Y-SHAPE OPTICAL FIBER BUNDLE IN MONITORING CORROSION

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ABSTRACT

Corrosion of the reinforcement is one of the major deterioration of reinforced concrete structures. The cause of corrosion can be either due to carbonation or chloride attack. The product of corrosion increases the reinforcement volume, hence causing cracking of concrete cover. With the advancement in the telecommunication industry, fiber optic has proven good track record to be resilient and durable to exposure even to extreme environment. The aim of this research is to look at the possibility of using fiber optic sensor to sense the occurrence of reinforcing steel corrosion. The Y-shape fiber optic bundle sensor was attached on a steel plate surface for corrosion determination. This corrosion sensor technique work is based on the detection of the colour changes of the steel plate surface from silvery to brown during the corrosion process. From the research, it was found that the Y-shape optical fiber corrosion sensor was capable to sense the occurrence of corrosion process in concrete.

***Keywords:** corrosion of reinforcement, Y-shape fiber optic sensor*

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INTRODUCTION

Reinforcing steel embedded in hydrating cement paste rapidly form a thin passivity layer of oxide which strongly adheres to the underlying reinforcement and gives it complete protection from corrosion due to the high alkalinity of the concrete pore water. This state of the steel is known to be as passive ***[Neville, 1996]***. The pH of which is usually even higher than 12 ***[American Society for Testing and Materials, 1966]***. However, this passivity layer can be disrupted by a reduction of pH of the concrete pore water to a value less than 9 due to the carbonation process when carbonic acid formed. ***[Page, et.al., 1996]***. The penetration of gas carbon dioxide into the concrete structures was mixed with the concrete pore water to formed carbonic acid. In the present of oxygen and water, corrosion occurred. Chloride ions that are transported through the concrete pore network and micro cracks can also depassivate the oxide film covering the reinforcing steel and accelerate the reaction of reinforcement corrosion. The depassivation mechanism for chloride attack is somewhat different from carbonation process. Chloride ions that diffused into reinforced concrete structures can cause corrosion of reinforcement at concentration as low as 600-900µg/mL ***[Berke and Hicks, 1993]***. Chloride act as catalysts to corrosion, when there was sufficient concentration of chloride ions at the reinforcement surface, it capable to break down the passivity layer of oxide on the steel even at high pH levels. This allowed the corrosion process to proceed quickly.

At present, there are very few non-destructive methods that determine the steel corrosions of reinforced concrete structures until visible damage such as cracking has occurred. The objective of this novel research was to develop a sensor using fiber optic to investigate its potential to continuously monitor the process of corrosion in reinforced concrete structures. The corrosion process was detected by the attached Y-shape optical fiber bundle on the steel plate surface. This sensor function based on the detection of the colour changes at the surface of the steel plate after it has been embedded in a cement mortar.

LITEARTURE REVIEW

Fiber optic sensors have the potential and have demonstrated the ability to take some of the key structural evaluation and performance measurements ***[Huston (a), 1995]***. Fiber optic sensors are similar to electrical sensors in that fiber optic sensors use light as both the sensing and information transduction medium. Electrical sensors operate by modifying the voltage, current, frequency, or phase of an electrical signal. Fiber optic sensors operate by modifying the intensity, fast frequency (wavelength), slow frequency (time-modulated intensity), polarisation, phase, and coherence ***[Huston (b), 1999]***. In majority of optical fiber sensors, the transduction steps are ***[GilBert, 1996]***:

> electrical→ optical→ chemical→ optical→ electrical (as shown in Figure 1.1)

The first electrical to optical step corresponds to the production of light from electrical power by a light source acting as a transducer. The optical to chemical to optical step consist of the internal properties changing of the reinforced concrete structures when exposed to aggressive environment such as acid, chlorides or carbon dioxide gas. These internal properties change will either increase or decrease the light transformation through the fiber that embedded in the concrete structures. The last step, the optical to electrical transduction, is achieved using the photo detectors. The light signal received from the detector was based on the internal properties changing of the reinforced concrete structures ***[GilBert, 1996]***. For example, the increase of the porosity in a concrete structure will decrease the light transmission through the fiber that embedded in the concrete. The decreased of light transmission reduce the transmitted optical power recorded by the photo detector.

Fiber Optic Corrosion Sensor

Recently, at least three methods were tried to monitor the corrosion process of the reinforcement in a concrete structure using fiber optic sensors.

i. Based on the principle of the changes of reflected or transmitted light of the optical fiber when the colour of reinforcement changes and pitting occur due to the corrosion process of the reinforcement.

ii. The surface of the fiber may be coated with a substance that reacts with the corrosion products.

iii. Metallic fuses may be used to put loops in the fibers. The frequency of the reflected light will change when the fuse breaks and the length of the fiber changes.

At present, the first sensing method is a field of great interest because it is easy and simple. This research was focus on this type of corrosion sensor. The optical fiber corrosion sensor was developed by using the optical fiber tips to detect the corrosion process. Normally Y-shape fiber optic bundle was use for corrosion detection as in Figure 1.2.

Sensing Method Using Twin (Y-shape) Optical Fiber Bundle Corrosion Sensor

This measurement is straightforward, as shown in Figure 1.2. In the illustrated “twin-fiber” or bundle-fiber technique, transmitting and receiving fiber were used. Spectrally broadband light is coupled into an optical fiber and subsequently illuminates the region under measurement.

The colour of reinforcement surface change from silvery to brown when corrosion occurred. The Y-shape fiber optic bundle was based on the principle of colourimetry which was used in the research as the detector and data transmitter for the determination of corrosion of reinforcement in concrete structure ***[Wolfbeis,***

1991]. These fiber optic bundles offer the advantages being simple to construct, ease of implementation and cost-effective. This sensor consists of two optical fibers. A white light from the source was made incident to the sample surface to detect the colour changes of the surface through the transmit fiber. Then, the light was reflected based on the reflective index of the sample surface that influenced by the colour changes. The reflected signal carried by the receiving fiber to a detector. Thus, it is possible to assess the extent of corrosion damage on the steel surfaces using this technique when corrosion occurred ***[Nahar, 2000].***

MATERIALS AND RESEARCH TECHNIQUE

Samples Preparation

The Y-shape fiber optic bundle with half portion of its common end made from the source fibers and the other half from the detector fiber was obtained directly from the supplier.

A steel plate (2mm x 50mm x 30mm) was cleaned with sandpaper to remove all the stain on its steel surface. The steel plate was silver in colour after cleansing.

The cement mortar was mixed using the Portland cement, sand (zone II) and tap water in the ratio of: C/S = 0.36 and W/C = 0.64 as required by ASTM reinforcement corrosion test method.

Experimental details

Before the Y-shape fiber optic bundle was used as a corrosion sensor, the separation distance between the Y-shape optical fiber bundle end and the clean steel surface was determined to get the optimum reflected optical power for the non-corroded sample. This separation distance was determined by placing the clean steel sample at different distances from the fiber end. The reflected optical power for each distance was recorded with a photo detector; the separation distance was determined with a travelling microscope. The optimum separation distance was decided from the curve plot of reflected optical power (μW) versus the separation distance (mm) as shown in section of results and discussions.

Preliminary Test: Steel Corrosion Determination in Sodium Chloride Solution

The Y-shape fiber optic bundle based on the principle of colorimetry was used in the research to detect the corrosion of reinforcement. For preliminary experiment, the corrosion of the steel plate when immersed in a different concentration (0%, 1 %, 2%, 3% and 4%) of sodium chloride solution for 35 days had been carrying out. The data was recorded every 24 hours. The separation distance between the fiber end and the steel plate surface is 1.5 mm. The setup of using the fiber optic bundle for steel plate corrosion monitoring immersed in solution as shown in Photo 1.1.

Steel Corrosion Determination in Cement Mortar Structures

The Y-shape fiber optic bundle was embedded in the cement mortar to detect the corrosion process of the steel plate in a structure. The Y-shape fiber optic bundle was attached on the steel plate surface using the glass tube and super glue as shown in Photo 1.2. The separation distance between the fiber end and the steel plate surface is 1.5 mm. The sample was casted using a cement mortar mixed containing 1% of NaCl by the weight of cement. The cover of the steel plate embedded in mortar was 20 mm. After 24 hours of casting, the cement mortar was immersed in a 5% NaCl solution and the electrochemical process was carried out to speed up the corrosion process with steel acting as an anode electrode. The control sample was prepared without NaCl in the mortar mix and immersed in tap water. The setup of the Y-shape fiber optic bundle sensor for corrosion determination in cement mortar was as shown in Photo 1.3.

This Y-shape optical fiber corrosion sensor consists of two optical fibers. A white light from the source is made incident to the sample surface through the source fiber to detect the colour changes of the surface. The light was reflected based on the reflective index of the sample surface that influenced by the colour of the sample surface. The other arm of the optical fiber (detector fiber) carried this reflected signal to a detector.

RESULTS AND DISCUSSIONS

The Y-shape optical fiber bundle corrosion sensor was excellent for steel corrosion determination either for steel immersed in NaCl solution or embedded in cement mortar. The details of the results obtained from using and discussions about this sensor are discussed below.

The Effective Separation Distance Between the Y-Shape Optical Fiber Bundle End and the Steel Surface

A typical variation between the separation distance and the reflected optical power is shown in Figure 1.3. This figure clearly indicates that the reflected optical power increased rapidly as the separation distance increase up to 1.5mm. The optimum reflected optical power at this distance was 8.50 μW. Beyond 1.5mm, the reflected optical power began to decrease. Thus, the optimum separation distance of 1.5mm was adopted for further investigations.

Preliminary Test: Steel Corrosion Determination in Sodium Chloride Solution

From visual observations, the colour of the steel surface changed from silver to black, then yellow and finally dark brown as the immersion time is prolonged. The change in colour was due to oxidation and formation of rust when corrosion occurred. The density of rust formation was dependent on the concentration of the sodium chloride solution and the immersion period. The rust formation was faster and denser in higher concentration of sodium chloride. The thickness of the rust on the steel surface also increased with longer immersion time.

The results of Y-shape fiber optic bundle used to determine the corrosion of steel plate immersed in a different concentration of sodium chloride is shown in Figure 1.4. For a clean steel plate, the maximum reflected optical power for the clean steel sample (silver colour) was found to be 14.5μW. After being immersed in the sodium chloride solution for 1 to 2 days, the sample surface gave a lower reflected optical power of about 2.3 μW due to the oxidation of the steel plate that forms black ferric oxide at the surface of the steel plate.

After about 15 days, the steel surface changed from black to yellow. The value of the reflected optical power increased to a maximum value from 2.3μW to about 4.2μW due to the colour changes. After 35 days being immersed in the NaCl solution the value of reflected optical power reduced to about 1.70μW. This reduction was due to the rust colour that changed from yellow to dark brown. The simultaneous increased of the rust thickness, reduced the separation distance between the fiber and the steel plate surface. Thus, a reduced reflected optical power was obtained.

From the results obtained, the Y-shape fiber optic bundle, which is based on the absorption/reflected principle, was promising for continuous non-destructive monitoring of reinforcement corrosion. This method is applicable both at the early state as well as the later state of the corrosion process as summarised in Figure 1.5.

Steel Corrosion Determination in Cement Mortar Structures

After 20 days of immersion, the sample was broken for visual observed of the steel plate. The steel plate shows a severe corrosion problem after being immersed for 20 days in 5% NaCl solution due to the electrochemical process. The surface of the steel plate changed from silvery to dark brown when corrosion occurred. Crack was observed on the cement mortar due to formation of internal stress when the corrosion process became serious.

The reflected optical power obtained from the Y-shape optical fiber bundle corrosion sensor was reduced as shown in Figure 1.6. This is due to the steel corrosion process. After 14 days of immersion, the reflected optical power reduced to a value about 4μW. The more severe the corrosion of steel plate, the lower the reflected optical power. The reduction in the reflected optical power was due to the changed in the colour of the steel surface to dark brown. The reflected optical power reduced to about 1μW when corrosion was severe.

As the steel plate sample that was immersed in the tap water for 20 days, it was clean and silver in colour. This means that the steel plate was not corroded even after 20 days being immersed in tap water. The reflected optical power showed very small variation (in a range of about 3 μW) in these 20 days as shown in Figure 1.6. Thus, the reflected optical power can be considered stable if there is no corrosion occurred. The average of reflected optical power for non-corroded steel plate is 22 μW.

A great difference was observed between the reflected optical power curve obtained from the sample immersed in water (not corroded) and that immersed in NaCl solution (corroded) as shown in Figure 1.6. This proved that the Y-shape optical fiber bundle corrosion sensor is capable of functioning as a monitoring tool for steel corrosion. This can be accomplished by embedding a steel plate in the structure and monitoring the colour changes of the steel. The reflected optical power reduced based on the state of steel corrosion. The more serious the steel corrosion, the darker the colour of the steel surface and the lower is the reflected optical power.

CONCLUSIONS

1. The Y-shape optical fiber bundle corrosion sensor was capable to function as an intrinsic monitoring tool for corrosion of steel based on the colour changes of the steel surface when corrosion occurred. This can be accomplished by embedding a steel plate in the structure and monitoring the colour changes of the steel.

2. The corrosion data obtained from the Y-shape optical fiber bundle was from a steel plate embedded in concrete structures. The accuracy of this sensor in determining the corrosion of reinforcement depends on the corrosion of the steel plate. Assumption was made that; if the steel plate was corroded, the reinforcement was corroded as well. The Y-shape optical fiber bundle was not glued directly on the reinforcement surface for corrosion determination because the rounded surface of the reinforcing steel was poor in optical power reflection.

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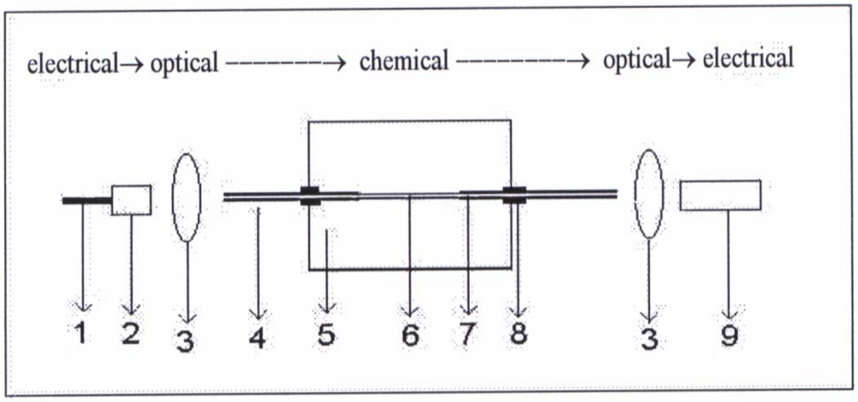


Figure 1.1: The command transduction steps of a chemical optical fiber chemical sensor. In this case (1) is current supply (2) light source (3) optical lens (4) optical fiber cladding (5) test sample (6) sensing element of the fiber (7) fiber core (8) connection protector (9) optical power detector.

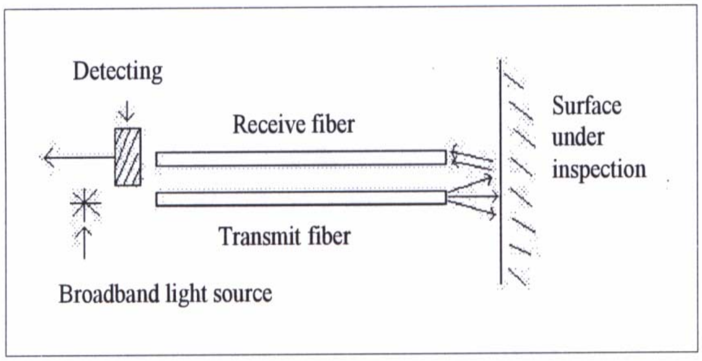


Figure 1.2: Twin fiber spectroscopic sensing ***[Peter (b), 1995]***.

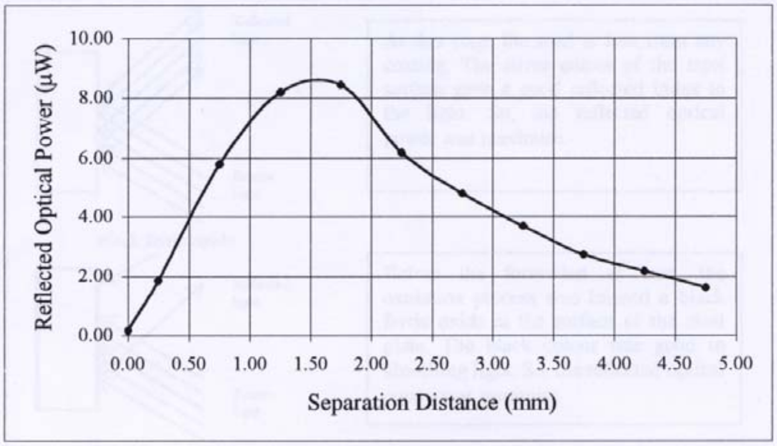


Figure 1.3: The separation distance versus the reflected optical power.

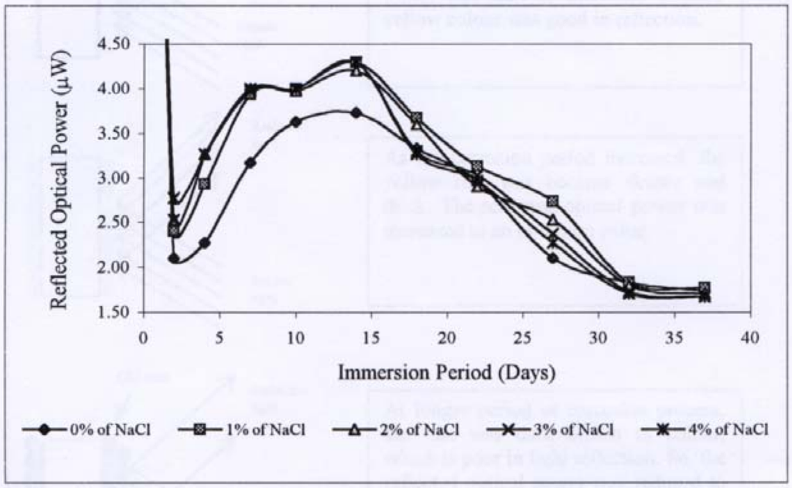
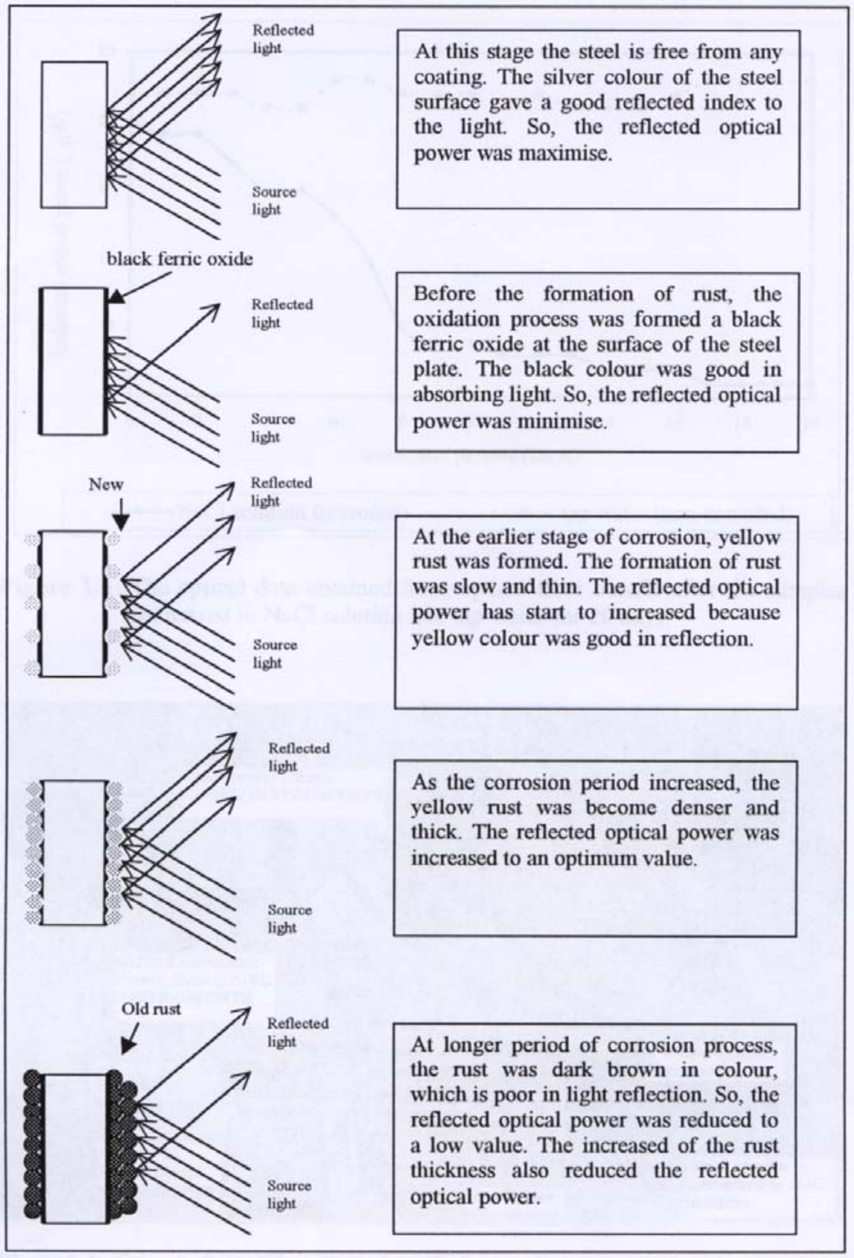


Figure 1.4: Reflected optical power for corroded steel plate versus time period when immersed in different NaCl concentration.



At this stage the steel is free from any coating. The silver colour of the steel surface gave a good reflected index to the light. So, the reflected optical power was maximise.

Before the formation of rust, the oxidation process was formed a black ferric oxide at the surface of the steel plate. The black colour was good in absorbing light. So, the reflected optical power was minimise.

At the earlier stage of corrosion, yellow rust was formed. The formation of rust was slow and thin. The reflected optical power has start to increased because yellow colour was good in reflection.

As the corrosion period increased, the yellow rust was become denser and thick. The reflected optical power was increased to an optimum value.

At longer period of corrosion process, the rust was dark brown in colour, which is poor in light reflection. So, the reflected optical power was reduced to a low value. The increased of the rust thickness also reduced the reflected optical power.

Figure 1.5: The relationship between the steel plate corrosion process in solution and the reflected optical power of the Y-shape fiber optic bundles.

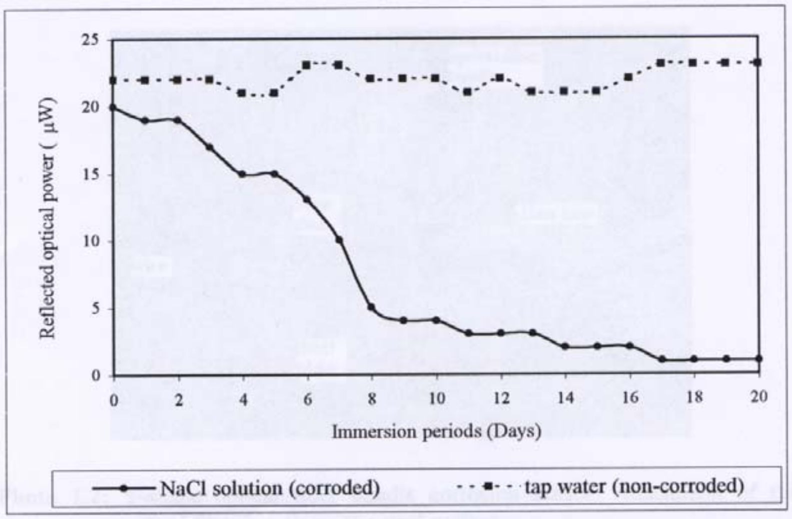


Figure 1.6: The optical data obtained form optical fiber bundle after the samples immersed in NaCl solution and tap water for 20 days.

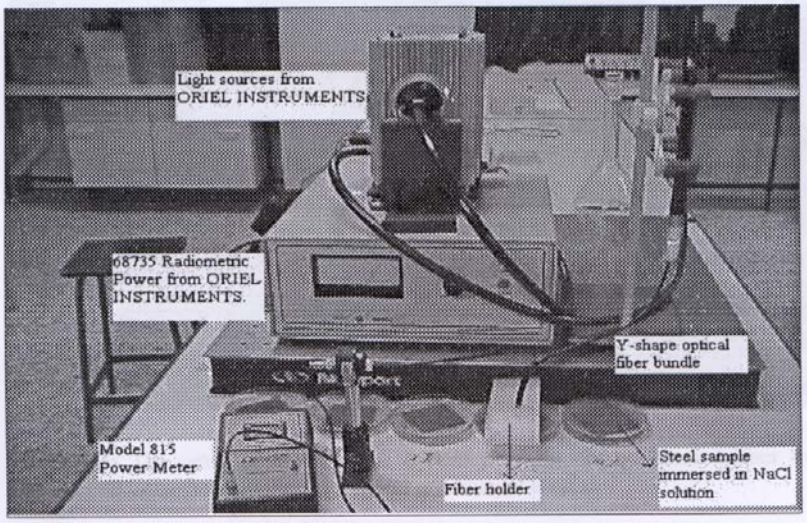


Photo 1.1: Set-up of the Fiber Optic bundle for steel corrosion when immersed in NaCl solution.