is used to set the required DC current and continuous monitor the fluctuations. The optical connections are used for observing the response of the embedded FBG with time. A light source is connected to a port 1 (RED) of a three ports circulator. Port 2 (Blue) is connected to the embedded FBG sensor, while port 3 (Green) is connected to the interrogator as shown in figure 4.2.

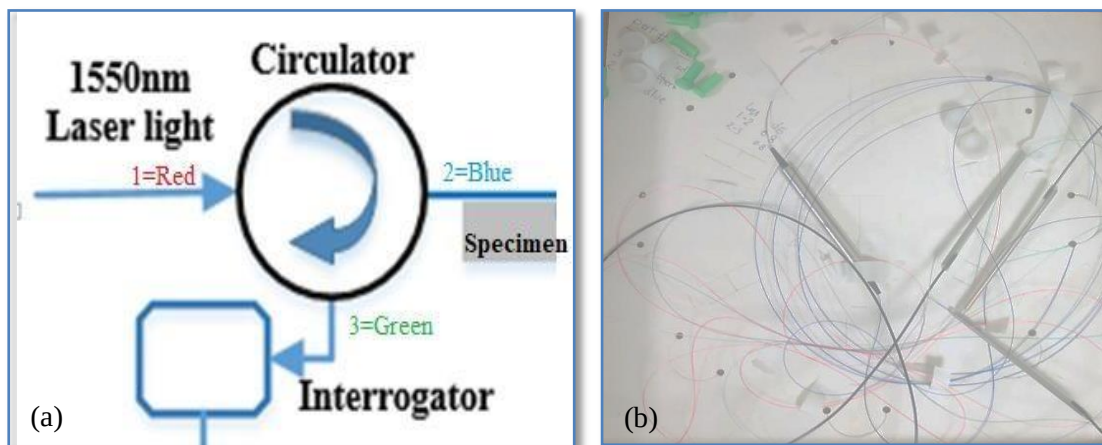


Figure 4. 2: **(a)** Circulator connectivity and sketch **(b)** connections of Circulator during experiments

The light from the broadband source is transmitted to the FBG sensor through port 1 and the reflected light from the FBG sensor connected to port 2 is guided towards the interrogator through port 3 of the circulator.

The computer connected to the interrogator records the wavelength shift continuously. This entire connectivity of experimental configuration is shown in figure 4.3. The most important and sensitive device i.e., I-MON interrogator has two types of ports connectivity.

One port is optical while other one is electrical. Optical port is connected with optical circulator while electrical port is connected to a computer through a USB port.

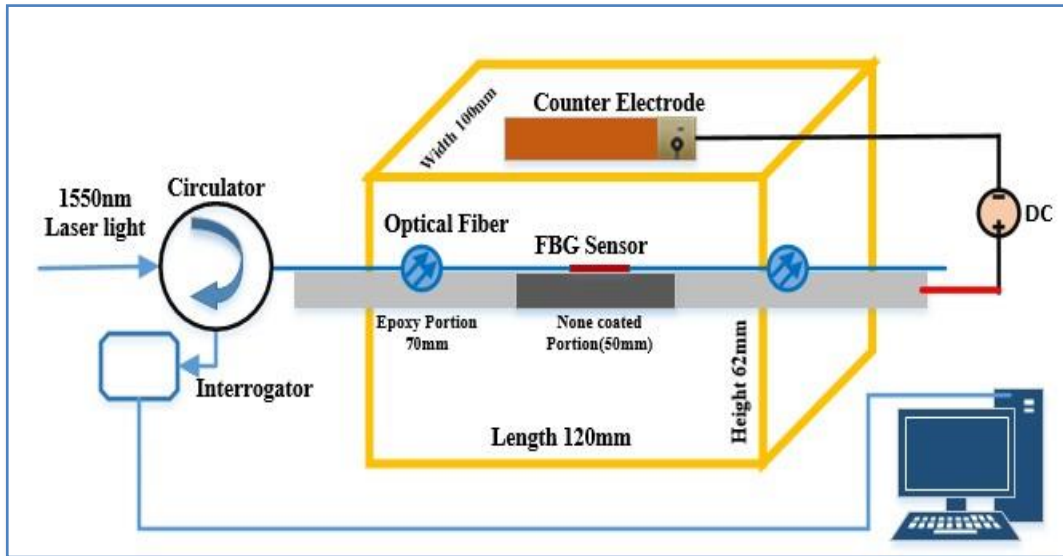


Figure 4. 3: Complete practical setup with circulator, Interrogator and computer system

The broadband light source used in our experiments operate in the C band (1525 -1560 nm) and covers all the available FBGs wavelengths in this range as shown in figure 4.4 (a). I-MON interrogator is a device used to detect reflected wavelength from FBG sensor. FBG sensor reflecting a part of wavelength from designed specimen that is detected via port 3 through I- MON interrogator and displaying with the help of I-MON software through a computer monitor.

The I-MON interrogator has two ports for connectivity. One port is optical while other port is electrical. Optical port connected with optical circulator while electrical port is connected with computer by USB port as shown in Figure 4.4 b and 4.4c.



Figure 4. 4: (a) Optical source

(b): I-MON interrogator

(c): I-MON interrogator Ports

4.2 Experimental Findings of Specimens

In each specimen only one FBG sensor is used to detect corrosion on embedded steel bar over specified area. For a fair comparison, a standard dimension of the specimens was decided except the applied current on non-epoxy area. All these dimensions are already elaborated in figure 4.3. The dimension of each specimen is as follows, L=120mm, Width=100mm, H=62mm, while the total length of steel bar is 190mm. The steel bar was divided in two parts i.e., epoxy coated (70mm) at the outer ends of the steel rebar and the non-coated central part (50mm) of the rebar for corrosion detection. The FBG sensor used has a length of 20mm and was attached to the non-coated portion of the steel rebar for corrosion detection as shown in figure 4.3.

Embedded steel bar in reinforcement concrete is connected to the +ve terminal of DC power supply while counter electrode is connected to negative terminal of power supply. In this experiment we have started to apply 0.20mA/cm² DC current and increase it for each specimen as shown in table 4.1.

The current density applied on the non-epoxy length of the steel rebar is calculated below.

Length of Steel Bar / L_{corr} : 50mm / 5cm

Diameter of Steel Bar: $d = 16\text{mm} / 1.6\text{cm}$

Area of the steel bar: $A_{corr}: \pi dl/\text{cm}^2 \Rightarrow \pi 1.6 \times 5 = 25.1328\text{cm}^2$

I Applied Current: $i_a = 0.2\text{mA}/\text{cm}^2$

Applied Current Density: $0.20 \times 25.1328 = 5.0265\text{mA}$

Applying a 5.0265mA of DC current to the first specimen will uniformly corrode the embedded steel bar.

Table 4. 1: Details of all the specimen test results

Specimen#	Applied current (mA /cm ²)	λ before corrosion (nm)	Bragg " λ " before crack (nm)	Wavelength shift ($\Delta\lambda$) nm	Crack appearance time (hours)
1	$i_1 = 0.20 \text{ (mA /cm}^2\text{)}$	1535.0879	1535.0114	0.0765	252
2	$i_2 = 0.25 \text{ (mA /cm}^2\text{)}$	1540.0099	1540.0836	0.0738	228
3	$i_3 = 0.30 \text{ (mA /cm}^2\text{)}$	1539.7126	1539.7795	0.0668	192
4	$i_4 = 0.35 \text{ (mA /cm}^2\text{)}$	1540.2019	1540.1207	0.0812	168
5	$i_5 = 0.40 \text{ (mA /cm}^2\text{)}$	1540.3642	1540.2120	0.1522	132

4.2.1 Experimental Results of Specimen (0.20mA/cm²)

In this section we are going to elaborate on the experimental findings of the first specimen with the FBG embedded sensor. Here we applied a DC current of 0.20mA/cm². This current travels through counter electrode from the specimen as shown in figure 4.3. The light source producing a 100 mW of optical power is connected to the FBG sensor through the circulator. The original wavelength of the FBG embedded in the first specimen was $\lambda=1535.0879$ nm. At this stage there was no corrosion while continuously applying a DC current to accelerate corrosion. The wavelength shift was recorded after every 12 hours continuously using the I-MON interrogator connected to a PC.

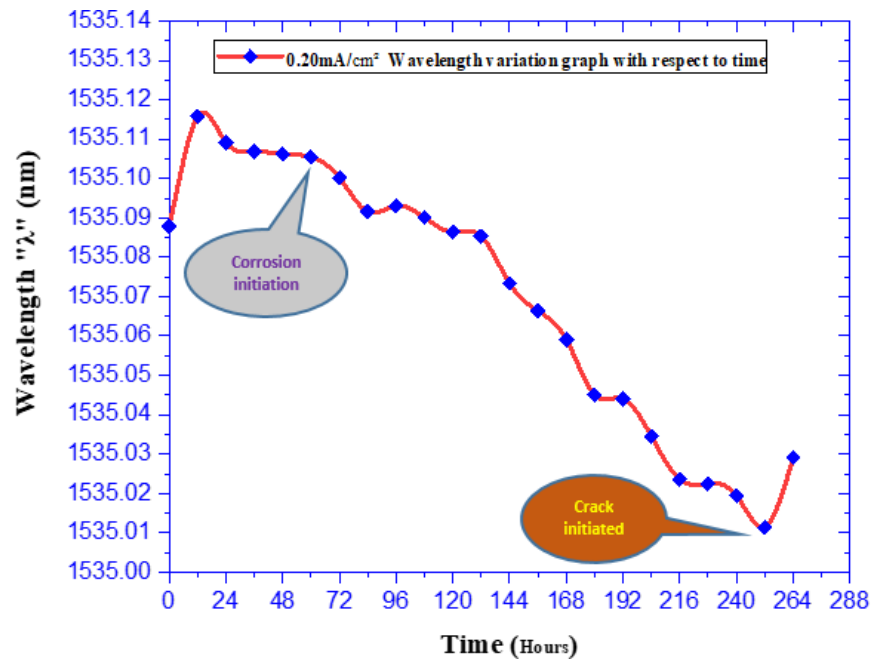


Figure 4. 5: Wavelength variation graph for 0.20mA/cm² specimen

The wavelength shift was continuously recorded as shown in figure 4.5. The first 12 hours were neglected since we believe that current was not uniformly distributed over the non-epoxy region. The corrosion initiated after 72 hours and increased gradually over the embedded steel rebar in concrete specimen. Increasing corrosion rate increased the pressure over FBG sensor. This pressure variation was responded by FBG sensor in form of wavelength shift.

Increasing the pressure over the sensor due to corrosion acceleration blue shifted the wavelength. For the corrosion measurements we are only interested in the wavelength shift of the FBG sensor. The direction of shift is not significant for our analysis. The wavelength is blue shifted with accelerated corrosion in a linear manner as shown in figure 4.5. Finally, after 252 hours of applying DC current for accelerated corrosion, the cracked appeared on the surface of the specimen as shown in figure 4.6.



Figure 4. 6: Crack appearance on 0.20mA/cm² Specimen

The distribution of the crack artifacts over the surface of specimen is very important to understand the relationship between the location of corrosion on the steel rebar and its subsequent effects on the concrete structure.

Therefore, a plot of the crack artifacts is plotted and is shown in figure 4.7 to identify the actual crack location over the surface of concrete structure. The crack initiation can be observed physically as well as it is detected by FBG sensor. As shown in figure 4.5, the crack appeared in the specimen when the recorded wavelength was 1535.0114 nm at 252 hours measured through the I-MON interrogator as shown in figure 4.5 and 4.8.

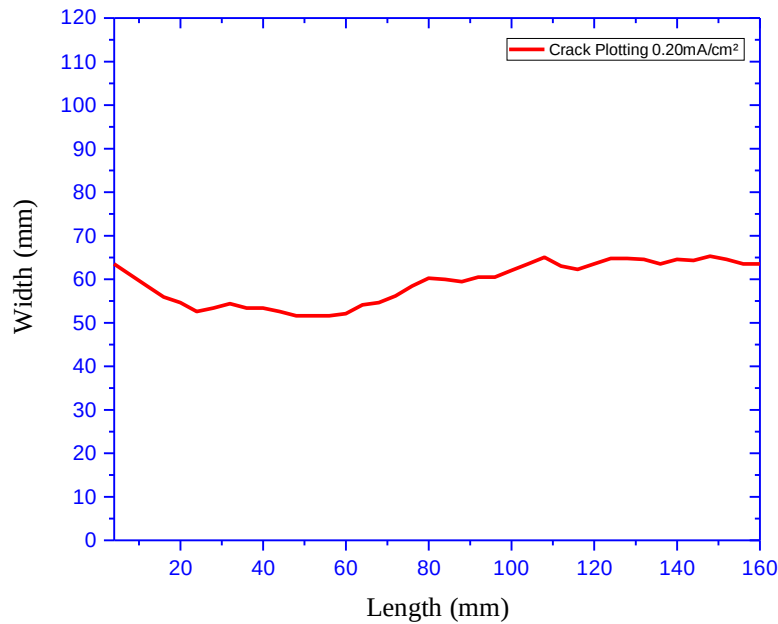


Figure 4. 7: Crack plotting of 0.20mA/cm² specimen

It is important to mention here that the FBG sensor's response will not be uniform after the crack appearance in concrete structure. This is because the pressure inside concrete on the FBG sensor is not uniform, as the pressure is released with the crack appearance. After the appearance of the crack its dimensions will increase with time. The increase in the crack width would reduce the pressure on FBG sensor and the reflected wavelength would return back to its original wavelength. This phenomenon elaborated in figure 4.5 shows the trend of wavelength shift returning towards its initial wavelength starting at 252 hours. With the help of I-MON interrogator the wavelength variation or wavelength shift according to corrosion has been recorded after every 12 hours. Where the first 12 hours are showing some irregularity due to cementation or chemical reaction of cement over the sensor while after the first 12 hours we have recorded a smooth wavelength shift according to corrosion due to continuous supply of DC current.

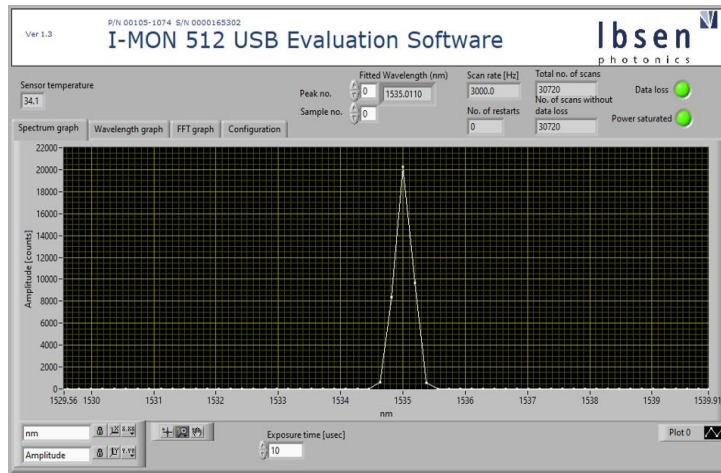


Figure 4. 8: Reflected signal from FBG sensor recorded by the interrogator

In figure 4.9 it is shown that corrosion rate increases with time for a fixed current of 0.20mA/cm². As discussed earlier that there is an irregular variation in the wavelength during the first 12 hours due to chemical process of cementation as well as non-uniform distribution of current through the specimen.

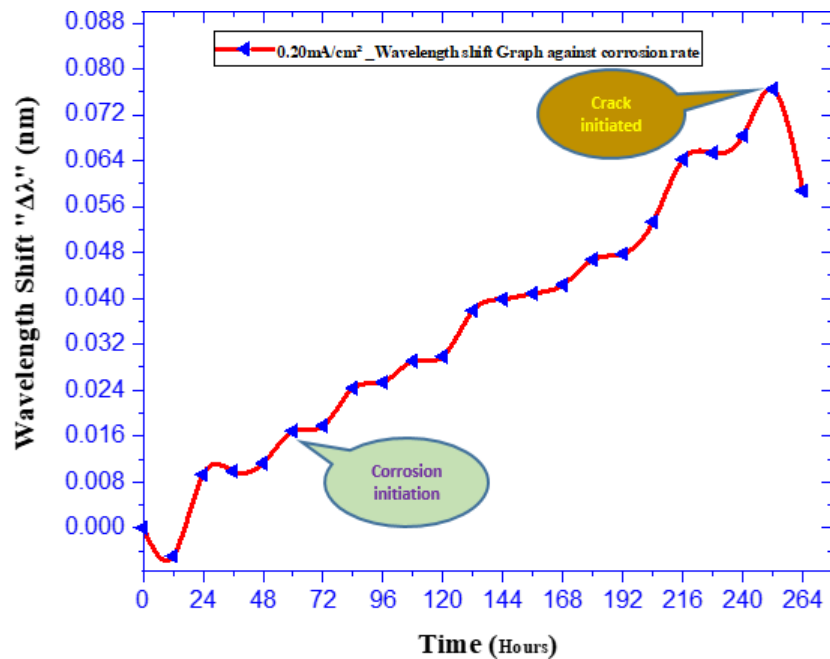


Figure 4. 9: Wavelength shift " $\Delta\lambda$ " graph for 0.20mA/cm² specimen

While after 12 hours it shows almost smooth line till 48 hours. Whereas, after 60 hours the sensor detects corrosion initiation and wavelength shift. As corrosion increased, the wavelength shift ($\Delta\lambda$) towards the longer wavelength side. This wavelength shift is directly proportional to the corrosion rate. The minimum wavelength shift observed at 60 hours was around 0.0175 nm in this specimen showing corrosion initiation while the crack on the surface of the specimen was observed at a maximum wavelength shift of 0.0775nm at 252 hours with a fixed current of 0.2mA/cm².

4.2.2 Experimental Results of Specimen (0.25mA/cm²)

In this section we are going to elaborate on the experimental findings of the second specimen with the FBG embedded sensor. Here we applied a DC current of 0.25mA/cm². This current travels through counter electrode from the specimen as shown in figure 4.3. The light source producing a 100 mW of optical power is connected to the FBG sensor through the circulator. The original wavelength of the FBG embedded in second specimen was $\lambda=1540.0099$ nm. At this stage there was no corrosion while continuously applying a DC current to accelerate corrosion. The wavelength shift was recorded after every 12 hours continuously using the I-MON interrogator connected to a PC.

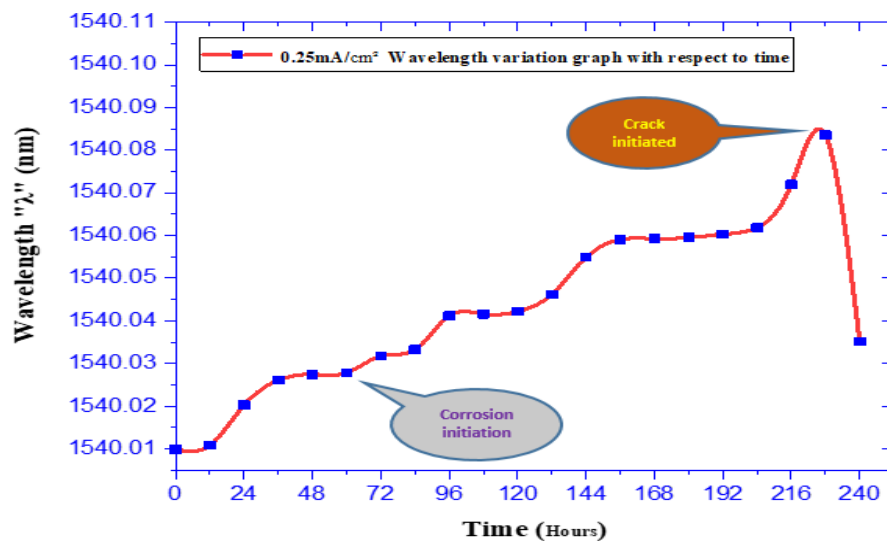


Figure 4. 10: Wavelength variation “ λ ” graph for 0.25mA/cm² Specimen

The wavelength shift was continuously recorded as shown in figure 4.10. The first 12 hours were neglected since we believe that current was not uniformly distributed over the non-epoxy region. The corrosion initiated at 60 hours and increased gradually over the embedded steel rebar in concrete specimen. Increasing corrosion rate increased the pressure over FBG sensor. This pressure variation was responded by FBG sensor in form of wavelength shift. Increasing the pressure over the sensor due to corrosion acceleration red shifted the wavelength. For the corrosion measurements we are only interested in the wavelength shift of the FBG sensor. The direction of shift is not significant for our analysis. The wavelength is red shifted with accelerated corrosion in a linear manner as shown in figure 4.10. Finally, after 228 hours of applying DC current for accelerated corrosion, the cracked appeared on the surface of the specimen as shown in figure 4.11.



Figure 4. 11: Crack appearance of 0.25mA/cm² Specimen

The distribution of the crack artifacts over the surface of specimen is very important to understand the relationship between the location of corrosion on the steel rebar and its subsequent effects on the concrete structure.

Therefore, a plot of the crack artifacts is plotted and is shown in figure 4.12 to identify the actual crack location over the surface of concrete structure. The crack initiation can be observed physically as well as it is detected by FBG sensor. As shown in figure 4.10, the crack appeared in the specimen when the recorded wavelength was 1540.0836nm at 228 hours measured through the I-MON interrogator as shown in figure 4.13.

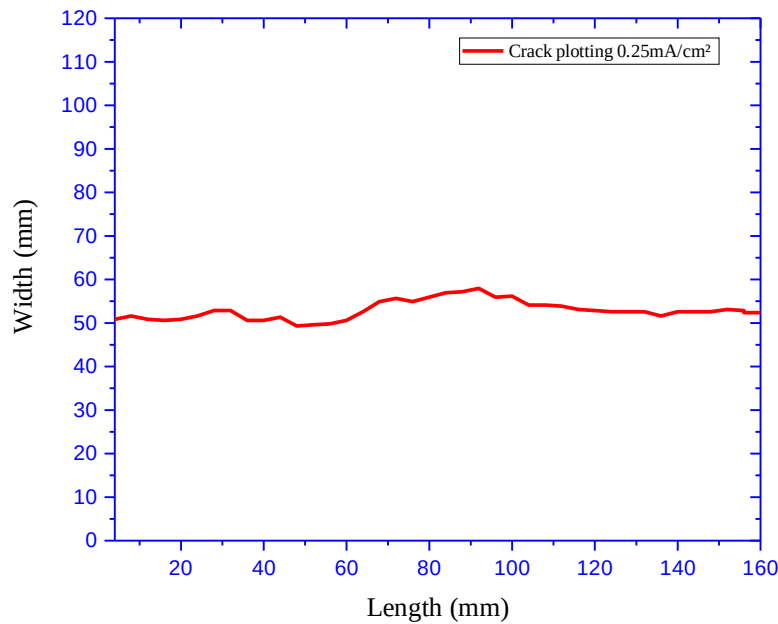


Figure 4. 12: Crack plotting graph of 0.25mA/cm² Specimen

It is important to mention here that the FBG sensor's response will not be uniform after the crack appearance in concrete structure. This is because the pressure inside concrete on the FBG sensor is not uniform, as the pressure is released with the crack appearance. After the appearance of the crack its dimensions will increase with time.

The increase in the crack width would reduce the pressure on FBG sensor and the reflected wavelength would return back to its original wavelength. This phenomenon elaborated in figure 4.10 shows the trend of wavelength shift returning towards its initial wavelength starting at 228 hours.

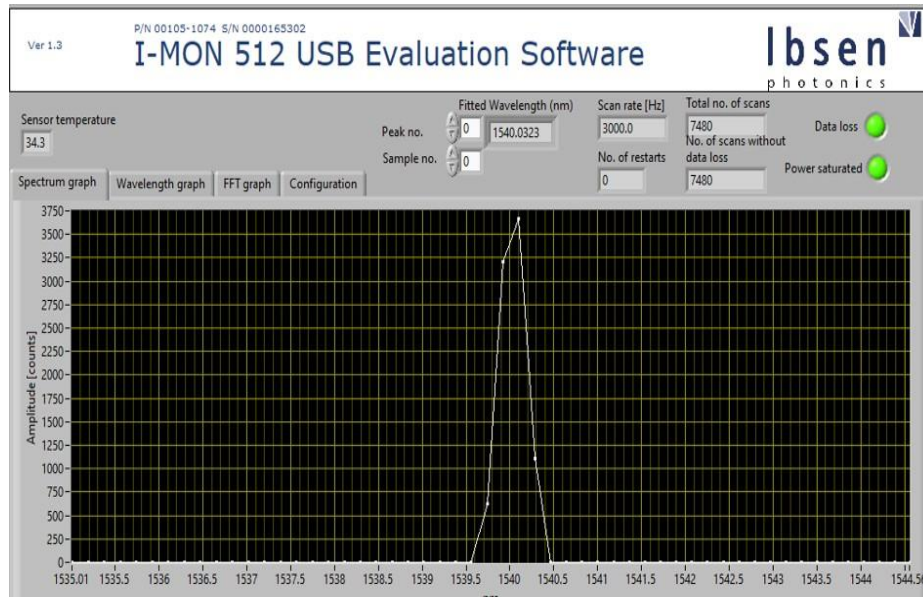


Figure 4. 13: Reflected signal from FBG sensor recorded by the interrogator

With the help of I-MON interrogator the wavelength variation or wavelength shift according to corrosion has been recorded after every 12 hours. Where the first 12 hours are showing some irregularity due to cementation or chemical reaction of cement over the sensor while after the first 12 hours we have recorded a smooth wavelength shift according to corrosion due to continuous supply of DC current $0.25\text{mA}/\text{cm}^2$. In figure 4.14 it is shown that corrosion rate increases with time for a fixed current of $0.25\text{mA}/\text{cm}^2$. As discussed earlier that there is an irregular variation in the wavelength during the first 12 hours due to chemical process of cementation as well as non-uniform distribution of current through the specimen. While after 12 to 36 hours it shows almost a linear trend. Whereas, at 60 hours the sensor detects corrosion initiation and wavelength shift. As corrosion increased, the wavelength shift ($\Delta\lambda$) towards the longer wavelength side.

This wavelength shift is directly proportional to the corrosion rate. The minimum wavelength shift observed at 60 hours was around 0.0179nm in this specimen showing corrosion initiation while the crack on the surface of the specimen was observed at a maximum wavelength shift of 0.0738nm at 228 hours with a fixed current of 0.25mA/cm².

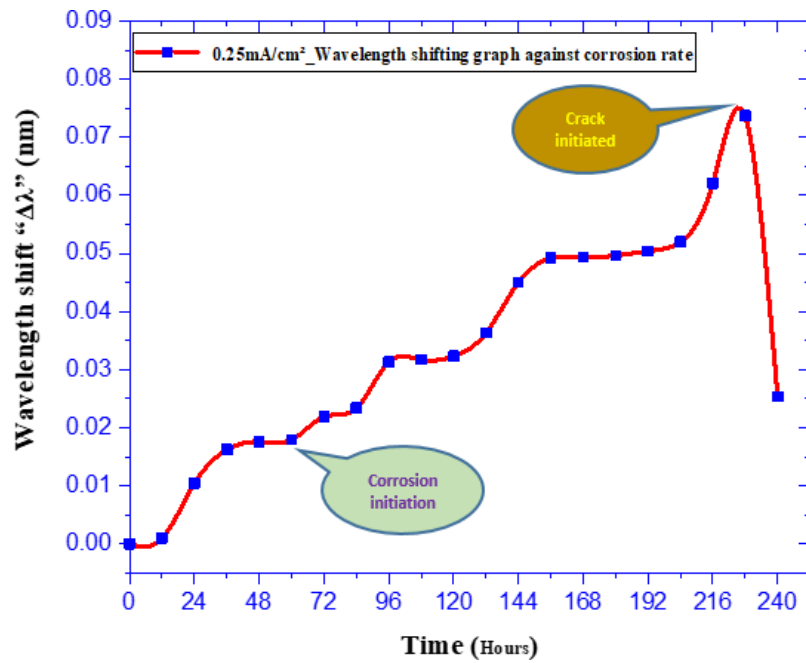


Figure 4. 14: Wavelength shift "Δλ" graph for 0.25mA/cm² Specimen

4.2.3 Experimental Results of Specimen (0.30mA/cm²)

In this section we are going to repeat the same procedure to elaborate the experimental findings of the third specimen with the FBG embedded sensor. Here we applied a DC current of 0.30mA/cm². This current travels through counter electrode from the specimen as shown in figure 4.3. The light source producing a 100 mW of optical power is connected to the FBG sensor through the circulator. The original wavelength of the FBG embedded in this third specimen was $\lambda=1539.7126\text{nm}$. At this stage there was no corrosion while continuously applying a DC current to accelerate corrosion. The wavelength shift was recorded after every 12 hours continuously using the I-MON interrogator connected to a PC.

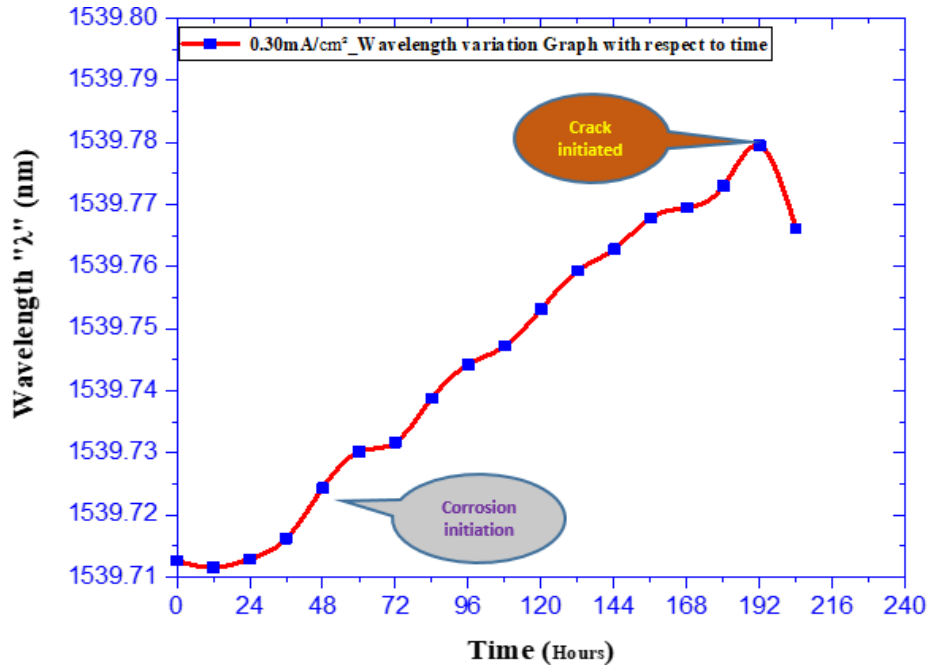


Figure 4. 15: Wavelength variation " λ " graph for 0.30mA/cm² Specimen

The wavelength shift was continuously recorded as shown in figure 4.15. The first 12 hours were neglected since we believe that current was not uniformly distributed over the non-epoxy region.

The corrosion initiated at 48 hours and increased gradually over the embedded steel rebar in concrete specimen. Increasing corrosion rate increased the pressure over FBG sensor. This pressure variation was responded by FBG sensor in form of wavelength shift. Increasing the pressure over the sensor due to corrosion acceleration red shifted the wavelength. For the corrosion measurements we are only interested in the wavelength shift of the FBG sensor. The direction of shift is not significant for our analysis. The wavelength is red shifted with accelerated corrosion in a linear manner as shown in figure 4.15. Finally, after 192 hours of applying DC current for accelerated corrosion, the cracked appeared on the surface of the specimen as shown in figure 4.16.



Figure 4. 16: Crack appearance of 0.30mA/cm² Specimen

The distribution of the crack artifacts over the surface of specimen is very important to understand the relationship between the location of corrosion on the steel rebar and its subsequent effects on the concrete structure.

Therefore, a plot of the crack artifacts is plotted and is shown in figure 4.17 to identify the actual crack location over the surface of concrete structure. The crack initiation can be observed physically as well as it is detected by FBG sensor. As shown in figure 4.15, the crack appeared in the specimen when the recorded wavelength was 1539.7795nm at 192 hours measured through the I-MON interrogator as shown in figure 4.15 and 4.18.

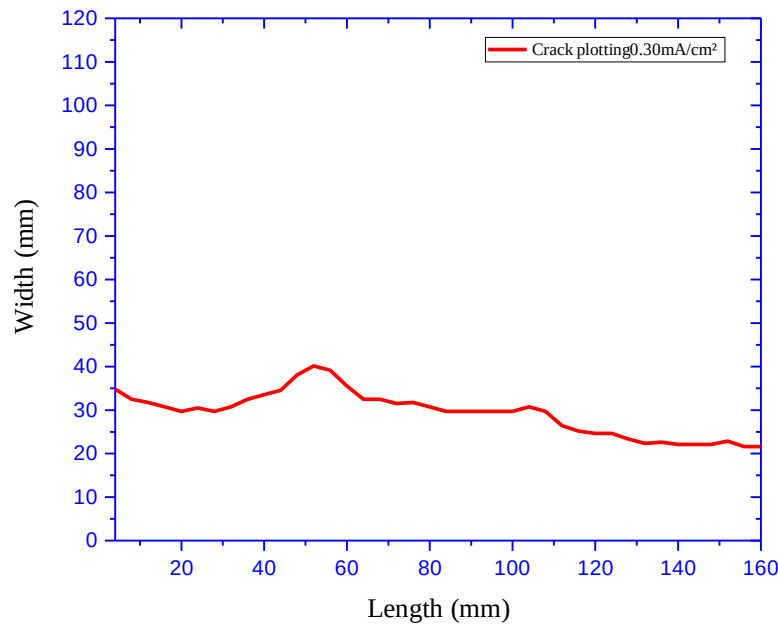


Figure 4. 17: Crack plotting graph of 0.30mA/cm² Specimen

It is important to mention here that the FBG sensor's response will not be uniform after the crack appearance in concrete structure. This is because the pressure inside concrete on the FBG sensor is not uniform, as the pressure is released with the crack appearance. After the appearance of the crack its dimensions will increase with time. The increase in the crack width would reduce the pressure on FBG sensor and the reflected wavelength would return back to its original wavelength.

This phenomenon elaborated in figure 4.15 shows the trend of wavelength shift returning towards its initial wavelength starting at 192 hours. With the help of I-MON interrogator the wavelength variation or wavelength shift according to corrosion has been recorded after every 12 hours. Where the first 12 hours are showing some irregularity due to cementation or chemical reaction of cement over the sensor while after the first 12 hours we have recorded almost a smooth wavelength shift according to corrosion due to continuous supply of DC current. In figure 4.19 it is shown that corrosion rate increases with time for a fixed current of 0.30mA/cm².

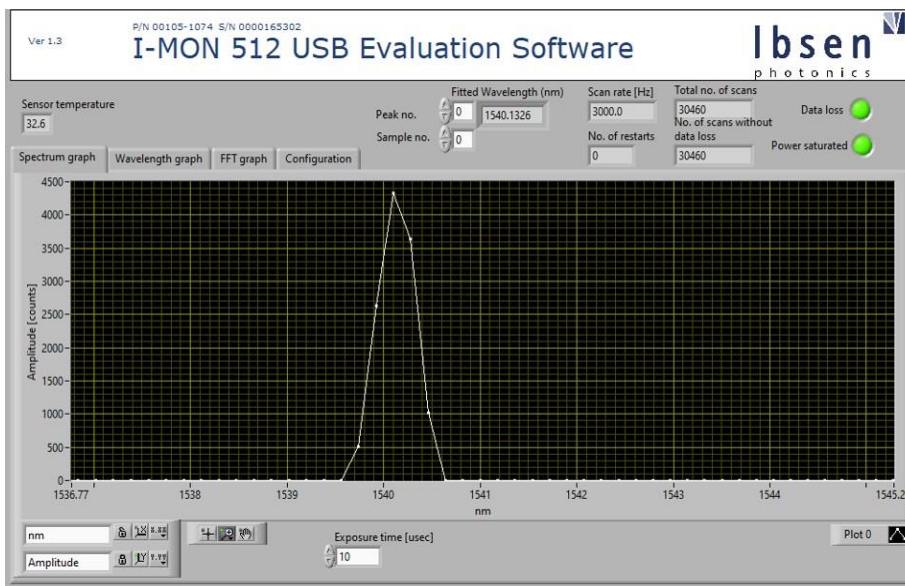


Figure 4. 18: Reflected signal from FBG sensor recorded by the interrogator

As discussed earlier that there is an irregular variation in the wavelength during the first 12 hours due to chemical process of cementation as well as non-uniform distribution of current through the specimen. While after 12 to 36 hours it shows almost a straight line trend of negligible variations in wavelength shift. Whereas, after 48 hours the sensor detects corrosion initiation and wavelength shift. As corrosion increased, the wavelength shift ($\Delta\lambda$) towards the longer wavelength side. This wavelength shift is directly proportional to the corrosion rate.

The minimum wavelength shift observed at 48 hours was around 0.012nm in this specimen showing corrosion initiation while the crack on the surface of the specimen was observed at a maximum wavelength shift of 0.0668nm at 192 hours with a fixed current of 0.30mA/cm².

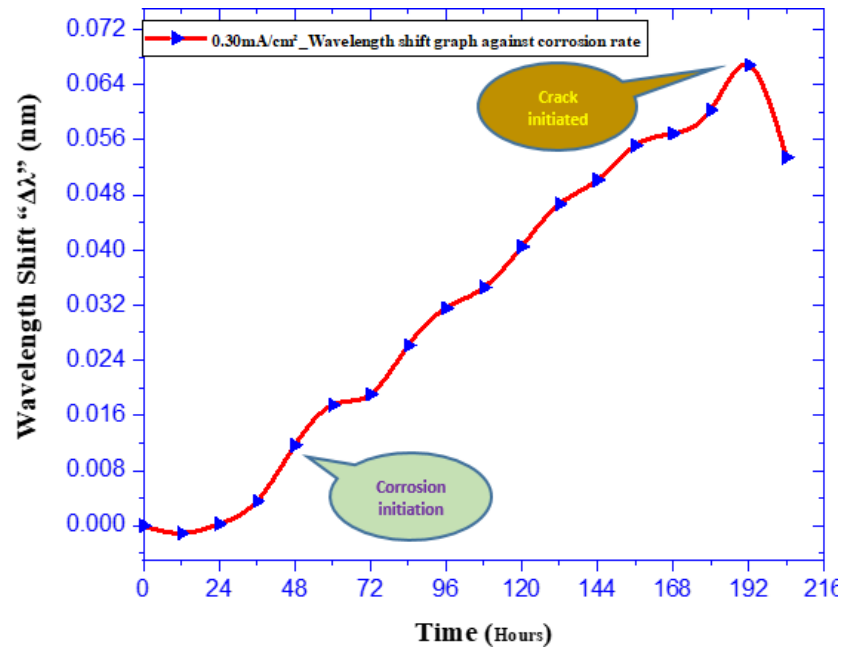


Figure 4. 19: Wavelength shift " $\Delta\lambda$ " graph for 0.30mA/cm² Specimen

4.2.4 Experimental Results of Specimen (0.35mA/cm²)

In this section we are going to repeat the same procedure to elaborate the experimental findings of the 4th specimen with the embedded FBG sensor. Here we applied a DC current of 0.35mA/cm². This current travels through counter electrode from the specimen as shown in figure 4.3. The light source producing a 100 mW of optical power is connected to the FBG sensor through the circulator. The original wavelength of the FBG embedded in this 4th specimen was $\lambda=1540.2019\text{nm}$. At this stage there was no corrosion while continuously applying a DC current to accelerate corrosion. The wavelength shift was recorded after every 12 hours continuously using the I-MON interrogator connected to a PC.

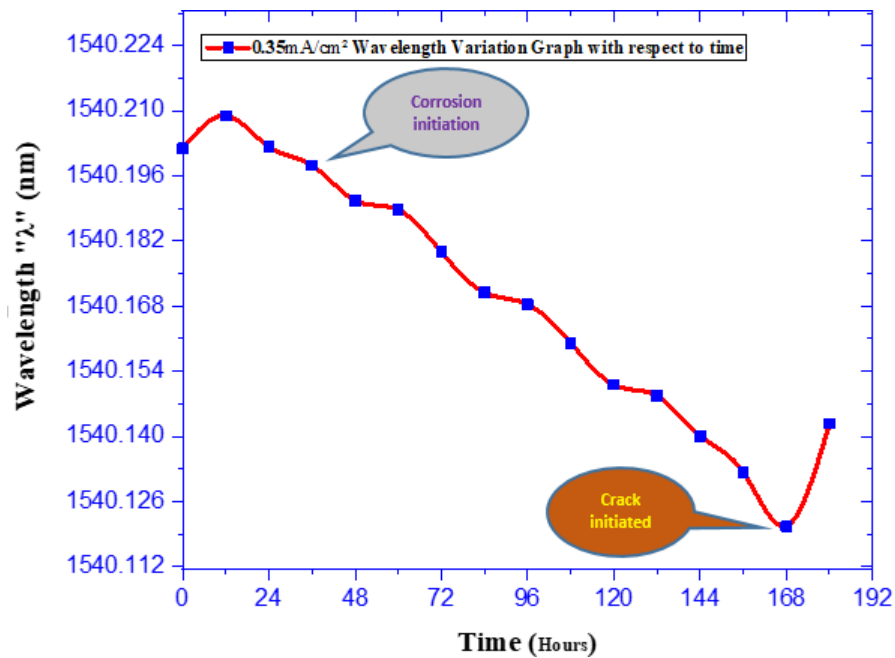


Figure 4. 20: Wavelength variation "λ" graph for 0.35mA/cm² Specimen

The wavelength shift was continuously recorded as shown in figure 4.20. The first 12 hours were neglected since we believe that current was not uniformly distributed over the non-epoxy region. The corrosion initiated at 36 hours and increased gradually over the embedded steel rebar in concrete specimen. Increasing corrosion rate increased the pressure over FBG sensor.

This pressure variation was responded by FBG sensor in form of wavelength shift. Increasing the pressure over the sensor due to corrosion acceleration blue shifted the wavelength. For the corrosion measurements we are only interested in the wavelength shift of the FBG sensor. The direction of shift is not significant for our analysis. The wavelength is red shifted with accelerated corrosion in a linear manner as shown in figure 4.20, which is following a blue shift trend. Finally, after 168 hours of applying DC current for accelerated corrosion, the cracked appeared on the surface of the specimen as shown in figure 4.21.



Figure 4. 21: Crack appearance of 0.35mA/cm² Specimen

The distribution of the crack artifacts over the surface of specimen is very important to understand the relationship between the location of corrosion on the steel rebar and its subsequent effects on the concrete structure. Therefore, a plot of the crack artifacts is plotted and is shown in figure 4.22 to identify the actual crack location over the surface of concrete structure. The crack initiation can be observed physically as well as it is detected by FBG sensor.

As shown in figure 4.20, the crack appeared in the specimen when the recorded wavelength was 1540.1207nm at 168 hours measured through the I-MON interrogator as shown in figure 4.20 and 4.23.

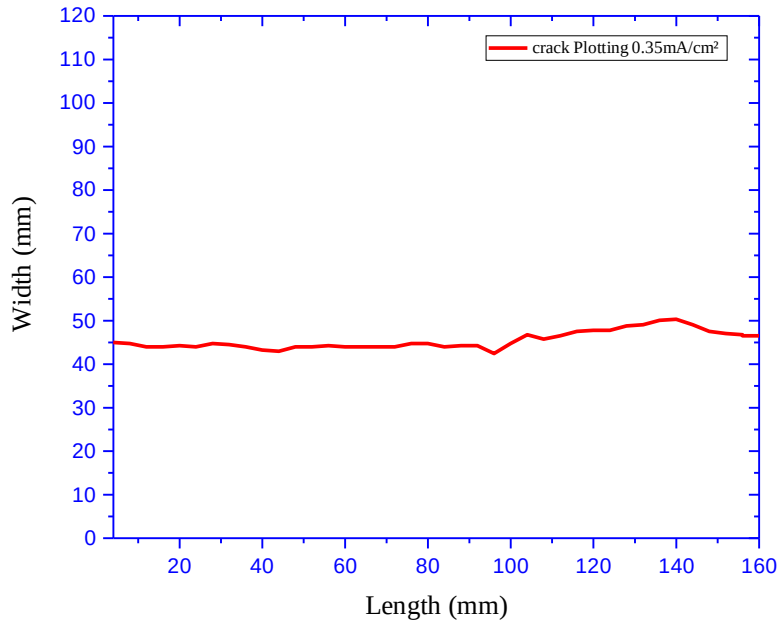


Figure 4. 22: Crack plotting graph of 0.35mA/cm² Specimen

It is important to mention here that the FBG sensor's response will not be uniform after the crack appearance in concrete structure. This is because the pressure inside concrete on the FBG sensor is not uniform, as the pressure is released with the crack appearance. After the appearance of the crack its dimensions will increase with time. The increase in the crack width would reduce the pressure on FBG sensor and the reflected wavelength would return back to its original wavelength. This phenomenon elaborated in figure 4.20 shows the trend of wavelength shift returning towards its initial wavelength starting at 168 hours. With the help of I-MON interrogator the wavelength variation or wavelength shift according to corrosion has been recorded after every 12 hours.

Where the first 12 hours are showing some irregularity due to cementation or chemical reaction of cement over the sensor while after the first 12 hours we have recorded almost a smooth wavelength shift according to corrosion due to continuous supply of DC current. In figure 4.24 it is shown that corrosion rate increases with time for a fixed current of $0.35\text{mA}/\text{cm}^2$.

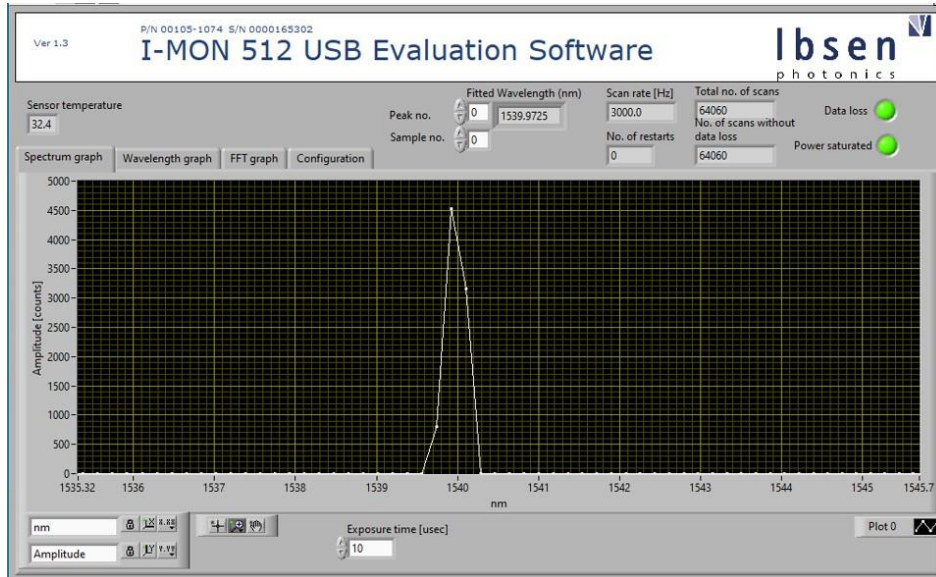


Figure 4. 23: Reflected signal from FBG sensor recorded by the interrogator

As discussed earlier that there is an irregular variation in the wavelength during the first 12 hours due to chemical process of cementation as well as non-uniform distribution of current through the specimen. While after 12 to 24 hours it shows almost a straight line trend of negligible variations in wavelength shift. Whereas, after 36 hours the sensor detects corrosion initiation and wavelength shift. As corrosion increased, the wavelength shift ($\Delta\lambda$) towards the longer wavelength side. This wavelength shift is directly proportional to the corrosion rate.

The minimum wavelength shift observed at 36 hours was around (0.0106nm) in this specimen showing corrosion initiation while the crack on the surface of the specimen was observed at a maximum wavelength shift of (0.0812nm) at 168 hours with a fixed current of 0.35mA/cm².

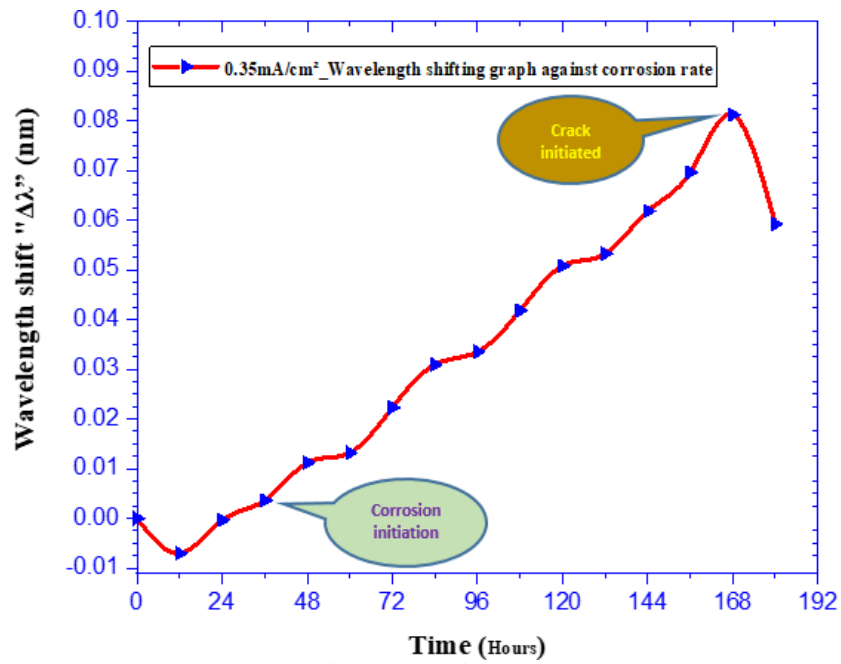


Figure 4. 24: Wavelength shift "Δλ" graph for 0.35mA/cm² Specimen

4.2.5 Experimental Results of Specimen (0.40mA/cm²)

This is the last specimen and here we are going to elaborate the experimental findings of the 5th specimen with the embedded FBG sensor. Here we applied a DC current of 0.40mA/cm². This current travels through counter electrode from the specimen as shown in figure 4.3. The light source producing a 100 mW of optical power is connected to the FBG sensor through the circulator. The original wavelength of the FBG embedded in this specimen was $\lambda=1540.3642\text{nm}$. At this stage there was no corrosion while continuously applying a DC current to accelerate corrosion. The wavelength shift was recorded after every 12 hours continuously using the I-MONinterrogator connected to a PC.

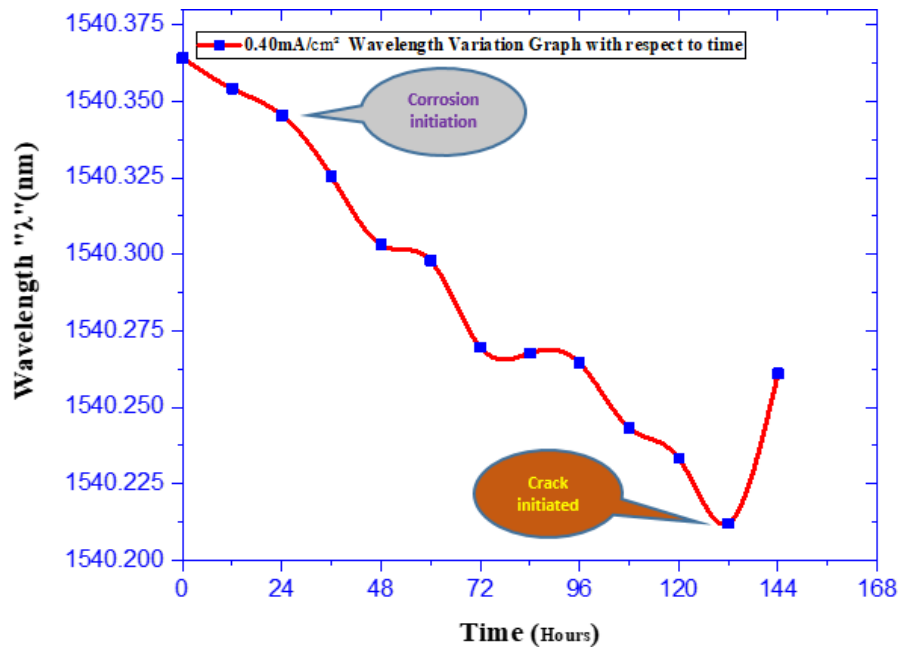


Figure 4. 25: Wavelength variation “λ” graph for 0.40mA/cm² Specimen

The wavelength shift was continuously recoded as shown in figure 4.25. In previous sections the first 12 hours were neglected since we believe that current was not uniformly distributed over the non-epoxy region. This time the case is quite different as the value of the current is comparatively higher than other, which distributed uniformly over the non-epoxy region and specimen.

The corrosion initiated at 24 hours and increased gradually over the embedded steel rebar in concrete specimen. Increasing corrosion rate increased the pressure over FBG sensor. This pressure variation was responded by FBG sensor in form of wavelength shift. Increasing the pressure over the sensor due to corrosion acceleration blue shifted the wavelength. For the corrosion measurements we are only interested in the wavelength shift of the FBG sensor. The direction of shift is not significant for our analysis. The wavelength is blue shifted with accelerated corrosion in a linear manner as shown in figure 4.25, which is following a blue shift trend. Finally, after 132 hours of applying DC current for accelerated corrosion, the cracked appeared on the surface of the specimen as shown in figure 4.26.



Figure 4. 26: Crack appearance of 0.40mA/cm² Specimen

The distribution of the crack artifacts over the surface of specimen is very important to understand the relationship between the location of corrosion on the steel rebar and its subsequent effects on the concrete structure. Therefore, a plot of the crack artifacts is plotted and is shown in figure 4.27 to identify the actual crack location over the surface of concrete structure.

The crack initiation can be observed physically as well as it is detected by FBG sensor. As shown in figure 4.25, the crack appeared in the specimen when the recorded wavelength was 1540.2120nm at 132 hours measured through the I-MON interrogator as shown in figure 4.25 and 4.28.

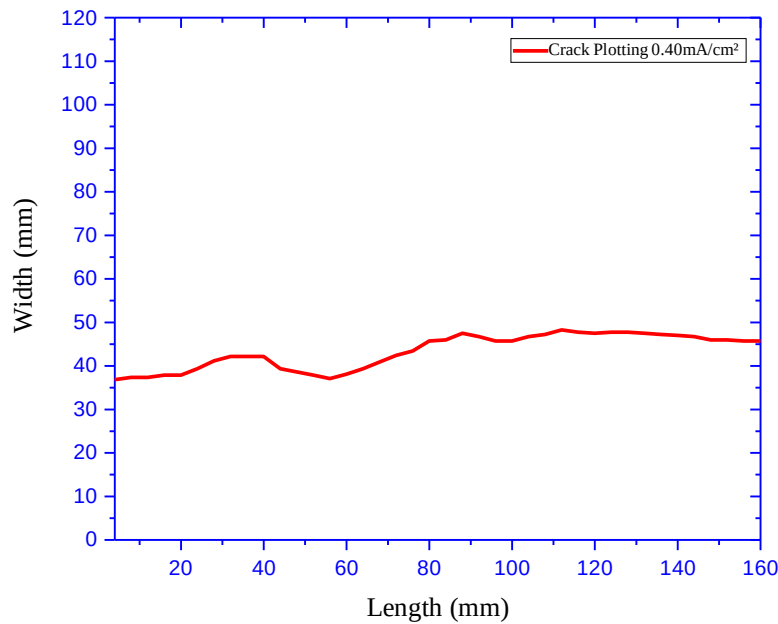


Figure 4. 27: Crack plotting graph of 0.40mA/cm² Specimen

It is important to mention here that the FBG sensor's response will not be uniform after the crack appearance in concrete structure. This is because the pressure inside concrete on the FBG sensor is not uniform, as the pressure is released with the crack appearance. After the appearance of the crack its dimensions will increase with time. The increase in the crack width would reduce the pressure on FBG sensor and the reflected wavelength would return back to its original wavelength. This phenomenon elaborated in figure 4.25 shows the trend of wavelength shift returning towards its initial wavelength starting at 132 hours.

With the help of I-MON interrogator the wavelength variation or wavelength shift according to corrosion has been recorded after every 12 hours. Where every 12 hours we have recorded almost a smooth wavelength shift according to corrosion due to continuous supply of DC current $0.40\text{mA}/\text{cm}^2$. In figure 4.29 it is shown that corrosion rate increases with time for a fixed current of $0.40\text{mA}/\text{cm}^2$.

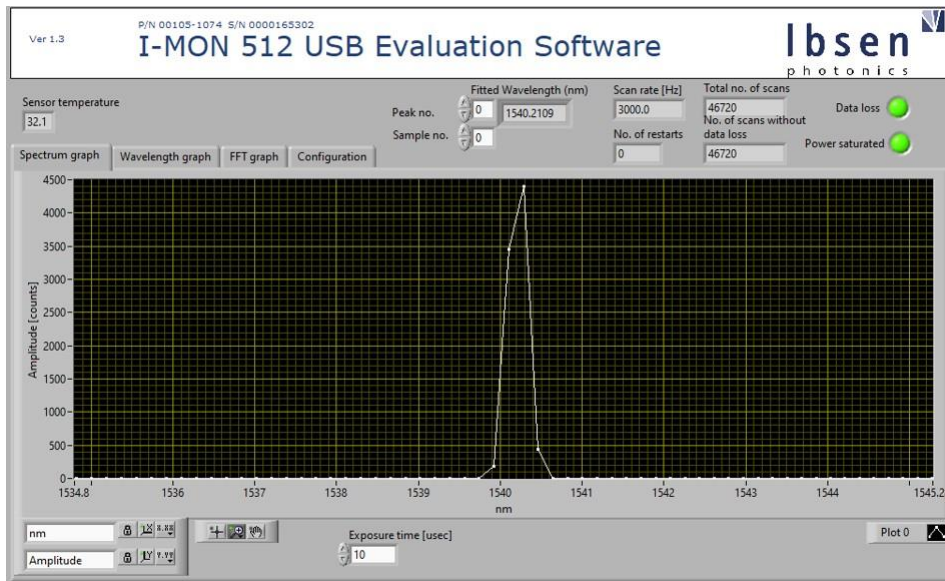


Figure 4. 28: Reflected signal from FBG sensor recorded by the interrogator

With the help of I-MON interrogator the wavelength variation or wavelength shift according to corrosion has been recorded after every 12 hours. Where the first 12 hours in previous specimens were showing some irregularity due to cementation or chemical reaction of cement over the sensor while after the first 12 hours we have recorded a smooth wavelength shift according to corrosion due to continuous supply of DC current. However in this experiment the first 12 hours have very good response and according to FBG sensor, where we observed that higher value of current distributed uniformly over the entire surface before 12 hours.

Therefore the FBG sensor response as normal trend form earlier hours. In figure 4.29 it is shown that corrosion rate increases with time for a fixed current of $0.40\text{mA}/\text{cm}^2$. After 24 hours the sensor detects corrosion initiation and the wavelength shift. As corrosion increased, the wavelength shift ($\Delta\lambda$) towards the longer wavelength side.

This wavelength shift is directly proportional to the corrosion rate. The minimum wavelength shift observed at 24 hours was around (0.018nm) in this specimen showing corrosion initiation while the crack on the surface of the specimen was observed at a maximum wavelength shift of(0.152nm) at 132 hours with a fixed current of $0.40\text{mA}/\text{cm}^2$.

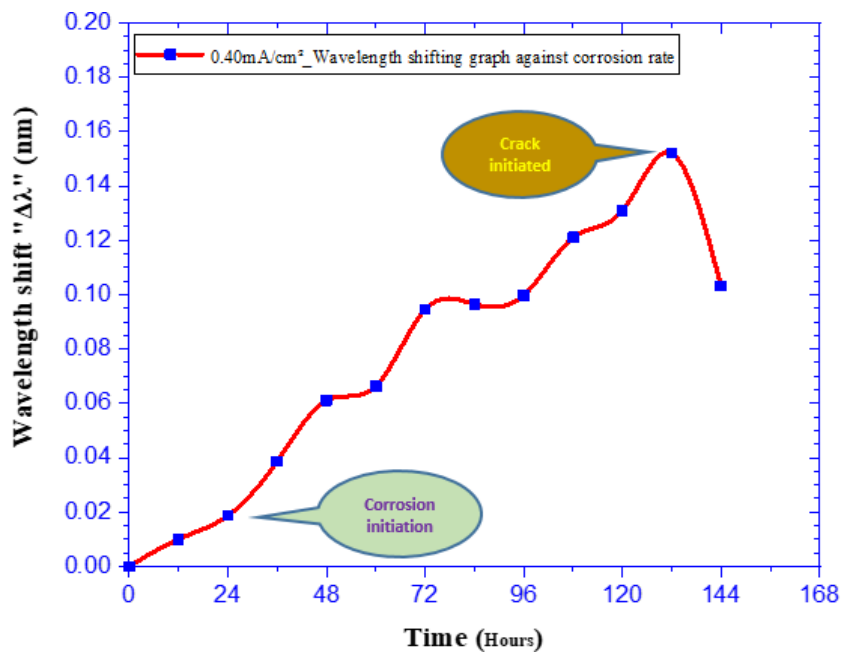


Figure 4. 29: Wavelength shift " $\Delta\lambda$ " graph for $0.40\text{mA}/\text{cm}^2$ Specimen

4.3 Results and discussions.

The summary of the five different concrete specimens tested with the FBG sensors is illustrated in table 4.1. The applied current (i_n) over a specified length of steel rebar of 50 mm varies according to the accelerated corrosion rate requirements. The embedded FBG sensors respond according to the corrosion rate. This experimental work showed corrosion rate according to accelerated current for the five tested specimens. Low current density leads to a slow corrosion rate resulting in longer time period to corrode the embedded steel rebar. Similarly, higher current density leads to faster corrosion rate with shorter time period to corrode the embedded steel rebar as evident from table 4.1. We started with the applied current density of “ $i_1 = 0.20 \text{ (mA /cm}^2\text{)}$ ” for corrosion acceleration. At this current density it took 252 hours to observe a crack on the surface of the specimen. We increased the current density by (0.05 mA/cm^2) for all the remaining specimens. The last specimen took 132 hours to observe the crack on the surface of the specimen at a current density of ($i_5 = 0.4 \text{ mA /cm}^2$) to accelerate the corrosion rate.

4.3.1 Weight loss or gravimetric test.

Using FBG sensor for corrosion detection has excellent response with corrosion initiations and corrosion rate until concrete structures or concrete cover cracks. In light of experimental findings, we are now able to explain the corrosion rate from the weight loss or gravimetric test. Therefore, next, we conducted the weight loss or gravimetric test as discussed below. Five different specimens are tested with different corrosion rates to evaluate weight loss due to corrosion over embedded steel bars in concrete structures. The steps performed to undertake the weight loss tests are shown in figure 4.30 (a), 4.30 (b) and 4.30(c). In figure 4.30 (a) concrete specimen had broken over the crack by a hydraulic force machine to separate steel bars from concrete.

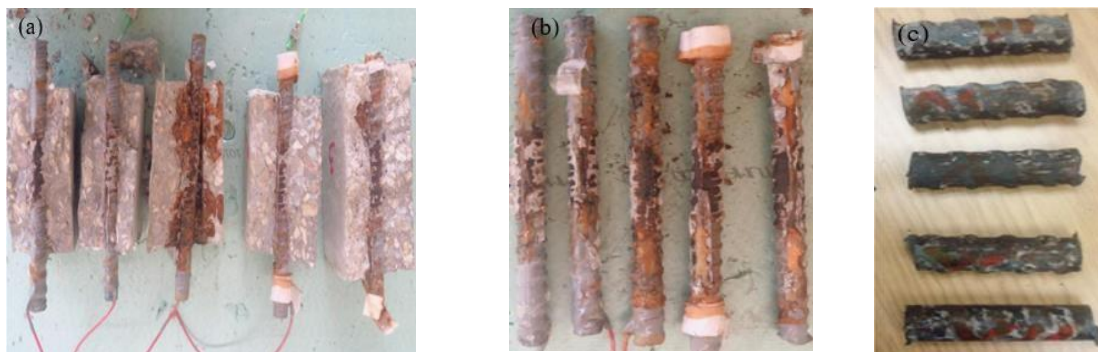


Figure 4. 30: **(a)** Extracting steel bar from concrete **(b)**: Steel bars **(c)**: Steel bars corroded part

Figure 4.30 (b) shows that the steel rebar are safely separated from concrete. Next the rebar's are cut with a grinder from the middle section (corroded section) which was 50 mm in length as shown in figure 4.30 (c). As seen in figure 4.30 (c), corroded parts of each specimen are not uniform in length, therefore we used a lathe machine to precisely cut the middle portion of the rebar's which are 50 mm long for accurate weight loss analysis.

After cutting in equal sizes, all the specimens are properly cleaned step by step to perform the weight loss. The steps required for cleaning process are shown in figure 4.31. To remove corrosion footprints from the corroded steel bars we utilized a procedure provided in ref [134]. A standard technique is used to make a solution of 250 ml HCL, 5 gram antimony trioxide and 12.5 gram stannous chloride and mixed it in a glass beaker. All these corroded steel rebar's are put in this solution for few minutes and washed again with pure water to remove corrosion footprints using a steel brush. This procedure followed repeatedly till cleaning up the steel rebar's perfectly. After removing these corrosion particles, all specimens are reweighted by digital weighting machine having high accuracy. It is very important that we have to weight these specimens before corrosion or we should have a reference rebar made of same material to compare the weight before corrosion and after corrosion.

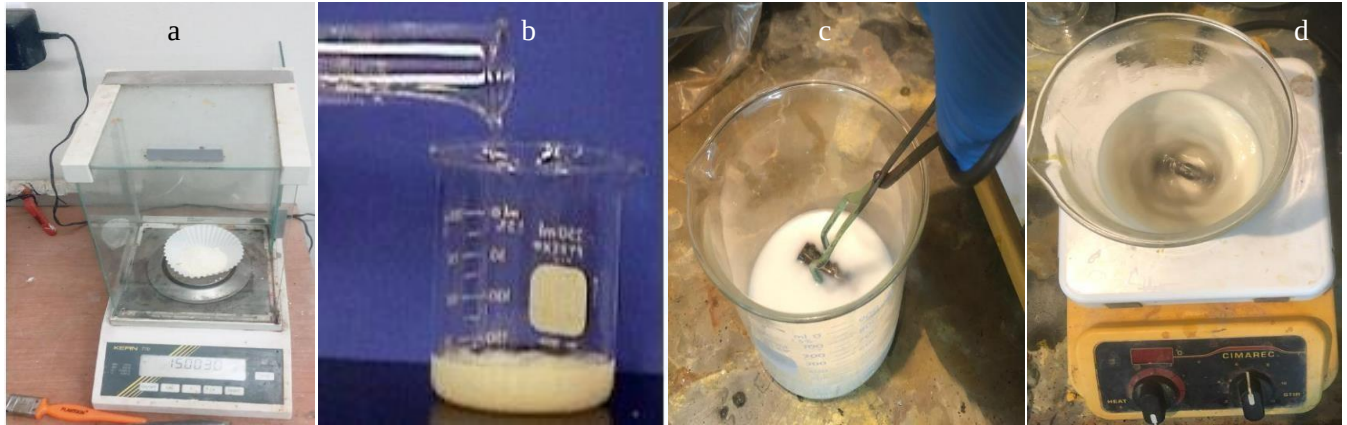


Figure 4. 31: Corrosion cleaning process. **(a)** Taking weight, **(b)** taking (HCL), **(c)** Mixed solution and **(d)** cleaning process of each specimen

After the cleaning process, all specimens along with non-corroded rebar's are shown in figure 4.32(a) as well as these specimen weight measurements are shown in figure 4.32(b).



Figure 4. 32: **(a)** all specimen after cleaning and **(b)** Weight measurement after corrosion cleaning.

After cleaning of steel rebar's we observed that those steel rebar's were subjected to low values of DC currents took longer duration to corrode. Due to longer duration of exposure to DC current heavier corrosion byproducts were measured during the weight loss test performed on the steel rebar specimens.

Similarly, those specimens that were subjected to high current density took a shorter duration i.e., faster corrosion rate resulted in lighter corrosion byproducts (corrosion particles removed from the rebar's). In weight loss test we have different measurement techniques to find the corrosion rate CR, whereas using a standard established techniques [130] where the corrosion rate in terms of weight loss is mentioned in equation 4.1.

$$CR = W_0 - \frac{W_1}{A} \times T$$

$$CR = kW/DAT \quad (4.1)$$

$$\text{Corrosion Rate (CR)} = \frac{\text{Weight loss (g)} * K}{\text{Alloy Density (g/cm}^3) * \text{Exposed Area (A)} * \text{Exposure Time (hr)}}$$

The weight of the specimen or coupon is **W₀** is before corrosion whether **W₁** is indicating the weight of specimen / coupon after its corroded. In this equation 4.1 “**A**” in square meter (m²) showing the area of the specimen or coupon and **T** is time (in hours) of those which used to corrode the steel bar and **D** is density in g/cm³ The units for corrosion rate **CR** is g/ m²h [131- 132]. The **k** is constant value of 8.75x10⁴ which can be varied according to different units. By applying equation 4.1 to find corrosion rate the coupon or steel rebar is weighed before corrosion process and then reweighed after being left to corrode for a specific time. This is the easiest way to find or calculate corrosion rate, however weight-loss techniques are limited for uniform corrosion detection only. As it is difficult to determine without physical or visual inspection and using other characterization method or techniques which exist in the nature for the corrosion detection. On the other hand this method is not providing real time of environmental corrosive factors for particular time period. To test different samples of steel rebar's having same material properties we can use above procedures and equation 4.1.

The simplest way to analyze corrosion rate by the weight loss method that is used in our study is to weight sample or coupon of metal before corrosion and reweight after removing corrosion i.e., reducing the weight of steel rebar /sample. This weight loss can be easily converted into corrosion rate. To calculate corrosion rate, we have used equation 4.2 as mentioned below.

$$J_r = (W/F) \quad (4.2)$$

“F” = A x (corrosion time)

$$A = d l \pi$$

“ J_r ” is instantaneous corrosion rate in (g/cm²/year).

“W” is weight loss in grams.

“F” represents product of surface area and time of corrosion.

Using equation 4.2 on each specimen to calculate J_r excluding I_{corr} in initial stages with respect to time and surface area as calculated in table 4.2. The most important point to calculate “ J_r ” is that it should be taken per year in calculations.

Table 4. 2: Weight loss and Instantaneous corrosion rate for all specimen

Specimen#	Weight Before corrosion (g)	Weight After corrosion (g)	Weight loss (g)	Loss in %	Time (hours)	Instantaneous corrosion rate “ J_r ” (g/cm ² /year)
$i_1=0.20$ (mA /cm ²)	61.6	55.81	5.79	9.40%	252	8.0080
$i_2=0.25$ (mA /cm ²)	61.6	56.24	5.36	8.70%	228	8.1940
$i_3=0.30$ (mA /cm ²)	61.6	56.62	4.98	8.08%	192	9.0408
$i_4=0.35$ (mA /cm ²)	61.6	56.97	4.63	7.52%	168	9.6060
$i_5=0.40$ (mA /cm ²)	61.6	57.30	4.30	6.98%	132	11.354

4.3.2 Corrosion penetration rate based on weight loss and I_{corr} value

As corroded rebar induced tensile pressure over the FBG sensor, this phenomenon was recorded by FBG sensor in the form of wavelength shift previously in section 4.2. Furthermore, to correlate corrosion rate or corrosion penetration rate “ P_r ” with wavelength shift, it is very important to determine corrosion initiation and corrosion penetration rate with respect to time. This will provide more information about corrosion penetration rate over embedded steel bars. As it is well known that corrosion penetration is changing with time. The relation between corrosion penetration rate and wave length is more important to elaborate exact situation inside in the concrete. Corrosion penetration rate “ P_r ” calculated in ($\mu\text{m}/\text{year}$) has a standard form as shown in equation 4.3.

$$P_r = 11.7 * I_{corr} (\mu\text{m}/\text{year}) \quad (4.3)$$

To find I_{corr} we have to use equation 4.4 as we already know about instantaneous corrosion rate J_r ($\text{g}/\text{cm}^2/\text{year}$) in equation 4.2.

$$J_r = 0.00912 * I_{corr} (\text{g}/\text{cm}^2/\text{year}) \quad (4.4)$$

Using equation 4.4 and equation 4.5 we find the actual current density and corrosion penetration rate after weight loss test as shown in table 4.3.

Table 4. 3: Weight loss and corrosion current density with corrosion penetration rate.

Weight Loss (g)	Loss in %	Time (hours)	Instantaneous corrosion rate “ J_r ” ($\text{g}/\text{cm}^2/\text{year}$)	Corrosion current density “ I_{corr} ” (mA/cm^2)	Corrosion penetration rate “ P_r ” (mm/year)
5.79	9.40%	252	8.008	0.878	10.274
5.36	8.70%	228	8.194	0.898	10.512
4.98	8.08%	192	9.040	0.991	11.598
4.63	7.52%	168	9.606	1.053	12.323
4.3	6.98%	132	11.354	1.245	14.566

4.3.3 Corrosion penetration rate and wavelength shift correlation.

In this section, we will correlate the corrosion penetration rate to the wavelength shift. After calculating the corrosion current density I_{corr} value and corrosion penetration rate “ P_r ” it is easy to correlate with wavelength shift. Corrosion penetration defined in (mm/year) with respect to given time period. Since we recorded the wavelength shift after every 12 hours, therefore we will correlate the corrosion penetration also with respect to 12 hours’ time duration, as it is discussed in section 4.2, with complete detail for each specimen. This wavelength shift has been correlated with same time period after corrosion penetration rate in one year after weight loss and I_{corr} calculation. Corrosion penetration rate calculated per hour is plotted in figure 4.33. The corrosion penetration is dependent upon corrosion current density I_{corr} . The smaller the I_{corr} the longer the time duration it takes for corrosion penetration while the higher the I_{corr} the shorter the time duration it takes for corrosion penetration as shown in table 4.3.

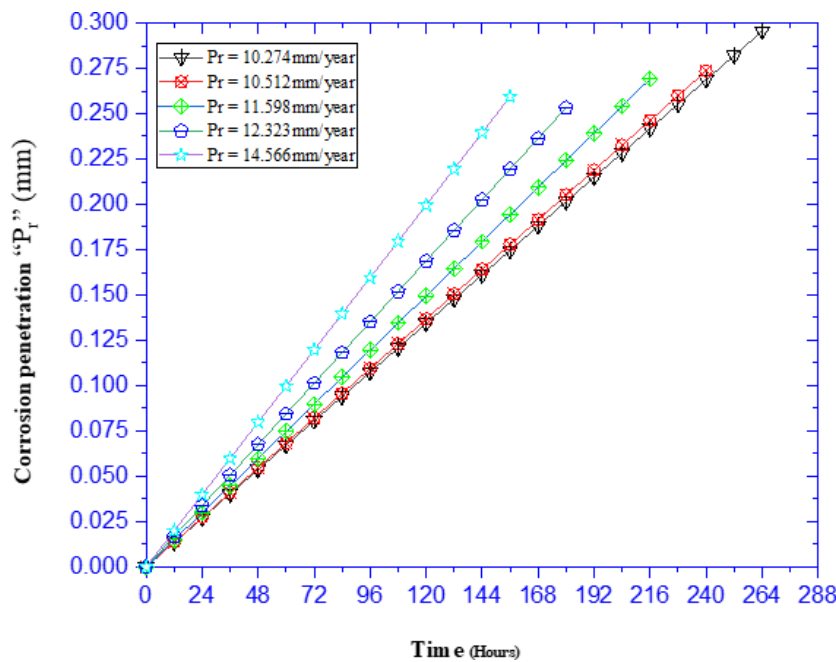


Figure 4. 33: All specimen corrosion penetration rate

After the conversion of corrosion penetration rate to 12 hours' time period it is properly correlated with wavelength shift. The wavelength shift was recorded after every 12 hours for all specimen till the crack appeared on concrete surface. Finally, the corrosion penetration rate is calculated in terms of 12 hours' time duration by using equation 4.3 to relate it to wavelength shift recorded after every 12 hours. Corrosion penetration rate calculated with the help of instantaneous corrosion and corrosion current density using equation 3.2 and 4.3. These calculations are tabulated in table 4.4 and plotted in figure 4.34.

Table 4. 4: Corrosion current density with corrosion penetration rate per hour and total time period for all specimen.

Time (hours)	Instantaneous corrosion rate " J_r " (g/cm ² /year)	Corrosion current density " I_{corr} " (mA/cm ²)	Corrosion penetration rate " P_r " (mm/year)	Corrosion penetration per hour " P_r " (mm)	" P_r " at crack initiation (mm)
252	8.008	0.878	10.274	0.00117	0.294840
228	8.194	0.898	10.512	0.00120	0.273600
192	9.040	0.991	11.598	0.00132	0.253440
168	9.606	1.053	12.323	0.00141	0.236880
132	11.354	1.245	14.566	0.00166	0.219120

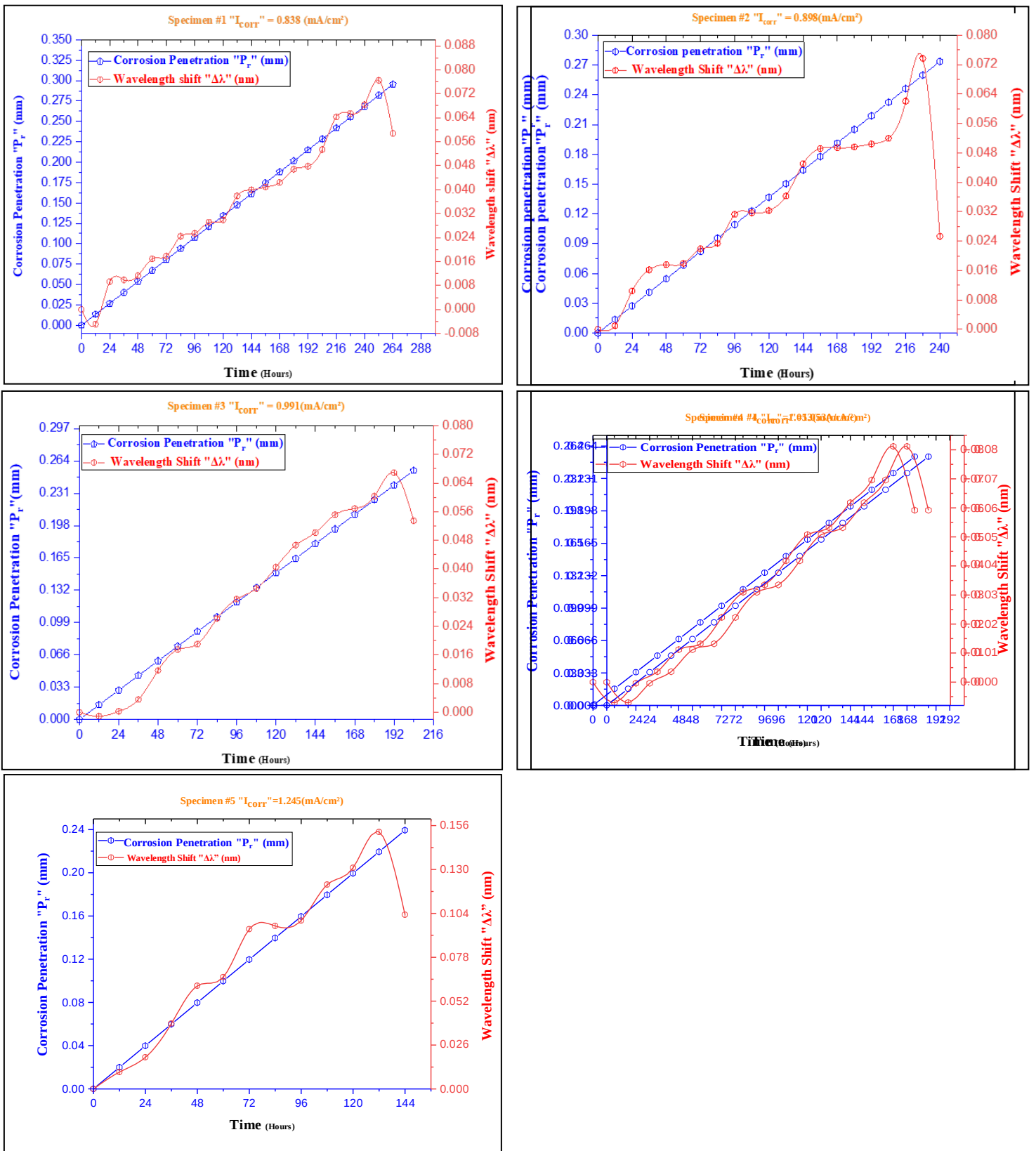


Figure 4. 34: Corrosion penetration rate Vs wavelength shift for all specimen.

In figure 4.34, the corrosion penetration vs wavelength shift is shown for all the tested specimens. Here it is observed that the wavelength shift for specimen #1 in the earlier stage started from 0.012nm after 60 hours, which indicated corrosion initiation over embedded steel rebar. This wavelength shift gradually increases with respect to time and corrosion rate. As the corrosion rate is increased with time, the wavelength shift also increase accordingly. From the study performed on multiple specimens, we can infer that the corrosion initiation depends on external environmental effects. In real scenarios the external environment of the concrete has different effect over the embedded steel bar to initiate fast corrosion that will be detected by FBG sensor within short time period and vice versa slow corrosion initiation will detect by FBG with longertime period. In our case we have applied 5 different currents to initiate corrosion over embedded steel rebar in different time and all these external changes recorded by FBG sensor in the form of wavelength changes with respect to time period.

As discussed earlier in table 4.4, we calculated a small amount of current, $I_{\text{corr}} = 0.878\text{mA/cm}^2$ which initiated corrosion at 60 hours and this corrosion initiation was recorded by FBG sensor having wavelength shift of $\Delta\lambda=0.012\text{nm}$. At this stage corrosion penetration rate is very slow with the approximated value of $P_r = 0.067\text{mm}$. This ratio gradually increased with time, as time increased the corrosion rate increased. This increase in corrosion was recorded by FBG sensor with higher value of wavelength shift. In first specimen the wavelength shift recorded up to 252 hours, where the specimen got cracked. All these changes were recorded by FBG sensor where an obvious drop in wavelength in figure 4.34 at 252 hours showing a wavelength shift of $\Delta\lambda=0.076\text{nm}$. At this stage, the corrosion penetration also increased to $P_r = 0.294\text{mm}$. This practice is repeated for the remaining four specimens with different values of I_{corr} to know the relationship between wavelength shift and corrosion rate, which is linear and directly proportional. The results of different specimens are shown in table 4.4 and Figure 4.34. All these specimens were tested according to different I_{corr} values as elaborated.

Next, the wavelength shift relationship with corrosion initiation, corrosion penetration rate, and crack appearance are shown in figure 4.34 and table 4.5 for all specimens. The I_{corr} value in second specimen is $I_{\text{corr}} = 0.898 \text{mA/cm}^2$ which initiates corrosion at 60 hours where the wavelength shift value is $\Delta\lambda = 0.018 \text{nm}$ while the corrosion penetration rate of $P_r = 0.068 \text{mm}$. With the same value of corrosion current density, the crack was recorded over concrete surface due to high tensile pressure of corrosion in 228 hours with wavelength shift $\Delta\lambda = 0.073 \text{nm}$ while the corrosion penetration rate $P_r = 0.274 \text{mm}$. All these values are recorded very well by FBG sensor with respect to time in terms of wavelength shift.

In third specimen, the $I_{\text{corr}} = 0.991 \text{mA/cm}^2$ which initiate corrosion in 48 hours where the wavelength shift value $\Delta\lambda = 0.012 \text{nm}$ while the corrosion penetration rate $P_r = 0.060 \text{mm}$. With the same value of corrosion current density, the crack recorded was over concrete surface due to high tensile pressure of corrosion in 192 hours with wavelength shift $\Delta\lambda = 0.066 \text{nm}$ while the corrosion penetration rate $P_r = 0.254 \text{mm}$. All these values are recorded very well by FBG sensor with respect to time in term of wavelength shift.

Moreover taking the 4th specimen by considering $I_{\text{corr}} = 1.053 \text{mA/cm}^2$ corrosion initiated in 36 hours. The wavelength recorded over this stage for 4th specimen $\Delta\lambda = 0.011 \text{nm}$ while the corrosion penetration rate $P_r = 0.051 \text{mm}$. Keeping the same value of corrosion current density the crack recorded over concrete cover due to high tensile pressure of corrosion in 168 hours with wave length shift $\Delta\lambda = 0.081 \text{nm}$ while the corrosion penetration rate $P_r = 0.236 \text{mm}$. All these value are recorded very well by FBG sensor with respect to time in term of wavelength shift.

In the last specimen the same practice repeated except the change in corrosion current density where $I_{\text{corr}} = 1.245 \text{mA/cm}^2$ which initiate corrosion in 24 hours where the wavelength shift value $\Delta\lambda = 0.019 \text{nm}$ while the corrosion penetration rate $P_r = 0.040 \text{mm}$. With the same value of corrosion current density, the crack recorded over concrete cover due to high tensile pressure of corrosion in 132 hours with wavelength shift $\Delta\lambda = 0.152 \text{nm}$ while the corrosion penetration rate $P_r = 0.219 \text{mm}$.

All these value are recoded very well by FBG senor with respect to time in termof wavelength shift. All these values are shown in figure 4.34 and tabulated in table 4.5 to understand easily. This analysis concluded that both wavelength shift and corrosion penetration rate have a strong relationship. The main theme of this study is to utilize wavelength shift for non-destructive monitoring system of concrete structures to facilitate in term of real time monitoring. Based on this experimental work a very comprehensive relation of wavelength shift at both stages of corrosion initiation and crack initiation is defined. The wavelength shift at crack initiation point minimum five times and maximum eight times higher or maximum then wavelength shift at corrosion initiation as shown in table 4.5.

Table 4. 5: Corrosion initiation and crack time Vs corrosion penetration rate.

Corrosion current density " I_{corr} " (mA/cm ²)	Corrosion Initiation time (hours)	Corrosion penetration at Initiation time " P_r " (mm)	Wavelength shift " $\Delta\lambda$ " at corrosion initiation (nm)	Crack Time (hours)	Corrosion penetration at crack time " P_r " (mm)	Wavelength shift " $\Delta\lambda$ " at crack initiation (nm)	Wavelength shift difference b/w corrosion initiation and crack initiation
0.878	60	0.067	0.012	252	0.2946	0.076	6.33 times
0.898	60	0.068	0.018	228	0.2736	0.073	5.21 times
0.991	48	0.060	0.012	192	0.2535	0.066	5.50 times
1.053	36	0.051	0.011	168	0.2363	0.081	7.36 times
1.245	24	0.040	0.019	132	0.2194	0.152	8.00 times

The main theme of this study is to utilize wavelength shift for non-destructive monitoring system of concrete structures to facilitate in term of real time monitoring. In real life the corrosion penetration are calculated in $\mu\text{m}/\text{year}$.

To detect the real life corrosion penetration from the wavelength shift values of FBG sensor, the existing values of corrosion penetration extracted from gravimetric test are converted from mm/year into units of $\mu\text{m}/\text{year}$. Where the corrosion penetration of 1st specimen at corrosion initiation time is $P_r = 0.067\mu\text{m}$ while it is increased at crack initiation time up to the value of $P_r = 0.295\mu\text{m}$.

The same trend is followed by the second specimen, the corrosion penetration $P_r=0.068\mu\text{m}$ at corrosion initiation time, while it is increased up to $P_r=0.274\mu\text{m}$ at crack initiation time. In the same manner the 3rd specimen have $P_r = 0.060\mu\text{m}$ while this value increased up to $P_r =0.254\mu\text{m}$ at the crack initiation time. However the 4th specimen recorded $P_r = 0.051\mu\text{m}$ at corrosion initiation time which increased up to $P_r = 0.236\mu\text{m}$ at crack initiation time. At last the 5th specimen corrosion penetration is $P_r = 0.040\mu\text{m}$ at corrosion initiation time, while it is reached to $P_r = 0.219\mu\text{m}$ at crack initiation time.

Chapter 5

5.1 CONCLUSIONS

Many electrochemical techniques for detecting corrosion in embedded rebar have been reviewed. All of these reported techniques have certain limitations and advantages. Electrochemical corrosion is normally qualitative and only provides semi-quantitative benefits. Developing durable embedded sensors in reinforced concrete structures with communication control systems has encouraged progress in corrosion monitoring systems. Therefore, this study recommends combining different techniques to obtain maximum information about the corrosion in a particular structure. Developing such an integrated monitoring system could reduce costs and approach to work in concrete structure assessments. Continuous monitoring systems of covered steel in concrete via real-time monitoring could increase the availability of information related to near future and structure performance. Corrosion monitoring is vital to plan the preventive maintenance of concrete structures to predict the life and quantitative information related to chloride ingress and carbonation. On the other hand, such information can be used to assess the rehabilitation system of coating or corrosion inhibitors. This increases the visibility of preventive maintenance parameters to repair the structure easily. The deployment of this system has different pros and cons in identifying corrosion over steel bars covered by concrete. However, the sensors systems for rehabilitation strategy to describe the future repairing cycles are highly effective and important to recognize the total management system of concrete structures. In this study, we realized an FBG-based optical sensor system to identify the infected steel bar due to corrosion. Although the initial deployment of this technique in civil structures is costly, the continuous monitoring of concrete structures will pay dividends in the long run as targeted maintenance can be done upon the requirement and prevent collateral damages and other fatal incidents.

To monitor concrete structures using optical sensing techniques, the FBG sensors are mainly integrated inside concrete along the steel bar before concrete casting. After concrete casting, the cementation process inside the concrete causes some variation or changes parameters of the optical sensors and are therefore ignored for up to 28 days of the curing period. After the curing period, the wavelength response from FBG sensors must be recorded. As the corrosion is developed on the embedded steel rebar, the wavelength shift is observed, which relates to the corrosion penetration rate. Using multiple sensors in concrete structures identified the corrosion initiation over steel rebar embedded in concrete structures. From our experiments, we concluded that if the wavelength shift over a range from $\Delta\lambda=0.011\text{nm}$ to $\Delta\lambda=0.019\text{nm}$, it indicates the corrosion initiation or low-risk corrosion. At this stage, we have to take preventive action for initiated corrosion over steel rebar. Any delay or irregular maintenance of concrete structures will increase the corrosion rate. However, if no preventive action for the corrosion over steel rebar is not taken, the corrosion will gradually increase toward its peak level. At this stage, the wavelength shift range is from $\Delta\lambda=0.066\text{nm}$ to $\Delta\lambda=0.152\text{nm}$ showing a peak level of corrosion. During this stage, the concrete cover will get cracked and will probably be visible on the surface of the concrete structures. Based on this experimental work a very comprehensive relation of wavelength shift at both stages of corrosion initiation and crack initiation is defined. The wavelength shift at crack initiation point minimum five times and maximum eight times higher or maximum than wavelength shift at corrosion initiation. Moreover, it is well known that every experimental work has some pros and cons. below, we have tabulated some pros and cons of this work as shown below in table 5.1.

Table 5. 1: Pros and Cons of using optical fiber sensor in concrete structures to detect corrosion.

Criteria	Pros/Cons
Non-intrusive design	Pro
The complexity of output data	Con
Response of the system	Pro
Ruggedness	Con
Initial Cost	Con
Interference or cross-sensitivity	Pro
Remote monitoring system	Pro

5.2 Challenges faced in this study

In this research work, we have faced multiple challenges:

- ❖ Very limited work reported in the literature.
- ❖ Challenge faced due to working in civil and electrical laboratories simultaneously.
- ❖ Installation of optical sensors in concrete structure as optical fiber cable and sensors are highly sensitive.
- ❖ Limitation of the software to record the continuous response of the sensor as raw data for detecting pressure due to corrosion over steel bar.

5.3 Future Recommendations

To enhance or extend this research work, we recommend the following:

1. Multiple sensors installed in series to identify corrosion at different locations.
2. To perform a test in a natural environment to detect corrosion initiation and corrosion penetration rate.
3. Using the same FBG sensor to calculate the corroded embedded steel rebar's crack size and load-bearing ability.
4. To improve the design to avoid sensor damage during concrete casting.
5. To design a compact system for sensor data transmission.

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