Optical Fiber Sensors Embedded in Concrete Structures: Feasibility and Durability Studies

by

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ABSTRACT

Infrastructures and buildings age and deteriorate with time. Fiber optic technology is a new nondestructive evaluation (NDE) technique which promises to revolutionize the civil engineering discipline. The fiber-optic sensor which is embedded in a host cement paste has the potential of providing a vast amount of information. This thesis studies the physics of optical fibers. Two experimental works are presented about embedment of optical fiber sensors in concrete. One real application is presented. Feasibility studies as well as durability studies are presented. Models of innovation for optical fiber sensors are presented along with the implementation and final diffusion into the construction industry. The durability studies (pull-out tests and SEM observations) were conducted to establish a good relation between the interfacial strength and fiber coating durability. The durability of three coatings; polyimide, acrylate, and teftzel-silicone, are tested in order to observe their interactive behavior in concrete structures. The crack opening measurement is conducted to demonstrate the potential use of optical fiber sensors. The optical fibers were embedded at three different angles namely; 15, 30, and 45 degrees to study different intensity loss characteristics and thus determine the most sensitive angle.

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Dedicated to my father, Alex Darmawangsa

Make me know Thy ways, O Lord; Teach me Thy paths. Lead me in Thy truth and teach me, For Thou art the God of my salvation; For Thee I wait all the day.

Psalm 25 : 4-5 (NASB)

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Chapter 1

Introduction

As the 21st century rapidly approaches, the service life of most existing bridges and buildings is expiring. Hence the expenditure for rehabilitation, retrofit, repair and replacement of existing structures has become an enormous portion of the total construction budget. It is estimated that in the U.S., 40 percent of the total initial construction cost of a building will be required to maintain and repair the structure through its service life [Mehta, 1993].

Current inspection techniques sometimes cannot detect a problem until it is in advance stages. It would be better if the damage could be detected in earlier stages which could save many repair costs. Recent trends tend to emphasize life-cycle cost rather than initial cost, which forces designers to become more durability conscious.

1.1 Background

1.1.1 Deterioration of Concrete Structure

Most structural designs are strength based which sometimes overlooks the importance of the durability of the building over its intended service life. This is especially true for concrete structures where durability of the concrete is essential for good performance over the service life. Even when the concrete is properly constituted, placed, and cured, premature failure of concrete structures do occur and most of the time is unpredictable.

Deterioration in concrete structures is mainly caused by physical and chemical conditions of the material. Figure 1-1 shows the physical causes of concrete deterioration which can be divided into two major groups: surface wear due to abrasion, erosion, and cavitation; and cracking due to volume change, structural loading and exposure to temperature extremes. The chemical causes of deterioration are due to: (1) hydrolysis of the cement paste; (2) cation-exchange inside the concrete; and (3) formation of expansive products [Mehta, 1993]. Most of the time both surface wear and cracking occur superimposed on each other.

1.1.2 Durability versus Service Life

Due to a perceived lack of performance in structures built in the last forty years, there has been a growing interest in monitoring the condition of these structures. Although building codes provide several criteria for service life prediction, this is not always reliable

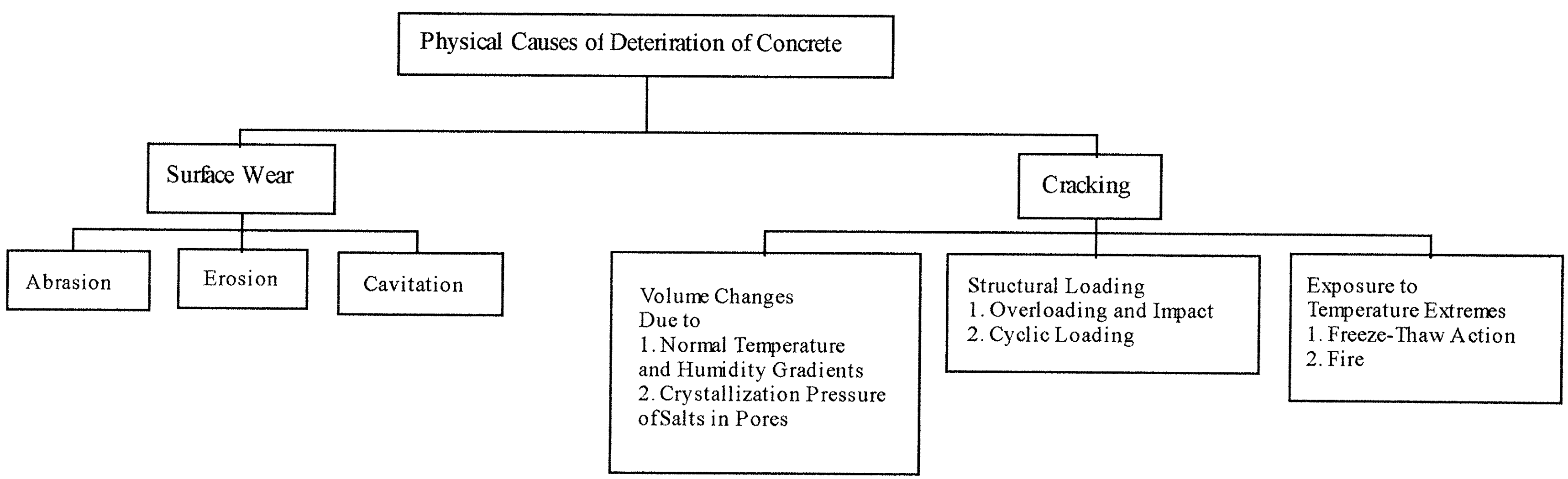

Figure 1-1: Physical causes of concrete deterioration [Mehta, 1993].

because it does not account for structural failure due to improper design, poor quality of materials or substandard workmanship.

Maintaining the condition of a structure has become a major concern in the construction world. However many building managers may see periodic inspections as expensive and unnecessary. Hence they may be inclined to overlook periodic inspections during the "normal" life of the structure. Skipping an inspection would mean a larger gap between inspections which could be dangerous because there is a greater likelihood for damage and possible failure to occur [Steven, 1993].

Concrete construction is prone to many possible errors from mixing until final completion. Defects can occur in mixing the concrete, pouring into the forms, as well as overall poor workmanship. These inherent defects of a structure may cause pre-mature failure. Although most codes permit certain imperfections in structures there are limits where a structure would be considered unsafe.

Given the previous discussion it is evident that identifying deterioration in existing structures is essential. Clearly it would be better to detect deterioration without introducing further damage to the structure and without having to rely solely on visually perceptible changes in geometry or surface appearance (a lot of damage is not visible to the naked eye). This sort of problem has been addressed in what is commonly called nondestructive evaluation.

1.1.3 The Need for Nondestructive Evaluation

In the past decade, engineers have had difficulties identifying which parts of a structure need replacement or rehabilitation. Until recently there has been no objective and reliable way to inspect existing structures except through subjective judgments which many times consists of visual inspections. The unsuccessful maintenance is usually due to the lack of qualified engineers to perform structural inspections and sometimes caused by lack of budget to acquire and maintain expensive equipment. Since one cannot avoid deterioration in structures, nondestructive evaluation (NDE) offers solutions in reducing the cost of rehabilitation by detecting deterioration in the early stage.

The term NDE refers to the examination of materials, elements, or structures to ascertain that they meet specifications, without any change or damage induced by the evaluation that would impair the usefulness of the structures being inspected. Nondestructive testing has become an important role in quality control of materials especially in concrete structures. Until recently the evaluation of existing structures with regard to their strength and durability have probably been the two most important issues. Several applications regarding NDE have shown the potential of this field yet improvement is still needed to make these tests become more reliable, widely available and cost effective.

The idea of collecting vast information regarding the condition of a building without making changes in the structure has become important in the late 20th century. Recent development in the area of nondestructive evaluation allows engineers to make a structural assessment without costly intervention.

1.1.4 Overview of Non-destructive Evaluation

Nondestructive Evaluation (NDE) has been widely used in inspecting the condition of metals and ceramics. However its practice is still at a stage of infancy in concrete due to the heterogeneous characteristics of the material [Sansalone, 1990].

The decaying of infrastructures as well as buildings has forced government agencies to put more research focus on the area of NDE in concrete, since concrete is the most widely used in construction today. Several NDE techniques show promise in their application to concrete technology however none of them is better than others; all of them have advantages and disadvantages which depends on the type of application.

One of the more common NDE tests is the ultrasonic technique which has proven effective in the construction area. However, only certain applications can take advantage of the ultrasonic technique and most of the work done in this area has had an emphasis on steel structures. Significant work on concrete structures has not been undertaken at this time. The ultrasonic testing is done on a small part of the structure. For a large scale structure, this type of testing would consume quite some time. The radar imaging system is a powerful tool for scanning the internal mechanical properties of concrete. Nonetheless some studies have shown its weakness since the results varied when the moisture content of the materials changed with a change in temperature[1,2]. Furthermore

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[1] Buyukozturk, O., Rhim, H., "Non-destructive Testing of Concrete using Radar", International Symposium Non-Destructive Testing in Civil Engineering (NDT-CE) 26-28 September, 1995.
[2] Rhim, H.C., Buyukozturk, O., Blejer, D.J., "Remote Radar Imaging of Concrete Slabs With and Without a Rebar", Material Evaluation, February, 1995.

the exponential cost of a good radar system would probably lessen engineers' interest in applying it at the site of construction.

Other techniques might offer solutions for civil engineering structures for example, acoustic holography, X-ray radiography, X-ray computed tomography. However due to the small amount of research that has been done in the civil structure area, these techniques might require several decades to mature before application in the construction industry.

1.1.5 Fiber Optic Sensors Technology

The need for a reliable technique in monitoring overall structural integrity has grown rapidly since the early 1980s. Numerous methods have been proposed to monitor the condition of structures, techniques such as, ultrasonic, radar sensing and acoustic emission which indeed offer favorable results in terms of monitoring the health of the structure.

Scientists keep trying to find an easier, more cost effective, and more reliable technique to monitor structural elements. The use of fiber optics for sensors emerged from the curiosities of some scientists during the 1980s. A major opportunity in fiber optic technology applied in civil engineering is certainly a new breakthrough in this information era. Massive amounts of sensor information can be accumulated through computer data acquisition and updated continuously in monitoring the health and integrity of a structural system thus providing day to day inspection of the structure.

Optical fiber sensor technology has advanced to the level where precision, low transmission loss and low-cost of sensors are not problems anymore. Optical fibers have advantages that make them attractive in a variety of applications. Fiber optic sensors offer environmental ruggedness which provides several advantages compared to other techniques. They are capable of performing under high temperature operation, can withstand extreme vibration and shock, while exhibiting high sensitivity and bandwidth. In addition, they can provide passive sensing of a wide range of physical fields, while being small in diameter and made of dielectric materials. Other advantages are high sensitivity, resistance to corrosion, lightweight, inexpensive, immune to the electromagnetic interference, and easily maintained.

Significant advances of fiber-optic technology spur their uses in several different fields such as, aeronautic, chemical, mechanical, material, as well as civil engineering. The needs of a dependable sensor to detect changes in strains, pressures, temperatures and crack openings have become more important matters than ever in this information era.

Predicting the service life of structures cannot be done solely on routine inspection, however it is a vital part of determining service life. Routine checks quite often are carried out by engineers who inspect only with the unaided eye which is inaccurate and time consuming. Because of the flexible character of optical fibers, they can be easily put into structural elements without causing changes in design while effectively monitoring the condition of the structure. New structures (e.g. dams, tunnel, bridges and buildings) could be instrumented with an integrated structure sensor (fiber optic) which could control/monitor the degradation of the structure over a period of time as well as self schedule for maintenance. Information gathered from the structure during its service life could then be used as part of the evaluation process.

Other applications of fiber optic sensors in engineering mechanics are as follows [Ansari, 1993] :

- Measurement of strains in composite structure.
- Fracture mechanics applications in measuring Crack Opening Displacement and Stress Intensity Factors.
- Measurement of temperature change in concrete.
- Measurement of hydrostatic pressure distribution.

Fiber optic sensor systems are still expensive however in the next decade it can be expected that the number of devices available at low cost will grow dramatically, allowing manufacturers to produce a wide variety of devices that offer superior performance at lower cost [Udd, 1992].

1.1.6 Smart Structures and Materials

The term *smart structure* is new to the civil engineering community however the term is commonly used in aerospace engineering. The smart structure operates by sensing the environment, processing the acquired information, and then deciding whether or not to take an action based upon the processed information [Spillman, Jr., 1993]. It may simply be constructed of intelligent material systems or may have dedicated or integrated actuators, sensors, and intelligence in a more discrete form.

The intelligent features of these smart structures and materials have lured civil engineers to implement them in real buildings and bridges. For active control in civil structures to become a reality it is necessary to use the smart structure concept since it matches the needs of active control structures. The instrumentation of a smart structure involves sensors, actuators and computational elements. Fiber optic technology therefore promises to play a significant role in contributing to the evolution of the smart structure concept. A smart structure provides feedback to inspectors regarding the condition of the structure on a day to day basis while a smart material supplies a "self-repair" characteristic. These two elements when added together create an *intelligent structure* which can respond as an engineer expects. An intelligent structure offers the possibility of a maintenance-free structure which is the dream of many engineers.

However, not too many researchers are interested in working in this area since the cost is enormous and the technology is not there yet. Most of the work on fiber optic sensors has been part of the research done in smart structure development. This technology offers benefits such as real time damage assessment, flaw location, real-time structural load determination, structural dynamic evaluation, active or even adaptive control of structure and prediction of the remaining service lifetime.

1.2 Objectives of Research

The general objectives of this present study are to identify the possibility of using optical fibers as sensors for crack growth in concrete structures and to evaluate the durability performances of different fiber coatings in water, calcium hydroxide solution and cement paste. Optical measurements are done to study the relationship between the crack opening and intensity losses of the optical fibers. The aging process and different environmental effects will be studied in relation to the durability of the optical fiber in concrete. Three types of coatings are tested to assess their performances in the harsh alkaline environment. The overall research consists of the following tasks:

1. To review the fundamental physics of light in order to understand the basics of optical fiber sensor technology. Also reviewed are the history of the theory of light, properties of optical fibers, types of fibers available in the market and the manufacturing process of optical fibers.
2. To study the feasibility of this new innovation in the construction market. Model of innovations as well as implementation and diffusion analysis are discussed to predict the future market of optical fiber sensors. Suggestions regarding the improvement of innovations are mentioned in each model to understand the direction of this technology.
3. To study the optical fiber inclination effect on the crack opening test. Experiments on mortar specimens with an embedded optical fibers at different angles will provide information regarding the recommended angle in the sensor application.
4. To study the pull-out curves for three different types of fiber coatings (polyimide, acrylate, and teftzel-silicone). Tests are carried out at different ages after specimens are subjected to different wetting/drying and freeze-thaw histories. From the results, the coating with the best performance can be identified.

5. Extensive studies on the coating surfaces under SEM (Scanning Electron Microscope) for several periods i.e. 2-week, 1 month, and 3 month, inside three different environments i.e. water, cement paste and in $Ca(OH)_2$ solution (pH = 13.0). It also includes SEM for 20 and 40 wetting/drying cycles as well as 30 and 60 freeze/thaw cycles. These results will supplement the pull-out results as well as show the coating survivability in different environments and time durations.

1.3 Thesis Organization

This thesis consists of seven chapters which are mainly focusing on optical fiber sensor in concrete structures. Chapter One contains an introduction of deterioration in concrete structure . Different types of nondestructive techniques are discussed briefly to look at alternative solutions in term of structural monitoring. Objectives of this study are also presented. The consecutive chapters are outlined in the following manner :

Chapter Two deals with the history of light theories which lead to the invention of the optical fiber. The fundamental of light covers properties of light, the theory of light from the past to the unified theory of today. Types of optical fibers available in the market and its functionality are discussed. Manufacturing of optical fibers are mentioned to study the process behind the technology. Detectors and receivers are covered to give engineers a sense of the system needed in this type of application. Multiplexing, which provides a better solution in sensor system to monitor several changes simultaneously are also discussed.

Chapter Three provides an overview of the research related to mechanical changes in concrete structures. Interferometric sensors are mentioned briefly to give different alternative approaches in measuring changes instead of a simple intensity sensor. Novel applications of optical fiber technology especially in sensing the behavior of structures have been studied and presented in this chapter. A technology transfer example of embedded optical fiber sensors in structures is also presented.

Chapter Four describes the experimental aspect of this study especially the equipment and materials using for these experiments. Specimen preparation and experimental procedures are described in detail.

Chapter Five studies the feasibility of optical fiber sensors in the construction market. Model of innovations are presented to predict the future market of this new technology. The next process of innovation i.e. implementation and diffusion of the technology are also presented to provide transition from the research laboratory into the market. Preliminary results from crack opening experiment is presented to strengthen the choice of this method in NDE discipline.

Chapter Six concentrates on studying the durability of optical fibers in several different environments. The pull-out tests as well as extensive studies of the coating surfaces under SEM provide guidelines to select optical fibers for concrete applications.

Finally, chapter seven will summarize and conclude the results form experimental work and also suggest future studies in the area especially for civil engineering applications.

Chapter 2
Optical Fiber: History and Concept

2.1 Introduction

Optical fibers technology has progressed rapidly since the invention of low loss optical fibers and has been directed towards optical communications applications; however its impacts have spread into different areas of engineering and it has affected civil engineering discipline and received considerable attention especially in the sensing area ever since.

Smart structure technology would certainly change the view of constructions by the 21st century. Potential applications in large scale structures (i.e. bridges, dams, tunnels, buildings, railways and highways) indicate that the use of optical fibers could become one of the promising nondestructive evaluation (NDE) techniques. This chapter briefly reviews the history and properties of light physics without going into all the details of a very complex subject. In addition, it introduces basic knowledge about optical fibers i.e. the properties, different types of fibers and sensors, and how fibers are manufactured. However, before addressing these issues related to optical fiber sensors, one should understand the birth of this potential technology by reviewing the theories behind these sensors.

2.2 History of Light Physics

The presence of light has been witnessed since the beginning of civilizations and it took several hundreds years until people finally understood the concept of this matter. Since light provides the means to probe the external perturbation in a fiber optic sensor, a clear understanding of light is essential to grasp the fundamental behavior of fiber optics.

The curiosity to the physical principles underlying the optical theory has started even before 500 B.C. by Greek philosophers and mathematicians. The chronicle development of light theory spans through more than two millennia; a scientist comes out with his theory while others try to prove it wrong.

There were several eras which the theory of light was being reconstructed to become today's theory of light. Before 500 B.C., there were two leading theories dominated the explanation the nature of light (i.e. the tactile and the emission theories).

2.2.1 The Tactile Theory

The tactile theory based on the ability of eye to transmit an invincible antennae and thus, capable to sense objects which are too distant to be touched by hands [Ditchburn, 1976]. Figure 2-1 shows the eye acts as an active observer in detecting object and in contrary, object becomes a passive matter to be observed by the eye.

The tactile theory is simple to understand since it relates sense of vision directly to the simple sense of touch. The tactile theory has some difficulties in describing why things can be felt, but not seen in the dark, and why bodies can be made visible in the dark by heating them. However, the tactile theory would assume this type of observation by postulating that the visual probes are able to feel only certain kind of surfaces therefore the simple relation to the sense of touch has been lost. The theory becomes intolerably complicated and certainly could not explain the nature of light thoroughly. For these reasons, the emission theory gradually replaced the tactile theory. About the year 1000, the tactile theory was finally abandoned under the influence of Arabian astronomer Alhazen [Ditchburn, 1976].

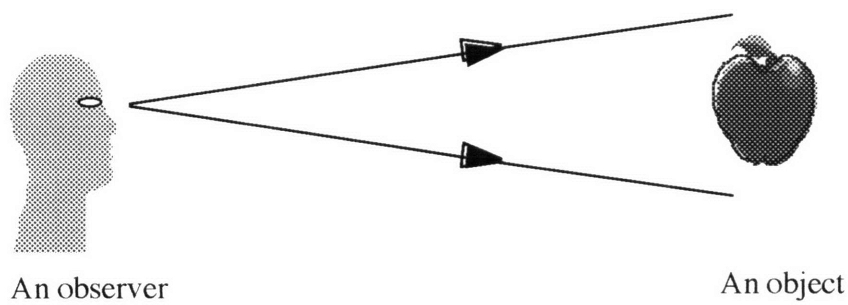


Figure 2-1: In the tactile theory, the eye acts as an active observer in detecting object and in contrary, object becomes a passive matter to be detected by the eye.

2.2.2 The Emission Theory

Contrary to the tactile theory, the emission theory considered something is emitted by bright objects and when this thing enters the eye, it is able to affect a sensitive part of the eye and thus gives rise to sensation of sight. The emission theory tried to explain the confusion of the tactile theory. It assumed that some bodies emit a radiation to which the eyes are sensitive, and some others are able to reflect or scatter this radiation so that it enters the eyes. Figure 2-2 shows the eye acts as a passive observer and in contrast, object emits a radiation which could be transmitted as particles or waves into the eye.

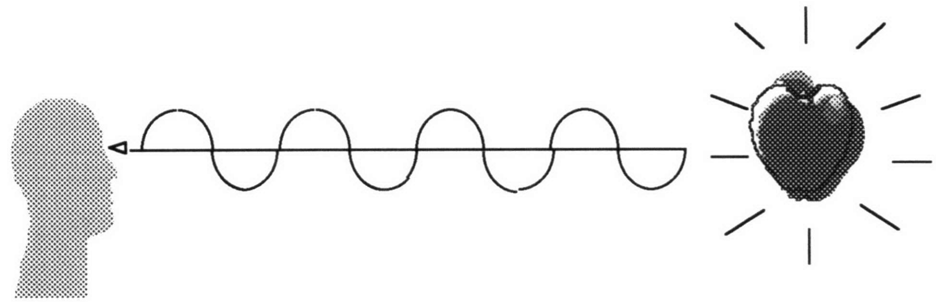


Figure 2-2: The emission theory, the eye acts as a passive observer and in contrary, object emits a radiation which could be transmitted as particles or waves into the eye.

2.2.3 Corpuscles or Waves

During the 500 years span, the emission theory remained to be an unchallenged theory until some physicists questioned how the light transmitted to eyes. René Descartes (1596-1650) was considered as a pioneer in explaining the "missing piece" of the nature of light on the basis of his metaphysical ideas [Born, 1975] [Descartes, 1637]. He was also the leading scientist who postulated that the light was transmitted as minute particles (i.e., corpuscles) while others confirmed the light was transmitted as waves.

The confusion on how the light is transmitted would not have been settled without proving it with experimental methods. Galileo Galilei (1564-1642) is the father of experimental methods, his technique in approaching problems demonstrated the power of experimental method, persuaded other scientists to emphasize more in doing experiments, thus led to the explanation of this intricated dilemma.

2.2.4 The Particle Theory of Light

Sir Isaac Newton (1642-1727) believed that bright bodies emitted radiant energy in very small particles instead of waves of light. These particles are irregularly ejected in straight lines pattern. Using his theory so called *particle theory of light,* he was able to clarify the laws of reflection and refraction[1].

Everyone agreed in Newton's theory regarding the reflection law. The law of reflection is easily explained by the particle theory, however, a small group of scientists opposed Newton's theory in explaining the refraction theory. According to Newton, at an air-water surface, light was attracted strongly to the water which elevated the perpendicular momentum to the surface. This shift in momentum would cause the light to bend towards the normal surface. From this statement, Newton then concluded that the velocity of light must be greater in water than in air [Tripler, 1976]. In order to explain the refraction law, the corpuscular theory has to assume that some, but not all, of the corpuscles are able to penetrate the surface. This assumption creates problem in explaining the theory since the corpuscles theory believed that corpuscles representing one kind of light that are all the same.

This type of theory involves many difficulties. If it were correct the corpuscles would certainly be scattered at the surface and there would be diffuse instead of regular reflection and refraction. The corpuscular theory cannot give an exact solution of how much light has been transmitted and the relation between the angle of incidence and the

[1] The law of reflection was discovered by Heron of Alexandria in the second century A.D., in his book *Catoptrica* where he derived the law of reflection using a principle of minimum distance. The law of refraction was not formulated until 1621, when it was discovered experimentally by Willebrord Snell [Meyers, 1991].

angle of refraction [Ditchburn, 1976]. The corpuscular theory also has a difficulty explaining interference and diffraction which could be explained clearly by the wave theory of light.

2.2.5 The Wave Theory of Light

In 1665, Robert Hooke, a famous English scientist, published a book called *Micrographia*. In this book, he tried to illustrate the *wave theory of light* [Seippel, 1983]. The other leading scientist who agreed with the wave theory of light was Christian Huygens, a Dutch physicist. He stated that light is created by the molecular vibrations in luminous material instead of small particles. In his finding in 1690, Christian Huygens stated that each point of a wavefront may be assumed as a source of new waves. Huygens' theory was derived based on geometrical construction, called *Huygens' principle,* which says : *All points on a wavefront can be considered as point sources for the production of spherical secondary wavelets. After a time t the new position of the wavefront will be the surface of tangency of these secondary wavelets.* Figure 2-3 shows how the wavefront moves from initial position to final position at time t ; ct is the radius of spherical waves where c is the speed of light in free space [Resnick et al., 1988]. This theory is employed to derive the law of reflection and Snell's law of refraction.

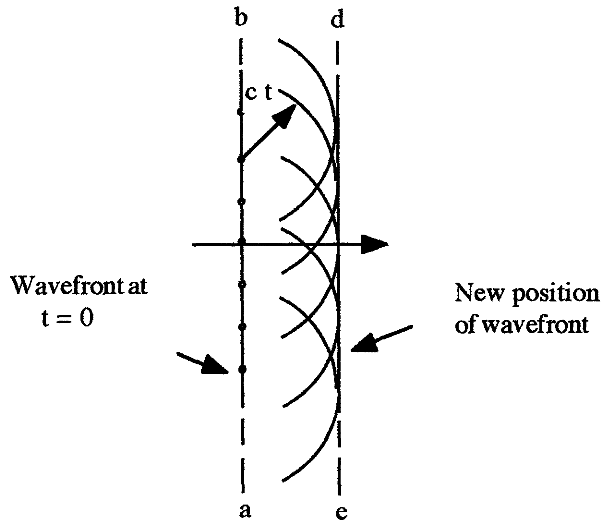


Figure 2-3: The propagation of a plane wave in free surface is described by the Huygens construction. Note that the ray (horizontal arrow) representing the wave is perpendicular to the wavefronts. (Adapted from R.Resnick, Fundamental of Physics, 1977, Sect. 43-2, pp. 943).

According to Huygens' theory, light traveled slower in the water rather in the air. However, Newton rejected Huygens' theory regarding the wave theory of light and because of Newton's reputation, the majority of scientists believed that Newton's theory was the correct one. Even until the middle of the seventeenth century, most scientists, particularly in the field of optics, acknowledged that the corpuscular theory of light was a sole theory to explain how the light is transmitted. Newton's particle theory of light was accepted for more than a century.

The significant works in the late nineteenth and early twentieth century gave birth to the new area of wave light theory. During this period of time, many young scientists got involved in this discipline. The revival of the wave theory of light initiated by Thomas Young, British physicist, by introducing the idea of interference as a wave phenomenon in both light and sound which reinforced Huygens' wave theory. Young discovered that the dividing of a beam of light into a refracted ray at the interface between two mediums was expected from the wave theory but had not been satisfactorily explained in the corpuscular theory. Figure 2-4 describes two-sources interference pattern. Although Young's work clearly explained that the light has a wave nature, his work went unobserved for more than a decade [Tripler, 1976]. It remained until 1862 for the controversy between the Newton corpuscular theory and the Huygens -Young

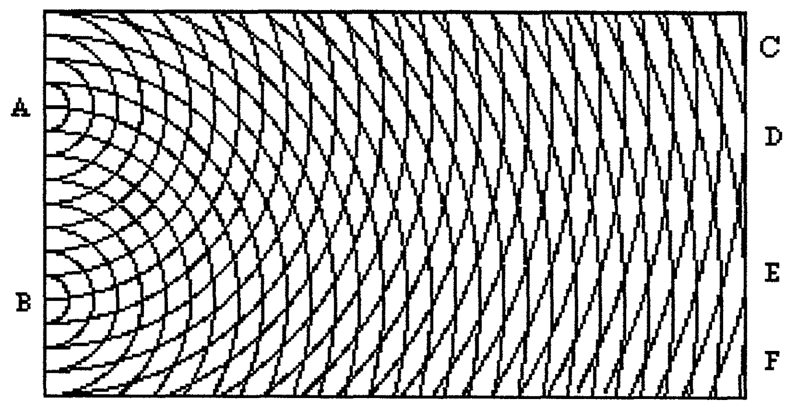


Figure 2-4: Thomas Young's drawing of a two-source interference pattern. (Adapted from P.Tripler, Physics Vol. 2, 1976, Ch. 26, pp. 606) (Courtesy of the Niels Bohr Library, American Institute of Physics)

wave theory to be resolved. The turning point of the wave theory took place when Augustin Fresnel challenged the Newton's particle theory; his extensive experimental works on interference, diffraction and derivation of the mathematical basis on the wave theory reinstated the wave theory of light. In the same year, Foucault showed that the speed of light was less in the dense medium, conclusively disproving the corpuscular theory of Newton. Their observations opened the eyes of many scientists to admit that wave theory of light as an undisputed theory.

2.2.6 The Electromagnetic Theory of Light

The interest in finding the ultimate theory in explaining the nature of light had progressed ever since. Consequently there had been an intense research effort to establish a concrete explanation regarding all contradictions against wave theory. Albert Michelson, American physicist, measured accurately the speed of light. Michelson's method involved modification of the techniques used by Fizeau in 1849 and Foucault in 1862 in measuring the speed of light.

The wave theory of light was discovered before the development of the electromagnetic theory. Although the wave theory could explain the fundamental phenomena of reflection, refraction, interference, diffraction and polarization, some complicated problems regarding the medium properties still cannot be resolved using this theory. In order to explain these details, it was necessary to make special assumptions concerning the density and elasticity of this medium, and also the conditions obtaining at the surface separating two media such as glass and air. These details clearly revealed the inconsistencies of the theory. These difficulties were finally resolved by Maxwell's *electromagnetic theory of light* [Ditchburn, 1976]. Maxwell with his mathematical theory of electromagnetism suggested the possibility of the propagation of transverse electromagnetic waves in which both the electric and magnetic induction field vectors oscillate perpendicularly to the direction of propagation. The velocity of propagation can be calculated from constants measured in laboratory experiments on electricity and magnetism. When Rudolph Kohlrausch (1809-1858) and Wilhelm Weber (1804-1891) carried out these measurements, the velocity turned out to be the velocity of light. This led Maxwell to postulate that light waves are electromagnetic waves and the theory was experimentally verified in 1888 by Heinrich Hertz (1857-1894). Maxwell was also able to show the phenomena of reflection and refraction including an account of the propagation of electromagnetic waves in media such as glass[2]. The best part of electromagnetic theory is that it did not introduce any arbitrary assumptions. However the weakness of Maxwell's theory is that it could not explain the process of emission and absorption, in which the interaction between matter and the optical field became important [Born, 1975].

Despite the success of electromagnetic theory in dealing with the propagation, interference, and scattering light, the experiments in the late nineteenth century and the beginning of the twentieth century led to reintroduction of the corpuscular theory however in a form different to that introduced by Newton.

2.2.7 Quantum Theory of Light

The law underlying the process of emission and absorption is the main subject of modern physics. The detailed theory of the interaction between the optical field and matter required the extension of the methods of quantum theory. It became obvious that classical mechanics is inadequate for a proper description of events occurring within the atom and must be replaced by the *quantum theory* which originated in 1900 by Max Planck (1859-1947). He developed his universal mathematical constant that light is emitted by atoms in multiples of a certain unit or quanta. In 1905, Albert Einstein (1879-1955) explained the

[2] The derivation of Maxwell's theories are covered in appendix A.

photoelectric effect by using the idea of light quanta and later applied it to the emission as well as the absorption of radiation by atoms [Meyers, 1991]. It was found that light could induce atoms to emit electrons. When light released an electron from an atom, the energy possessed by the electron greatly exceeded that which the atom could, according to the electromagnetic-wave theory, have received. Einstein suggested that, in order to give an adequate description of this observation, it was necessary to assume that the energy of a light beam is not evenly spread over the whole beam, but is concentrated in certain regions. These localized concentrations of energy are called *photons*. Albert Einstein also published what is understood as the *theory of relativity* which at the end showed that his theory is relevant to the theory of light.

During this period the confusion between the electromagnetic-wave theory and quantum theory arouse and became an interesting topic in scientific discussion. On one side stands all the phenomena of interference, diffraction and polarization, which are well described by the electromagnetic-wave theory. On the other side, modern experiments have greatly increased the number and range of the experiments which are readily described in terms of photons. Danish physicist Niels Bohr (1885-1962) proposed his famous *principle of complementarity* . It states that to understand any given experiment, one must use either the wave or the photon theory, but not both. However, Bohr could not figure out which one was the correct one. The facts that some experiments indicate that light behaves like a wave and others indicate that it behaves like a stream of particles, confused scientists at that time. These two theories seem to be incompatible but both have been shown to have validity. The complete understanding of the dual nature of light did not come until the 1920s, when the diffraction of electrons was discovered by

Davisson and Germer and the *theory of quantum mechanics* was worked out by Schrödinger, Heisenberg, Dirac, and others.

2.2.8 The Unified Theory of Light

Finally, the new theory called *quantum mechanics,* unifies the wave-particle duality into a single consistent theory. The *unified theory* (i.e., the modern quantum mechanics) was proposed by De Broglie and Heisenberg which based on the following statements :

1. Every moving element of mass has associated with it a wave which length is given by the equation :

$$\lambda = h / mv \tag{2.1}$$

where

λ = wavelength of the wave motion,
h = Planck's constant = 6.626×10^{-34} J . s,
m = mass of the particle,
v = velocity of the particle.

2. It is impossible to simultaneously determine all of the properties that are distinctive of a wave or a corpuscle.

The theory shows, in a systematic and logical way, that wave and particle concepts are each to be used in appropriate contexts, and it shows the relation between them. According to this theory, energy can be carried from one place to another basically in two ways: by particle or by waves. As a theory, quantum mechanics has performed extremely successful. This new theory could verify results from both modern and classical physics of light. The modern quantum mechanics combines the appropriate parts of the electromagnetic-wave theory, the quantum theory and the relativity theory. The question as to the "true" or "ultimate" nature of light remains unanswered. However, current technological developments certainly might change what one will believe in the future.

2.3 Properties of Light

The theory of light is of course being followed by the discovery of the properties of light itself. The theory should verify that the properties of light apply in the context. These combination of the properties explain the nature of light. The properties of light are reflection, refraction, interference, diffraction, and polarization.

2.3.1 Reflection and Refraction

Whenever a beam of light from one medium, such as air, strikes a second mirror like medium such as glass, part of the beam is reflected while the other part is refracted. Over 95 percent of the light may be reflected [Giancoli, 1988]. Figure 2-5 illustrates the *law of reflection* where *the angle of incidence equals the angle of reflection*. The angle is formed by the reflected beam and a perpendicular line to the intersection is called the

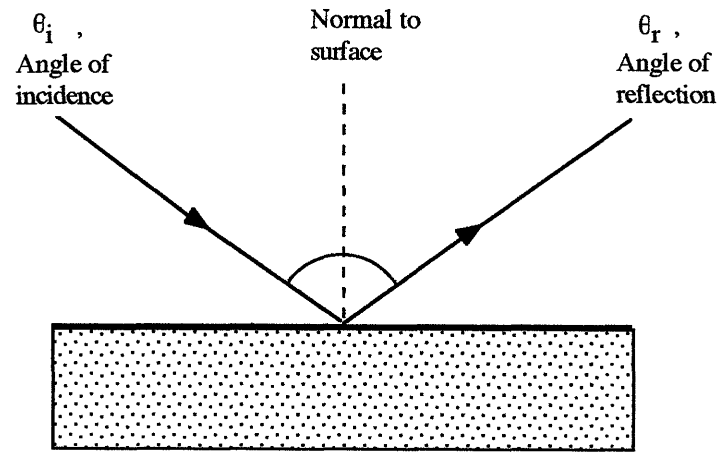


Figure 2-5: The law of Refection where the angle of incidence equals the angle of reflection.

angle of reflection. There are two kind of reflections i.e. diffuse reflection and specular reflection. Diffuse reflection which is shown in Figure 2-6(a), occurs when an incident beam of parallel light strikes upon a rough surface where an object could be seen in different angles. If the surface is smooth such as for optical fibers, the reflection is called specular reflection where the angle of reflection is equal to the angle of incidence (Figure 2-6(b)).

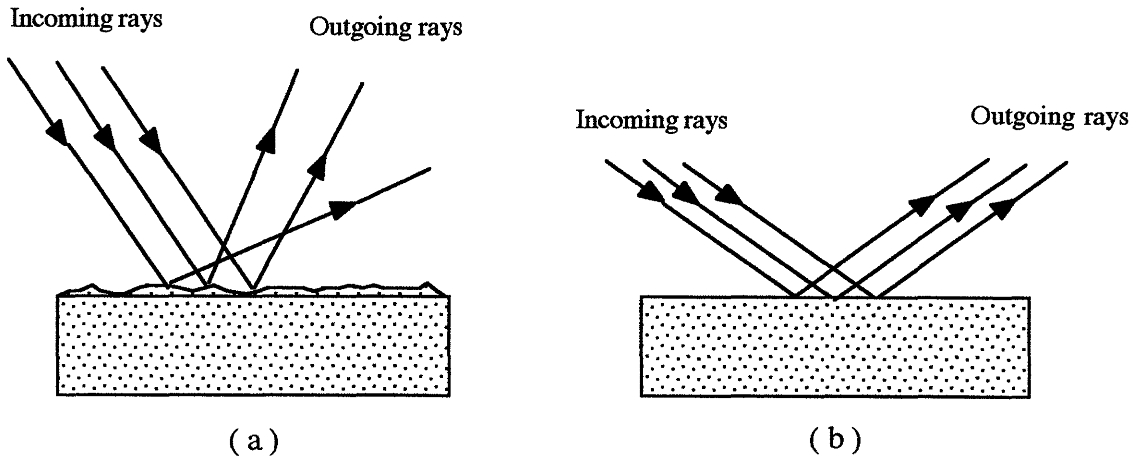


Figure 2-6: Type of reflections: (a) The diffuse reflection occurs when light strikes upon a rough surface where an object could be seen in different angles. (b) The specular reflection occurs when the surface is smooth (i.e. optical fiber).

Whenever a beam of light passes from one medium into another, part of the incident light is reflected at the boundary. The other part bends into the second medium. This bent part of light beam is called refraction. Refraction occurs when light travels at different velocities in the two media. Figure 2-7(a) displays a beam of light passing from air into water. The angle θ_i is the angle of incidence and θ_r is the angle of refraction. The bending of the ray toward the normal depends on the index of refraction (n). Figure 2-7(a) also shows that whenever a ray travels from lower index of refraction to higher one, the ray tend to bend closer to the normal. In contrast, Figure 2-7(b) shows the ray bends away from the normal when the ray travels from higher index of refraction to lower one.

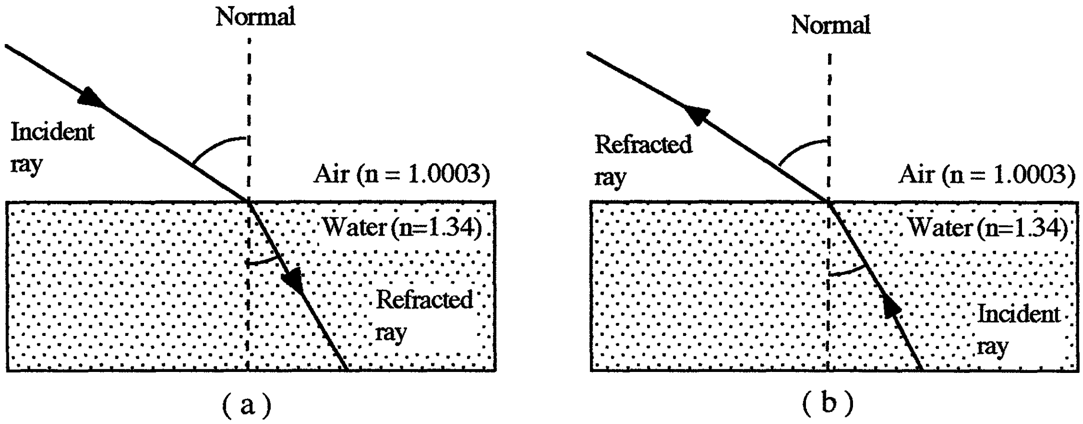


Figure 2-7: The refraction of a light beam: (a) a light beam travels from lower index of refraction to higher one. (b) a light beam travels from higher index of refraction to lower one.

The angle of refraction depends on the speed of light in the two media and on the incident angle. The *law of refraction* or the Snell's law states that *the ratio of the sines of the angles of incidence and refraction is equal to the ratio of the velocities of light in the two media.*

$$\frac{\sin i}{\sin r} = \frac{\upsilon_1}{\upsilon_2} \tag{2.2}$$

The ratio between the velocity of light c in free space and its velocity υ in a particular medium is called the *index of refraction* of the medium. The greater the index of refraction, the greater the extend to which a light beam is reflected upon entering or leaving the medium.

$$n = c / \upsilon \tag{2.3}$$

From equation (2.3), one can rewrite the Snell's law in term of index of refraction n_1 and n_2 of two successive media. In these media, light has the respectively velocities,

$$\upsilon_1 = \frac{c}{n_1} \quad \text{and} \quad \upsilon_2 = \frac{c}{n_2}$$

Substitute these two velocities into equation (2.2), Snell's law becomes

$$\frac{\sin i}{\sin r} = \frac{v_1}{v_2} = \frac{c / n_1}{c / n_2} = \frac{n_2}{n_1}$$

And the more common Snell's law is usually written in the form

$$n_1 \sin i = n_2 \sin r \tag{2.4}$$

When light passes from one medium into another medium where the index of refraction is less (i.e. glass to air), the ray bends away from the normal. At a certain incident angle , the angle of refraction will be 90° which is called the *critical angle* θ_c. To find the value of the critical angle, let $\theta_i = \theta_c$ and $\theta_r = 90°$ in Snell's law, equation (2.4) becomes

$$n_1 \sin \theta_c = n_2 \sin 90°$$

$$\sin \theta_c = n_2 / n_1 \tag{2.5}$$

For incident angles greater than θ_c , there will be no refracted ray, all of the light is reflected. This phenomena is called *total internal reflection* which is described in Figure 2-8. However one must note that the total internal reflection only occurs whenever a light strikes a boundary where the index of refraction of the medium is less dense.

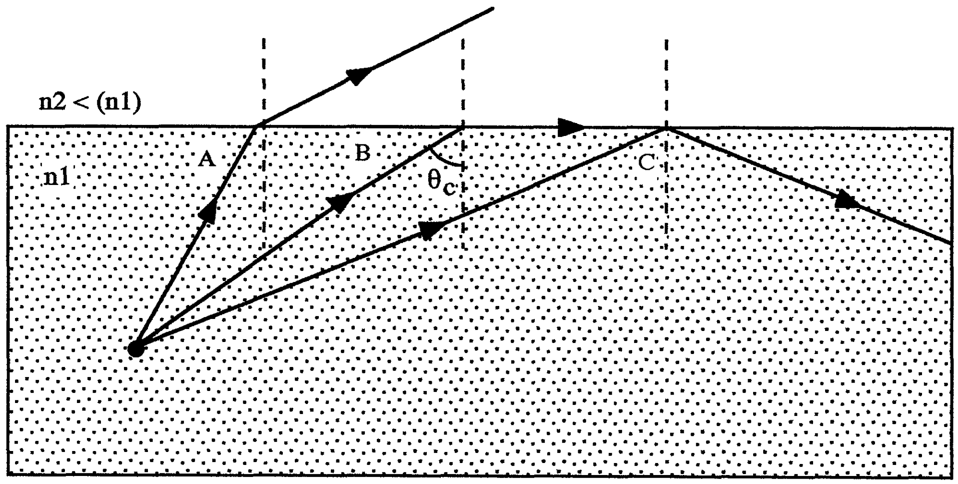


Figure 2-8: Total internal reflection occurs when $n_2 < n_1$. If $\theta < \theta_c$, light rays are totally internally reflected, if $\theta > \theta_c$, only part of the light is reflected and the rest is refracted.

2.3.2 Interference

When light waves from one source are mixed with those from another source, the two waves are said to *interfere*. The principle of superposition governs the interference of two or more waves. According to principle of superposition, when two or more waves of the same nature travel past the same region of space at the same time, the amplitude at that point is the sum of the instantaneous amplitudes of the individual waves.

Phase of a light wave can only be measured by comparing it to other light waves of the same wavelength. There are two kind of interferences, constructive and destructive interference. Constructive interference occurs when both of the waves are not opposite to one another and the resultant displacement is greater than that of either pulse, on the other hand, the destructive interference refers to partial or complete cancellation of waves out of phase with one another. Figure 2-9 describes the principle of superposition.

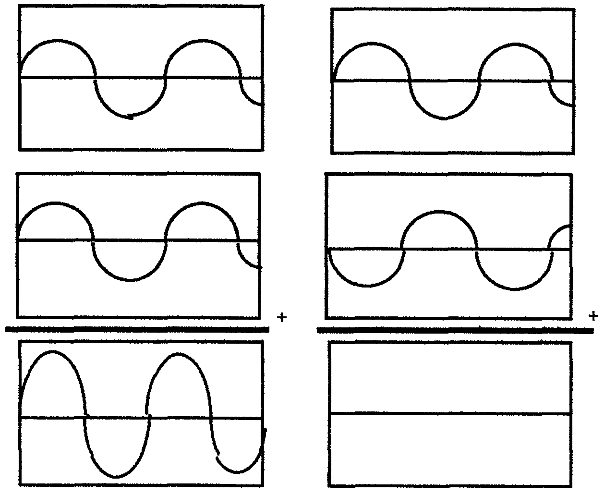


Figure 2-9: The principle of Superposition where two waves interfere: (a) constructively, (b) destructively. (Adapted from D.Giancoli, Physics, 1988, Sect. 16-9, pp. 371).

In 1801, Thomas Young demonstrated convincingly the evidence of interference of light and established a firm foundation to the wave theory. Figure 2-10 shows a diagram of Young's famous double-slit experiment. A source of monochromatic light (i.e., light consisting of only a single wavelength) passes through a slit S and another screen with two similar slits S_1 and S_2 and then falls on the viewing screen. If light consists of small particles, one would expect to see two bright lines on screen placed behind the slits as in Figure 2-10(b). However, one would see a series of bright lines as shown in Figure 2-10(c). Also bright line rather than dark one is found on the barrier between the slits S_1 and S_2. These observations prove that interference is governed by the wave theory. What actually happens is that each slit acts as a source of secondary wavelet as explained in the Huygen's principle.

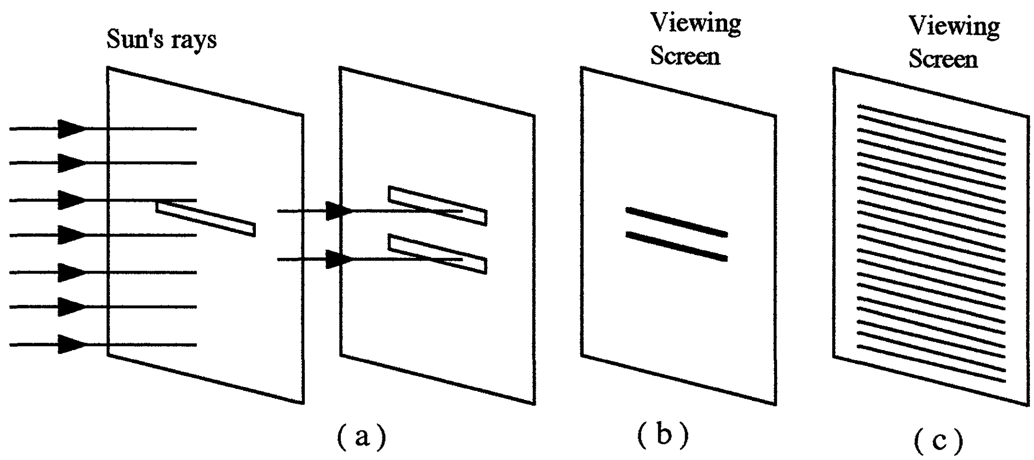


Figure 2-10: (a) Young's double-slit experiment. (b) If light consists of particles, one would expect to see two bright lines behind the slits. (c) Young observed many lines which he agreed that light consists of waves. (Adapted from D.Giancoli, Physics, 1988, Sect. 37-3, pp. 787).

There are two major reasons to identify light interference. First, light waves have a very short wavelengths and the human eye only could see wavelengths vary from 3.8×10^{-7} m for violet light to 7×10^{-7} m for red light. Second, the source of light only emits short waves of random phase, so that the human eye could not observe unless special procedure are used [Beiser, 1978]. Two wave sources are said to be *coherent* if there is a consistent phase relationship between the two waves and they both have the same wavelength. An interference pattern is observed only when the sources are coherent.

White light is a combination of all visible wavelengths and when the white light enters a prism, the different wavelengths are bent to different degrees, this phenomena is so called *dispersion.* Dispersion deals with the speed of light in medium and the variation of wavelength; since the index of refraction is greater for the shorter wavelengths, violet light is bent the most and red light is bent the least. Figure 2-11 illustrates a white light when it enters a prism.

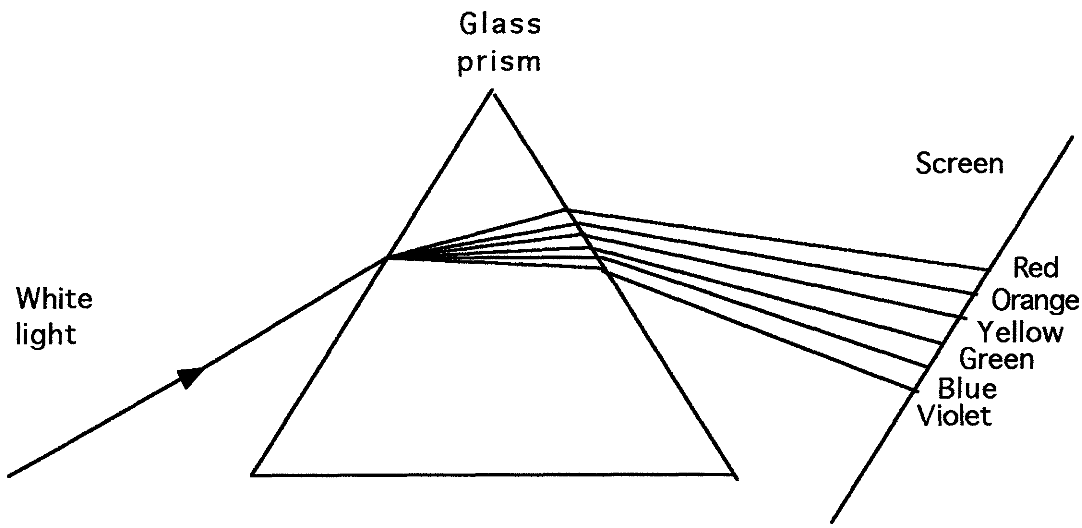


Figure 2-11: Dispersion by prism: white light is dispersed into its component colors by refraction when passed through a prism.

2.3.3 Diffraction

Not until the discovery of diffraction that the wave theory gained its winning to the particle theory. Propagation of a wave is quite different from the propagation of a stream of particles. Figure 2-12(a) indicates particles being released from a source, the barrier would stop any particles which striking it. Those getting through the opening would be confined to the narrow angle. However, if light consists of waves as shown in Figure 2-12(b), the rays appear to bend around the edge of the barrier. This bending of waves around the edge of an obstacle in their path is called *diffraction* as illustrated in Figure 2-13. Diffraction grating consists of a large number of equally spaced slits. The spacing of the slits for such grating is approximately 1.27 x 10^{-4} cm [Tripler, 1976].

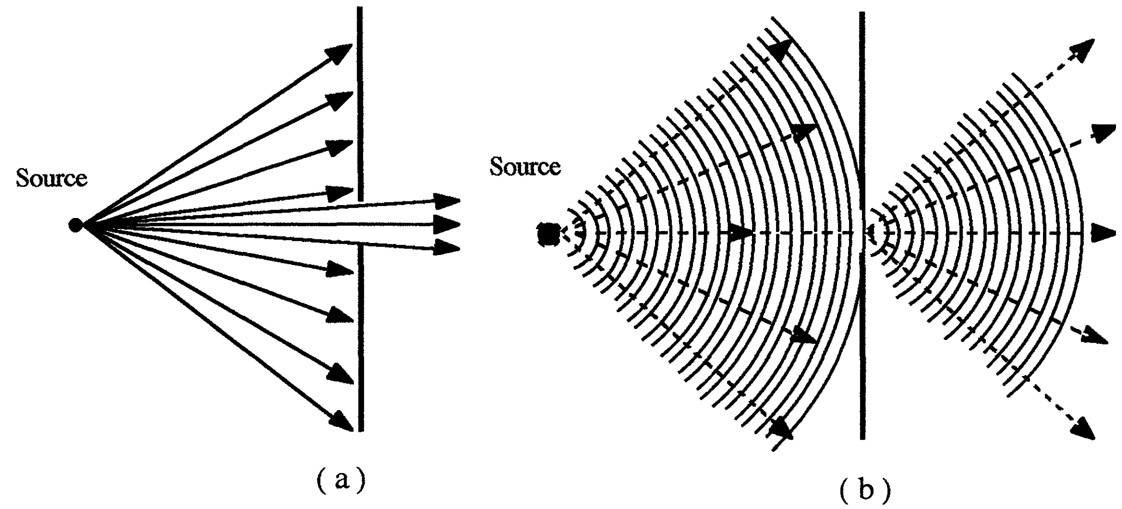


Figure 2-12: Comparison of the transmission through a narrow opening in a barrier of (a) a beam consists of particles and (b) a beam consists of waves. (Adapted from P.Tripler, Physics, Vol.2, 1976, Ch. 25-1, pp. 586).

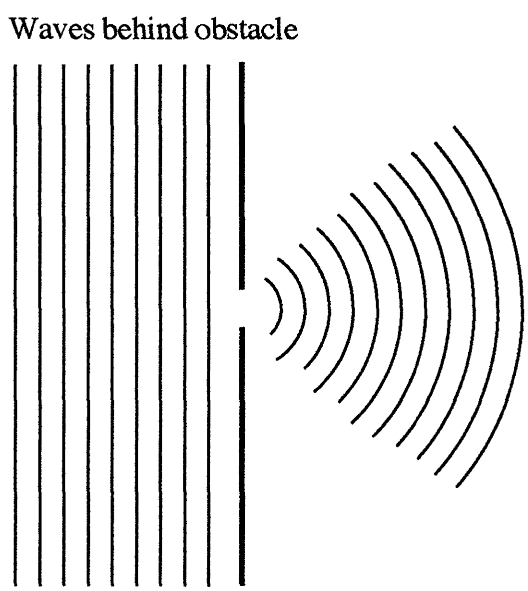


Figure 2-13: The bending of the waves resulting from the limiting of the wavefront at the barrier which is called diffraction. (Adapted from P. Tripler, Physics, Vol. 2, 1976, Ch. 25-1, pp. 586).

2.3.4 Polarization

According to Maxwell, light consists of transverse waves and like any electromagnetic wave, light can be polarized. An electromagnetic wave comprises electric and magnetic fields which are oscillating perpendicular to each other and propagating in a direction perpendicular to both, as displayed in Figure 2-14.

A *polarized* beam of transverse waves is a beam which vibrations occur in only a single direction perpendicular to the direction in which the beam travels, so that the entire wave motion is confined to a plane called the *plane of polarization*. An *unpolarized* beam of transverse waves is one whose vibrations occur equally often in all directions perpendicular to be the direction of motion. There are two important phenomena in producing polarized light from unpolarized light, *absorption* and *scattering*.

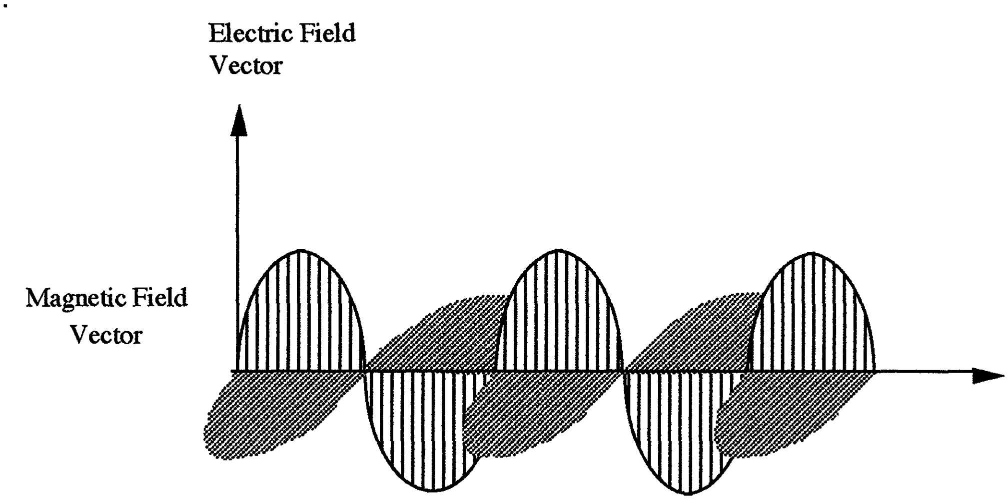


Figure 2-14: The electric and magnetic field vectors are in phase, perpendicular to each other, and perpendicular to the direction of propagation of the wave.

Absorption occurs whenever a beam of light enters matters causing reduction in intensity as it travels further into the medium. There are two types of absorption, general and selective [Seippel, 1983]. General absorption reduces all wavelengths of light by equal amount while selective absorption only absorbs certain wavelengths and rejects others.

Scattering is almost the same to absorption except the medium is occupied with a light cloud of smoke. The smoke would scatter some of the light from the main beams; therefore, the intensity of light from a fixed distance would decrease. Rayleigh scattering is caused by micro irregularities in the medium. Due to these irregularities the returned wave does not follow the main wave but scatters; therefore, the intensity of the beam is diminished.

2.4 Introduction to Fiber Optics

Fiber optics is the branch of optics dealing with the transmission of light through extremely thin fibers of glass, plastic, or other transparent material and generally includes the technology of their manufacture and application. The transmission of light through fibers is based on the phenomenon of total internal reflection, which occurs when light is obliquely incident on an interface between two media of different refractive index at an angle greater than the critical angle.

In the early 1970s, with the invention of relatively low-loss optical fibers, it became feasible to utilize the high bandwidth capacity of an optical carrier in a confined transmission medium. Since that moment, the use of fiber optics has been continuously expanded. First, it was used to establish a new technology in telecommunication area, and later the technology spread to different areas which enable other branches of engineering to take advantage of the developments.

2.4.1 Early Developments

Although the idea of transmitting light through a cylinder of transparent material by series of total internal reflection as a means of conveying light is not a recent invention, and, indeed, had been practiced by ancient glassblowers; it was not until 1870's that British physicist John Tyndall demonstrated the phenomena in a simple experiment [Seippel, 1984]. He displayed an effective way of conveying light from one place to another. According to Tyndall, total internal reflection kept the light from leaking out from water flow where the light will follow water into a container and flowing from the container. Water has a refractive index of about 1.33, while air has a value which is equal to unity , this difference guides a portion of light entering the water stream, even around bends. Figure 2-15 illustrates the Tyndall's experiment using water as a medium to trap the light. Based on this phenomena, many scientists spent their times in research laboratory to invent a more efficient system in transferring the light and finally found what is so called today as optical fiber.

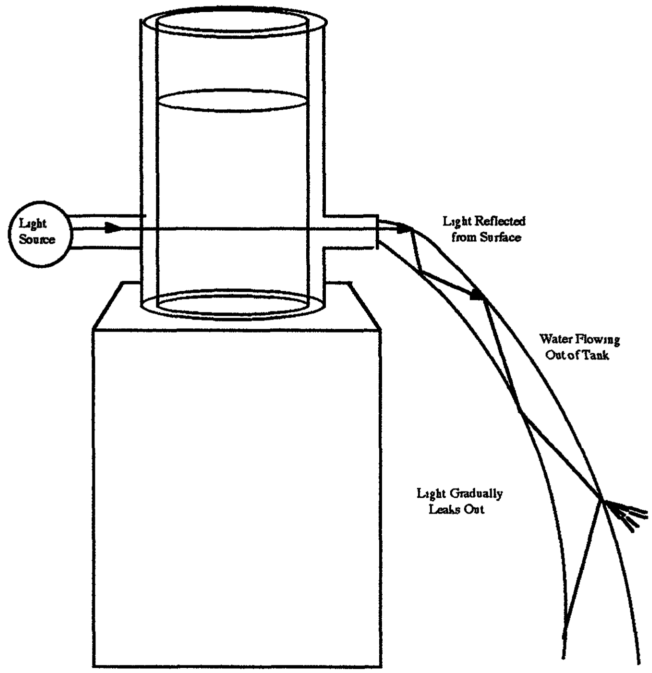


Figure 2-15: The early principle of fiber optic where a light could be transferred from one point to another. The light finally leaks out from the water as the turbulence is introduced in the system. (Adapted from J.Hecht, Understanding Fiber Optics, 1993).

2.4.2 Optical Fiber Materials

Optical fibers are fabricated from glass or plastic or sometimes a combination of the two; for instance, glass core-glass cladding, plastic core-plastic cladding, or glass core-plastic cladding. Plastic fibers have a major drawback i.e. a relatively high loss of light transmission and it could only use for short length of transmission. However, this kind of fibers provide a relative easy termination of the fiber ends. On the other hand, glass fibers have a relatively low loss and can be exploited over long distances of transmission, however the termination of the fiber ends is more difficult and sometimes create problems. Careful attention to polishing and controlling the cutting method will take care of this drawback.

In order to optimize the performance of the fiber, several mixtures have been selected to give better strength, lower attenuation, better flexibility, or specific parameter requirements. The mixtures of oxides, sulfides, or selenides are the most common ingredients in producing a high quality optical fiber [Seippel, 1984]. Coating optical waveguide fibers as they are drawn has been found to be an effective means of preserving waveguide strength. Coating can be a significant factor in the reduction of microbending losses in addition to improving the strength of the fiber.

2.4.3 Types of Fibers

There are several major types of optical fibers used commercially in the area of communication. Some of these are being used as medical instruments, or as sensors for both aerospace and civil engineering disciplines. They are made differently, operate in different ways, have different characteristics, and serve different functions.

There are many different applications which measured different parameters thus scientists invent several types of optical fibers according to their best suited applications. Interests on specific types of optical fibers have grown and declined. The discussion of types of fibers is limited to the ones related to current research, the rest of the types are not discussed because there are beyond the scope of this thesis. There are several criteria that one should notice in order to choose the most suitable fiber for specific applications. This includes the following [Hecht, 1993]:

- Low attenuation to maximize spacing of repeaters or amplifiers
- Maximization of transmission bandwidth or speed
- Cost of fiber
- Transmission wavelength
- Capability of surviving in high temperature or other environmental conditions
- Strength and flexibility of the fiber
- Immunity to electromagnetic induction (EMI)

The transmitting medium is the most important component in the optical fiber system. It is the rapid development of a low-loss and high bandwidth fiber that made this field grows rapidly. Technically, there has been a fiber with the loss as low as 0.16 dB/km at 1500 nm. In the telecommunication system, a fiber as long as 100 km has performed well without the use of repeaters [Aggarwal, 1984].

Nowadays, there are two most common operating classes of fibers based on their modal properties utilized in sensor technology, (1) single-mode fibers and (2) multimode fibers. Single-mode fibers are classified into three different types of fibers i.e. step-index, dispersion-shifted and dispersion-flattened. On the other hand, multimode fibers are grouped into two types, step-index and graded-index.

2.4.3.1 Single-mode Fibers

Single-mode fibers are mostly available with the step-index profile. The higher index of refraction of the core compared to the cladding results total internal reflection at the core cladding interface in step-index fibers. The peak difference in refractive indices of the core and the cladding is between 1 to 2%. This index difference determines the numerical aperture of the fiber, which in turn determines the amount of light the fiber can be collected from an optical source. Single-mode fiber usually has a very small core diameter (i.e. 5 to 10 μm) and because of its characteristic, only one mode is allowed to propagate effectively as shown in Figure 2-16.

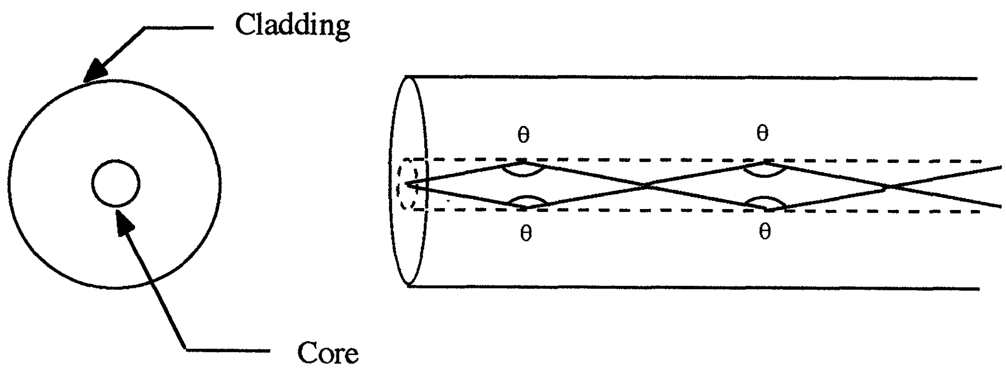


Figure 2-16: Transmission modes of light in the step-index single-mode core where the light is reflected with the same pattern of angle from wall to wall.

The primary advantage of single-mode fiber is that the modal dispersion is eliminated since only one mode is being propagated. In multimode fibers, modal dispersion limits the bandwidth. Other advantages compared to multimode fibers are that the fiber is not sensitive to microbending[3]. Also less repeaters are needed since this type of fiber can transmit light with little loss up to 30 to 40 km. Since there are less parts, less maintenance is necessary making the overall system more reliable and efficient [Christian et al., 1989]. On the other hand, there is a significant disadvantage for using single-mode fiber i.e. the small dimensions of the core make tolerances tight in transferring light into fibers which possibly create a maintenance problem. Figure 2-17 shows typical cross-section and refractive index profile of the single-mode fiber.

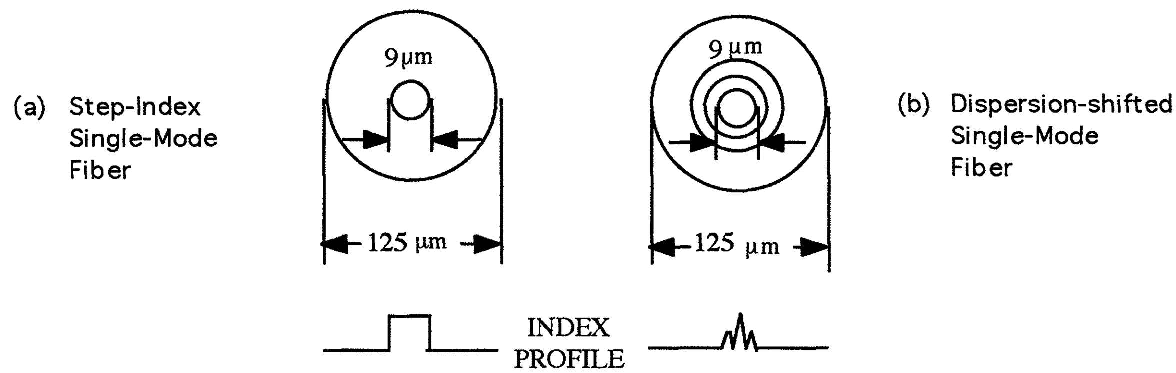


Figure 2-17: (a). The cross-section of the step-index single-mode fiber where the glass composition changes abruptly (b). The cross-section of the dispersion-shifted single-mode fiber with inner and outer layers change the refractive index profile of the fiber.

Another type of single-mode fiber is dispersion-shifted; the only natural difference is this type has two layers of core and cladding. The inner core has a refractive index graded with triangular profile which is surrounded by an inner cladding The next layer is the outer core layer which refractive-index is higher than the inner cladding but lower compared to inner core and this layer too is wrapped with an outer cladding. This different configuration shifted the point of zero dispersion from 1300 nm to 1550 nm

[3] For transmitting light purpose, microbending sometimes becomes a major obstacle which effect could be reduced by the presence of amplifier, however in the sensor application, microbending sometimes is utilized to sense the change in properties of a material.

where attenuation is considerably lower. The main advantage by shifting the zero dispersion is that repeater spacings could be stretched as far as 80 km range. The shifting does not come without cost, it will increase fiber attenuation slightly above that of step-index single-mode fibers and could only be operated at 1550 nm.

Different way to improve the range flexibility of the fibers is to flatten the dispersion curve so the attenuation is low between the range of 1300 nm to 1550 nm. This new type of fibers is still new and have yet been proven practical [Hecht, 1993].

2.4.3.2 Multimode Fibers

The term multimode means that light can be propagated in the same wavelength along different ways through a fiber which causes the waves to arrive at the opposite end of fiber at different times. Multimode fibers could be classified into two different types of fibers i.e. step-index and graded-index multimode fibers.

The major attraction of step-index multimode fibers is the relatively easy in collecting light because of larger core compared to single-mode. Typical numerical apertures (N.A) ranges from 0.2 to 0.4 for silica-core fibers and their core diameter usually ranges from 100 μm to 200 μm. This combination of large core diameter and high numerical apertures allows the use of inexpensive large-area light sources such as LED and avoids the precise connectors problem. Although almost all commercially produced fibers are multimode, signal bandwidth is considerably higher in single-mode fiber. Drawbacks of these fibers are: limited transmission bandwidth, smaller spacings between repeaters compared to single-mode fibers, sensitive to microbending and higher losses in transmission due to larger core.

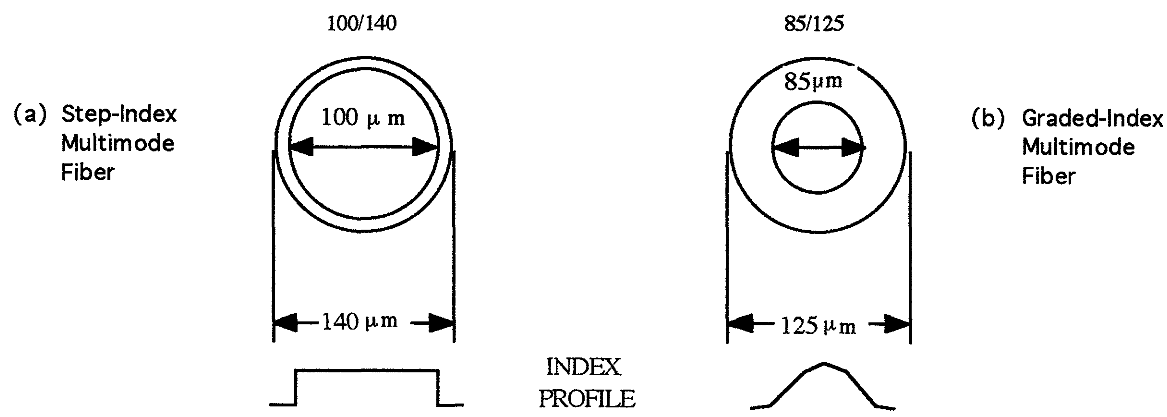


Figure 2-18: Typical multimode fibers cross-sections (a). The cross-section of step-index multimode fiber with an abrupt refractive index (b). The cross-section of graded-index multimode fiber with gradually changes from core to cladding of refractive index profile.

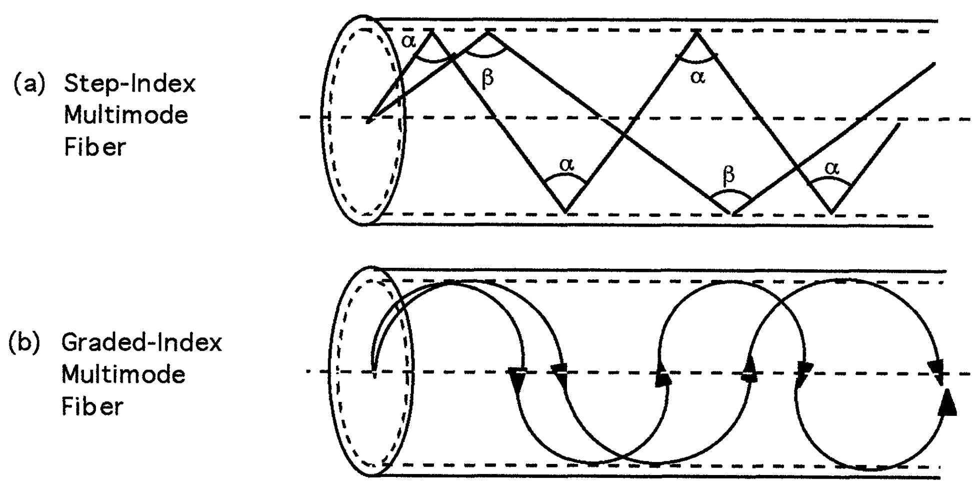


Figure 2-19: Typical light propagations inside the fibers (a). Step-index multimode fiber (b). Graded-index multimode fiber.

With the rapid advancement of technology in optical fibers, a new type of fibers was invented. The fibers could deal with the drawbacks of the step-index multimode, especially in reducing the high modal dispersion; these fibers are so-called graded-index multimode fiber.

The term "graded" conveys the meaning of fibers having a "gradually" change of refractive-index profile from core to cladding causes light rays to bend back toward the axis as they propagate, thus minimize the difference in time that light rays take to pass through the fiber. Graded-index multimode fibers have smaller dimensions in both core and cladding compare to step-index multimode. The core diameter typically ranges form 50 μm to 85 μm and the cladding diameter is usually around 100 μm. The graded-index multimode has a core diameter large enough compared to step-index single mode which results an ease of coupling tolerance but still carry many modes. The gradual changes in refractive-index affect the light travel which in the previous types depend on total internal reflection. The graded-index multimode depends on refraction thus light beams entering the fibers at different angles travel in the same distances throughout the fiber which reduce the modal dispersion of the fiber. Typical light propagation is shown in Figure 2-19(b) in the manner of sinewaves . In Figure 2-19(a), the light propagation of step-index multimode fiber is described as a zigzag path between core-cladding boundary on each side of fiber axis. However in Figure 2-19(b), the effect of graded refractive-index bends the light beams back toward the axis.

Using graded-index multimode fibers certainly solves some of negative issues of the previous types of multimode fibers. The effective way in limiting the dispersion in a graded-index fibers is to vary the refractive-index between core and cladding with the square distance from the fiber axis i.e. a parabolic index curve which alters the light traveling mode into the sine-wave light paths.

2.4.4 Optical Properties of Fibers

Before touching the property issues of fiber optics, one should understand what stands behind the basic principal of fiber optics. Figure 2-20 shows that light traveled through step-index fiber optic, is bounced back from wall to wall of cladding back into the core. The core half-angle or sometimes it is called as the acceptance angle is the maximum angle which the light will be reflected when entering the media otherwise it will be lost by radiation. The reflection of light is made possible by a higher refractive index of the core and a lower refractive index of the cladding since light will be totally reflected when it strikes a boundary with a material of lower refractive index at a large incident angle.

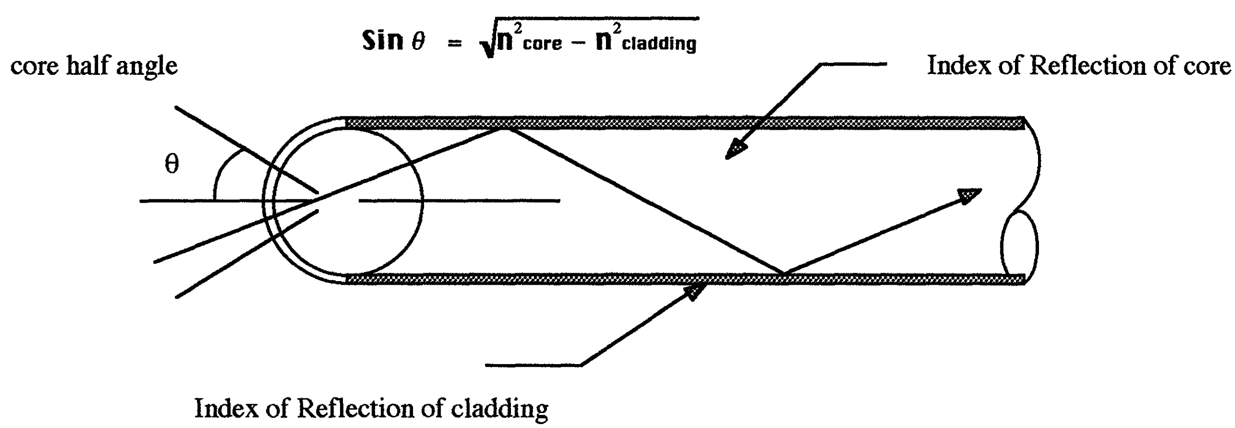


Figure 2-20: The basic principle of fiber-optic; the light that enters with an angle less than cone half angle will be reflected throughout the cladding walls while the light that enters with an angle larger than cone half angle will eventually lost by radiation.

The optical properties of fibers play important roles in controlling the performances of fiber-optic system. Properties such as attenuation, dispersion and numerical aperture, govern the decision in choosing the correct fiber for an optical system.

2.4.4.1 Attenuation

The extensive use of optical fibers is due primarily to progress that has been made in the last decades in reducing fiber attenuation from hundreds of decibels per kilometer to one decibel or less per kilometer.

Among the optical properties of fibers, one of the most important issues is the attenuation of the light power transmitted by the fiber. The term attenuation means the reduction of signal magnitude due to intrinsic material properties losses (absorption and Rayleigh scattering) and from waveguide properties losses (microbending and bending loss sensitivity, loss at connectors and splices) [Jeunhomme, 1983].

Intrinsic material properties losses are partly due to light scattering of transmitted energy. The most prevalent type is Rayleigh scattering which is mostly due to microscopic inhomogeneities of fiber material. The addition of dopants into the silica leads to an increase in the Rayleigh scattering loss, because the microscopic inhomogeneties become more critical [Jeunhomme, 1983]. In addition, considerable scattering could occur due to bubbles and crystallites in the fiber material. The other loss is the absorption loss in high-silica glasses which is composed mainly of transition metal impurities such as Fe, Co, Ni, Cu, Cr, Mn, and V is shown in Figure 2-21. Absorption loss is the major loss and can only be reduced by careful material and process selection. Another type of attenuation is due to waveguide attenuation. Power leakage is a part of waveguide attenuation which takes place when the inner cladding thickness decreases . When light rays strike a bend fiber, those in higher modes can leak out if they strike the fiber's wall at an angle larger than the critical angle. On the other hand, the lower modes could face the same problem since these modes will finally transformed into the higher modes which could leak out like the previous one. The bend should not be excessive, in fact the serious loss in multimode fibers resulted from microbending. Microbending produces tiny kinks which allow light to leak out and increase loss as it is shown in Figure 2-22.

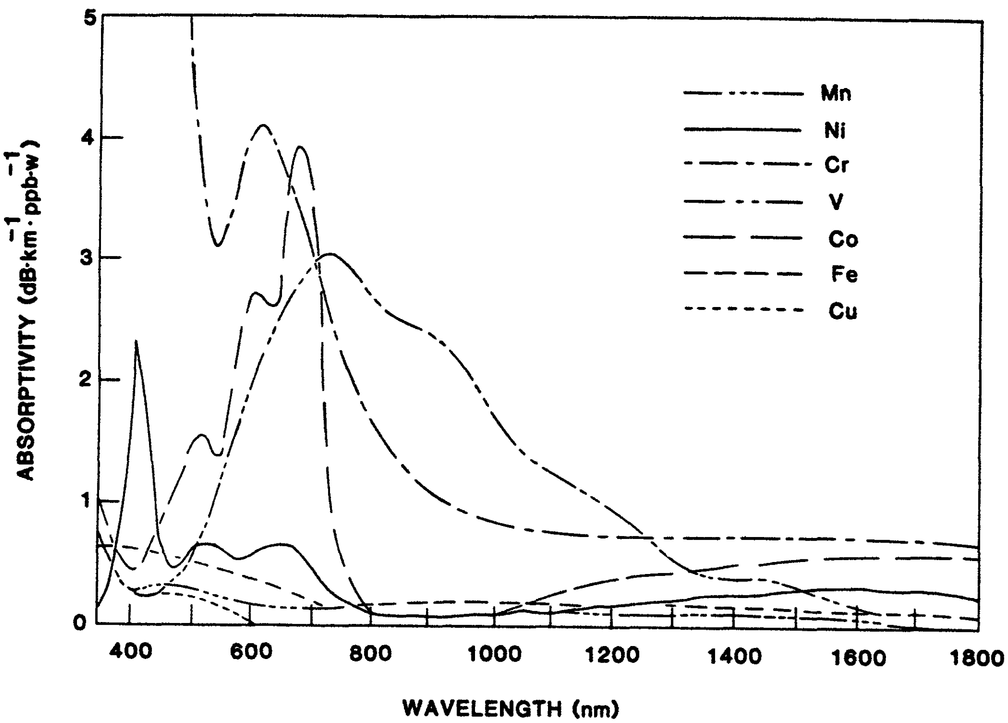


Figure 2-21: Absorptivity of transition metal ions vs. wavelength [Aggrawal, 1984, pp. 24].

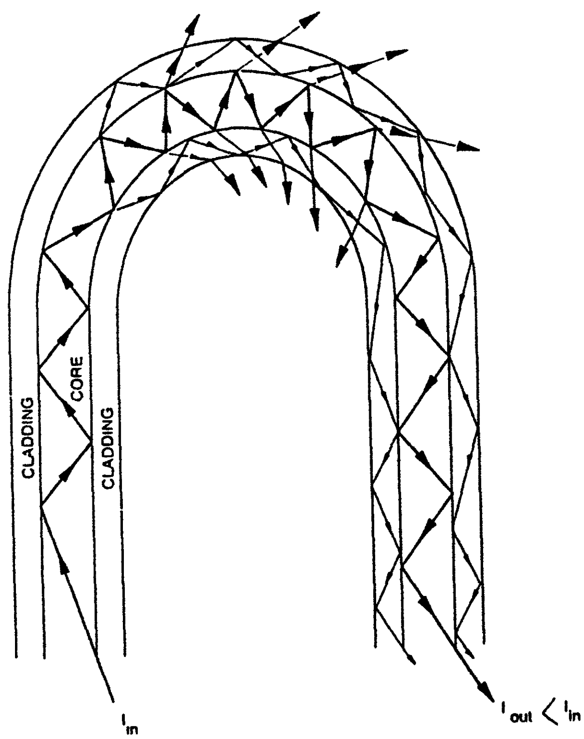
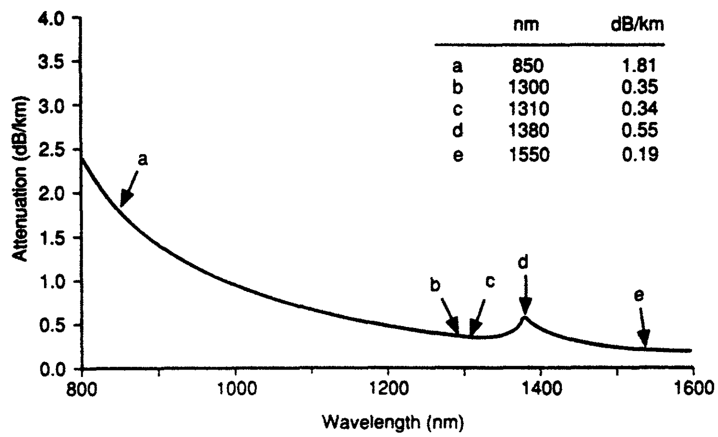


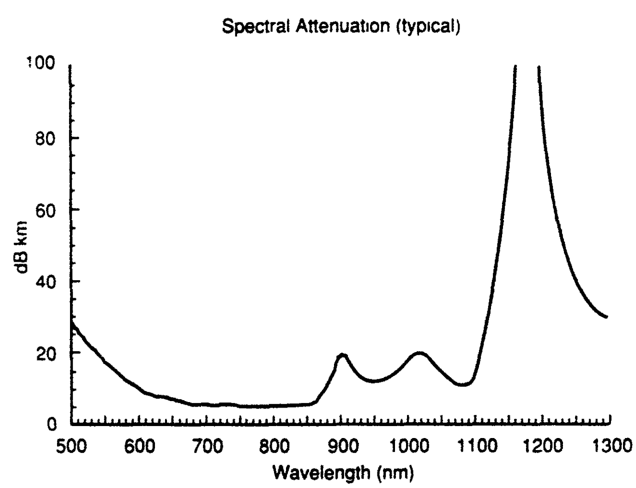
Figure 2-22: Light intensity perturbation for both higher and lower modes inside the fiber.

High attenuation regions usually exist at about 1250 nm and 1380 nm while the lowest attenuation could be reached at 1550 nm [Olsen, 1986]. Reduction of attenuation in any optical fiber is limited by the Rayleigh scattering losses due to the refractive tiny index fluctuations present at all times in optical fibers. Typical losses for good quality fibers at 850 nm are 4 to 5 dB/km while losses for good quality fibers at 1330 nm are less than 1 dB/km. This lower loss is one of the advantages of longer wavelength system. For wavelength larger than 1600 nm, ultraviolet absorption will increase dramatically. Figure 2-23 shows the typical attenuation versus wavelength comparisons among step-index single mode fiber, step-index multimode fiber, and graded -index multimode fiber. For step-index single-mode fiber, the lowest attenuations lay at approximately 1310 nm with

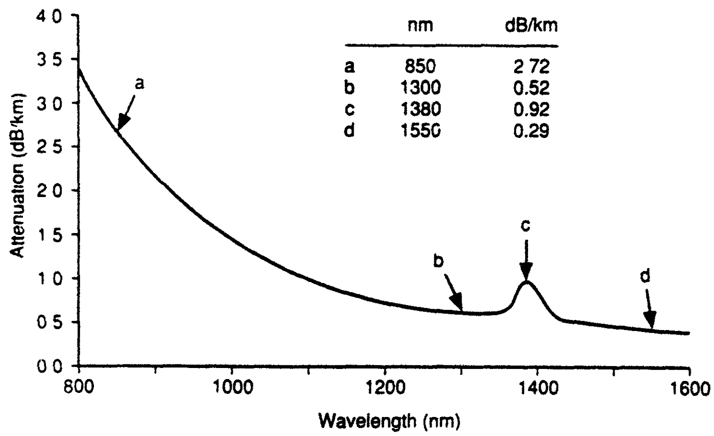
0.34 dB/km loss and 1550 nm with 0.19 dB/km loss while for step-index multimode fiber, the lowest attenuation point is 800 nm with approximately 5 dB/km loss and for graded -index multimode fiber is 1550 nm with 0.29 dB/km loss.



(a)



(b)



(c)

Figure 2-23: The typical spectral attenuation (loss (dB/km) vs. wavelength (nm)) comparisons among (a). step-index single mode fiber, (b) step-index multimode fiber, (c) graded-index multimode fiber [Hecht. 1993]

2.4.4.2 Numerical Aperture

Numerical aperture is another property of light propagation in optical fiber which is associated to the trigonometric function of the fiber as illustrated in Figure 2-24. It is the sine of half the angle over which a fiber can accept light. Differences in NA between

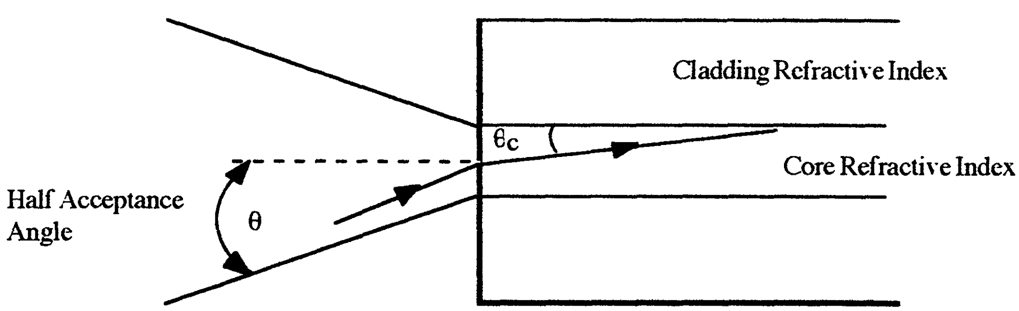


Figure 2-24: Numerical aperture depends on core refractive index, cladding refractive index, sine of half acceptance angle and sine of confinement angle.

$$NA = \sqrt{n_{core}^2 - n_{cladding}^2} = \sin\theta = n_{core}\sin\theta_c \qquad (2.6)$$

where,

NA = Numerical Aperture

n_{core} = core refractive index

$n_{cladding}$ = cladding refractive index

θ = half acceptance angle

θ_c = confinement angle

fibers may also contribute to connector losses; this is what is called the angular misalignment of fiber. Light will quickly leak out when the fiber delivering the light has a larger NA than one receiving the light, some light will propagate in modes that are not confined in the core. This loss can be defined with such formula[4] :

$$Loss(dB) = 10\log_{10}(NA_2 / NA_1)^2 \qquad (2.7)$$

where,

NA_2 = the numerical aperture of the fiber receiving the signal,

NA_1 = the numerical aperture of the fiber delivering the signal.

Numerical aperture measures how light is collected by an optical fiber and how it spreads out after leaving the fiber. Numerical aperture and acceptance angle are critical for multimode type of fibers since higher modes gradually leak out as light travels through a fiber. The normal range of NA is between 0.20 to 0.60.

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[4] This equation is only applicable when $NA_1 > NA_2$ since loss is commonly recorded as a negative value.

2.4.4.3 Dispersion

The next property that controls the light propagations in fibers is dispersion which can not be eliminated completely. The term dispersion means the spreading or widening of light rays which represents the shortcoming of optical fibers. Single-mode fibers have much lower dispersion than multimode ones since there is no modal dispersion in the single-mode fibers. Dispersion could cause the spreading and distortion of luminous pulse carried by optical fiber. There are three types of dispersion in optical fibers [Ungar, 1990]:

1). Intramodal dispersion,
2). Intermodal dispersion,
3). Chromatic dispersion.

Intramodal Dispersion is due to the dispersive properties of the material, the waveguide structure and cross-product dispersion. For a given mode, the variation of refractive index with wavelength causes a spreading of the signal which can be enormous in single-mode fibers but insignificant in multimode fibers. Material dispersion occurs when a pulse of light in the fiber consists of more than one wavelength and also when threre are variations of the index of refraction of the core and the cladding materials. On the other hand waveguide dispersion is part of the chromatic dispersion arising from the different speeds light travels in the core and cladding of a single-mode fiber. For single-mode waveguide, the dispersion due to the waveguide mode dispersion is small; the major contributions is due to material dispersion. Cross-product dispersion is due to leakage of optical energy from cable or connector to other materials.

Intermodal dispersion is caused by the propagation of rays of the same wavelength along different paths through fiber medium. This results in the waves arriving at the opposite end of the fiber at different times.

Chromatic dispersion is contributed by material dispersion, waveguide dispersion, and profile dispersion. Of these three components, material dispersion dominates its presence at wavelength between 800 to 900 nm. Material dispersion is part of chromatic dispersion that is due to the wavelength dependence of the refractive index. Waveguide dispersion is caused by the fact that the propagation characteristics of a mode are dependent on the geometric properties of the waveguide as a function of a wavelength. The last part, which is the profile dispersion is due to variation of the refractive index profile with a given wavelength. Figure 2-25 illustrates clearly the chromatic dispersion in single-mode step-index fibers.

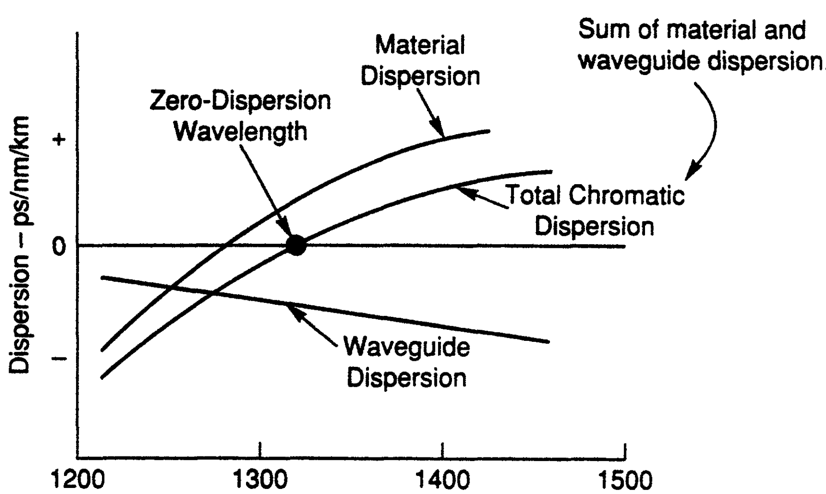

Figure 2-25. Total chromatic dispersion in single-mode step-index fibers which is the sum of material and waveguide dispersion.

2.4.5 Optical Fiber Manufacturing

In order to create precise and high quality optical fibers, special equipment and sophisticated processes are definitely needed. Basic process usually consists of four stages i.e. preform fabrication, fiber drawing, optical characterization, and mechanical characterization. In the first stage, a glass rod consisting of both cladding and core is prepared and drawn depending on type of fibers. Next, the optical properties of the drawn fiber are measured and finally screened to insure the fiber meeting certain minimum requirements of high chemical durability and mechanical properties i.e. tensile strength and static fatigue.

For this reason the following types of general processes used in manufacturing of optical fibers have been selected and are discussed in some details i.e., Double-Crucible method, Modified Chemical-Vapor-Deposition (MCVD), Vapor Axial Deposition (VAD).

2.4.5.1 Double-Crucible Method

In the first step, the rod-in-tube method is used to exude cladding glass over core glass as seen in Figure 2-26. The double-crucible furnace is built so that two crucibles holding cladding glass and core glass are vertically aligned. Simple silica crucibles, usually made of platinum, may be used, but they have a tendency to shatter when cooling to room temperature; each crucible has a narrow aperture at its base. Both cladding

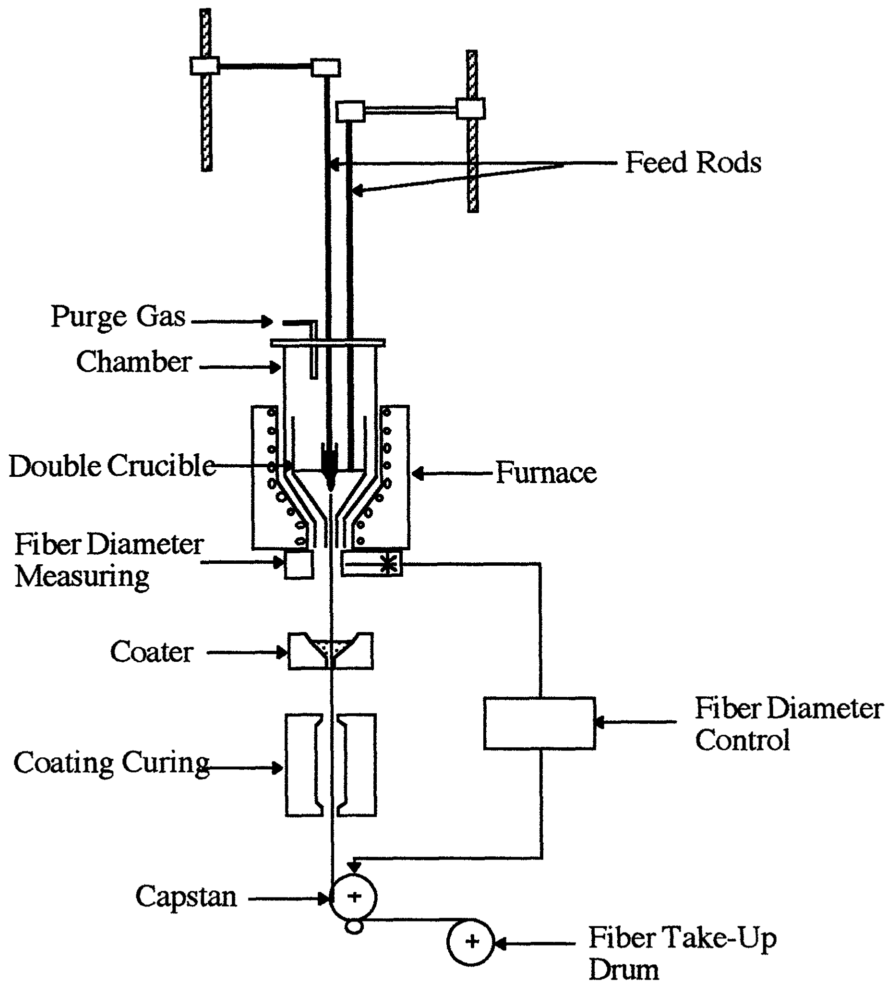

Figure 2-26: Schematic of a fiber drawing system in Double crucible fiber manufacturing process.

and core glasses are heated in furnace until the glasses are soft enough to flow through the orifice and be drawn into fiber. The composite glass may be pulled to form a perfect or nearly perfect fiber. The dimensions of the two crucibles are very exact, to ensure that core-to-cladding ratios are met in order to reduce the connection loss. The viscosities and densities of the materials must also be taken into consideration in flow restrictions, but usually are very similar in both cladding and core. The atmosphere around the crucibles is carefully controlled to prevent the glasses from any contamination and introduction of oxygen, which could cause bubbles in the glass and consequent high scatter losses. Step-index and graded-index fiber with losses of less than 5 dB/km at 850 nm wavelength have been fabricated using this technique [Aggarwal, 1984].

2.4.5.2 Modified Chemical Vapor Deposition

Modified Chemical Vapor Deposition (MCVD) which has an interchangeable term with Inside Vapor Phase Oxidation (IVPO), has received considerable attention in fiber processing because of the capability to produce low attenuation in both step- and graded-index multimode fibers as well as single-mode fibers. The process was first introduced by Corning Glass Works of Corning, New York.

The first step in fabricating glass fibers is to make a rod or "preform" of highly purified glass, with a core and cladding structure. The preform are fabricated in two successive stages which must be performed without removal and without interruption to avoid thermal shock which cause discontinuities in the refractive index. In Figure 2-26, raw materials such as silicon tetrachloride, polonium trichloride, boron trichloride, and germanium tetrachloride in a flame, yield silica (SiO_2) and germania (GeO_2). These materials are stored in all-glass vessels; oxygen gas is bubbled through each of the halides separately then the saturated vapors are transmitted into a vapor delivery system.

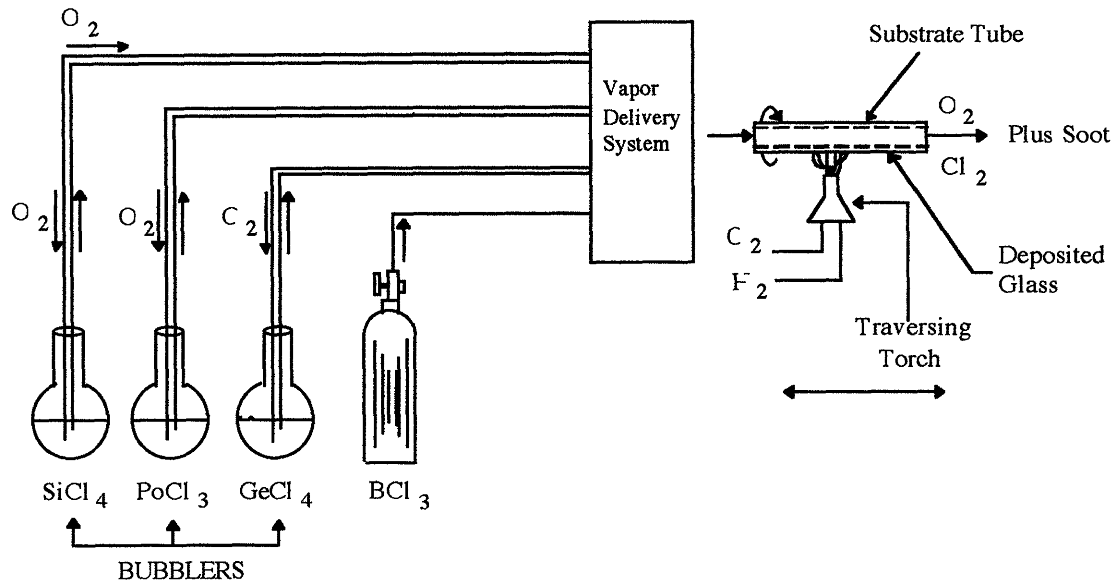

Figure 2-27: Modified Chemical Vapor Deposition fabrication process.

In the Next step the quartz tube is heated externally and mounted on a lathe bed and rotated. First the cladding material is deposited, then the composition is changed to deposit the core material. Finally, the glass rod is removed, and the remaining glass is heated and collapsed into a dense glass. Gases such as chloride and oxygen are then injected into chamber to build core and cladding of fibers. Attenuations as low as 0.5 dB/km at 1500 nm have been reported for multimode fibers [Horiguchi et al., 1976], and 0.5 dB/km at 1300 nm for single-mode fibers [Kawana et al., 1978]. The complete schematic of MCVD is illustrated in Figure 2-27.

There are several important advantages that can be achieved using this type of process such as :

- Raw materials are available in liquid state and high purity form.
- Extra distillation or purification step could be accomplished since the materials are vaporized before being collapsed.

- External contamination could be avoided since chemical reaction, vapor formation and deposition take place in a closed system.

2.4.5.3 Vapor Axial Deposition (VAD)

VAD process was intensively studied by researchers at NTT Laboratories [Izawa et. al., 1977]. In this process, both core glass and cladding glass soots are concurrently arranged in an axial direction of a rotating silica rod to shape a rod-like soot preform as illustrated in Figure 2-28. The soot preform is consolidated into clear glass either simultaneously as deposited or in a separate process step. The preform thus made is drawn into fiber. The use of axial deposition orientation will create a continuous blank making [Aggarwal, 1984].

The main advantage of using this process is that, it can produce large preforms continuously, resulting in reducing the cost of fibers. Attenuation could be controlled easily since the process uses a simultaneous sintering. Attenuation for both single and multimode fibers as low as 0.2 dB/km @ 1550 nm have been fabricated, and also single mode fibers as long as 100 km have been drawn using this process.

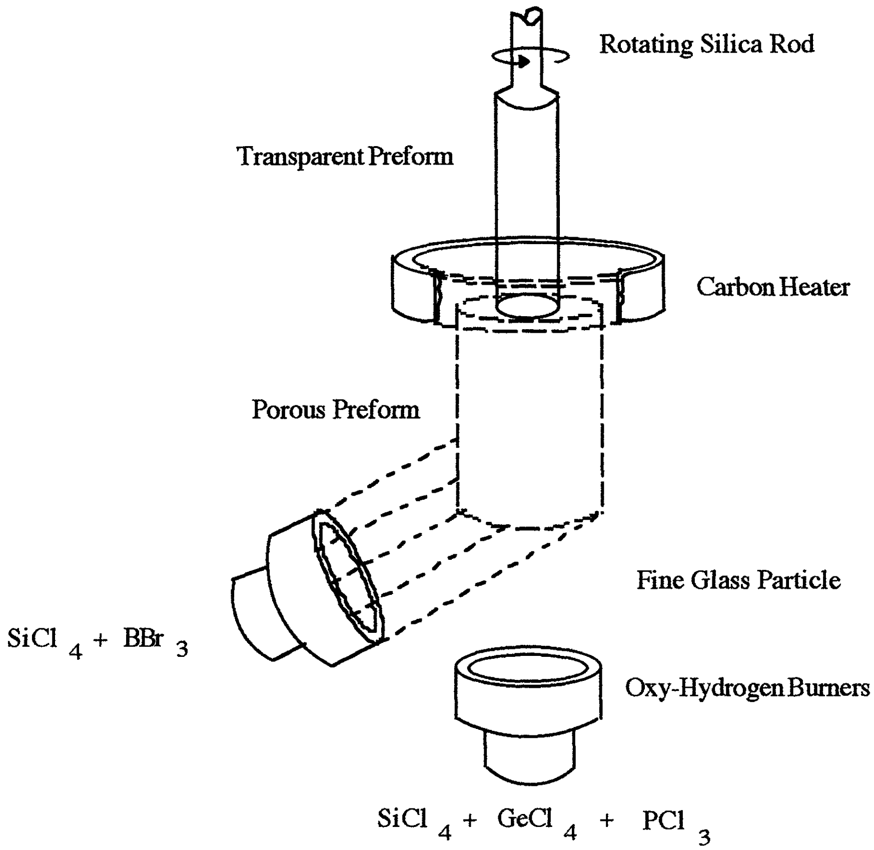

Figure 2-28: Vapor Axial Deposition process.

2.5 Light Sources[5]

The rapid progress in the field of optical communications and other related disciplines has been made possible by the development of low-loss optical fibers and light sources that are compatible with the spectral transmission characteristics and physical dimensions of these fibers.

Ever since the invention of laser, a new dimension of light source was introduced in telecommunication area which permit light signals to be transmitted in a smaller diameter than it used to be. Further development of semiconductor light sources allows the use of smaller core fiber which reduces high-loss signal inside the fiber. The term semiconductor refers to a class of materials which ability to conduct electricity lies somewhere between insulators and conductors. Semiconductors can have either an excess of electron carriers (n-type material) or an excess of "hole" carriers (p-type material), where a hole is the absence of an electron in allowed energy region.

Semiconductor materials can be excited into light emitting states by forming excess holes and electrons across the n and p regions of the semiconductor materials. The excited states could recombine either radiatively emitting a photon of energy $h\nu$ or nonradiatively recombining in the process dissipating energy in the form of heat. The efficiency of semiconductor materials depend on the duration of time of the excited states to decay back into their original state. The internal efficiency of the semiconductor materials η could be written as

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[5] Udd, Eric., "Light Sources", Fiber Optic Sensors: An Introduction for Engineers and Scientists", pp 37-68, John Wiley & Sons, Inc., 1991.

$$\eta = \frac{1}{1+\frac{\tau_r}{\tau_n}} \tag{2.8}$$

where

τ_r is the time it takes for a radiative recombination

τ_n is the time it takes for a nonradiative recombination

Nonradiative life time depends on several factors such as, the density of the nonradiative recombination centers N, the cross section σ, and electron thermal velocity υ so that

$$\tau_n \cong (N\sigma\upsilon)^{-1} \tag{2.9}$$

From equation 2.9, one can realize that nonradiative lifetime could drastically decrease by impurities introduce in the semiconductor material, electrically induced damage centers, or heating which sometimes result a decrease in the internal efficiency of the semiconductor materials as described in the equation 2.8 with consequential loss in light-emitting power.

Figure 2-29 shows that electron flows by activating pump energy to move lower ground state E_1 to a higher state E_3. To return to the original state E_1, the state may radiatively emit a photon hv and go to the lower-energy state E_2, which in turn nonradiatively decays back to the ground state E_1, or it may go through a series of nonradiative energy transfers to various intermediate states E_N. The faster the radiative process relative to nonradiative energy mechanisms, the greater the light-emitting efficiency of the material. This trend could be used to narrow down the effective materials to achieve optimization of emitted light.

In order for materials to be good candidates for light emitting or laser diode, it should have radiative lifetime as short as possible. Materials such as GaAs, InAs, InP, AlGaAs, and GaAsP allow direct recombination to the unexcited state with the emission of a photon. The radiative life for these kind of materials range from 10^{-8} to 10^{-10} s, which are commonly used for semiconductor materials. Table 2.1 shows the availability of the materials in terms of wavelength ranges, reliability, cost and availability.

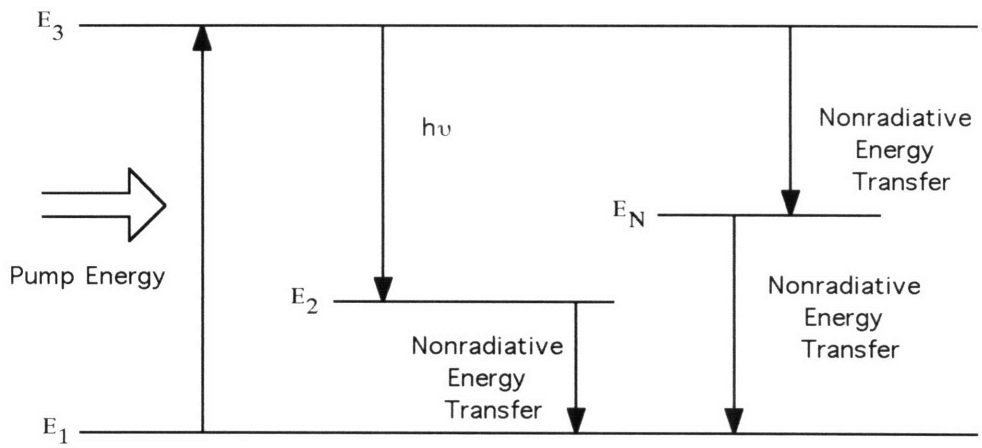

Figure 2-29: Energy is transferred to an active medium moving sites from its original ground state E_1 to a higher energy level E_3. The decay process could be done either by radiative or nonradiative energy transfer.

Table 2.1 Semiconductor Light Sources for Fiber Sensors

Wavelength Region (μm)	Material	Reliability (hr.)	Cost	Availability
≤ 0.5	Diode pumped frequency doubled Nd: YSG	10,000 +	Moderate to high	Moderate
0.6 - 0.7	InGaP/InGaAlP	10,000 +	Moderate	Limited
0.7 - 0.9	GaAlAs/GaAs	10,000 - 30,000	Very low to moderate	Very good
0.9 - 1.7	InGaAsP/InP	> 100,000	Moderate to high	Good

The wavelength range for each type of material play an important role in matching with different types of applications. For instance, InGaP/InGaAlP which offer the wavelength ranges from 600 nm to 700 nm could increase the sensitivity of certain classes of sensors where visible signals and signature are of interest. These types of semiconductor materials are sometimes used for monitoring chemical properties of materials. However, the downside for these types of materials is that attenuation of light in optical fibers is fairly high and they are not commercially available. For the next range which span from 700 to 900 nm, for instance GaAlAs/GaAs, are the materials used ever since the early development of optical fibers in telecommunication industry. They had been used for high-power, high-performance applications with very low cost and highly reliable light sources. InGaAsP/InP is used in the range which span from 900 nm to 1700 nm and has started to replace GaAlAs/GaAs. Its ultimate advantage is that these new type of materials perform in the lowest-loss and lowest-dispersion region of silica-based optical fiber which enable very high performance in transmitting signals. Another advantage is that these materials have higher reliability i.e. over 100,000 hours compared to GaAlAs/GaAs. However, these new materials have not matured to the point where it could replace the old materials thoroughly.

The basic task of light source is to launch signal into the optical fiber at an angle that provides maximum signal transfer. The physical characteristics of a light source that are important in optical communication systems are wavelength of maximum emission, spectral bandwidth, light-current characteristics, far-field pattern, dynamic response, polarization and coherence properties, and noise [Lengyel, 1984].

They are two common types of light sources used in fiber-optic system i.e. the light-emitting diode (LED) and the interjection laser diode (ILD). These kind of light sources could provide small size, brightness, low drive voltage, and are capable to send signals at desired wavelengths.

2.5.1 The Light-Emitting Diode (LED)

Some of the features of light-emitting diodes that are of interest to fiber optic sensors include a longer life span, a very long coherence length, greater stability, wider temperature range, very low sensitivity to back reflection from elements of the fiber optic sensor since emission is dominated by spontaneous emission, and relatively inexpensive compared to ILD.

LED consists of materials such as gallium arsenide phosphide (GaAsP), gallium phosphide (GaP), and gallium aluminum arsenide (GaAlAs). The effectiveness of the LED absolutely depends on the emitted wavelength; the shorter the wavelength the less efficient the LED becomes. The characteristics which generally considered when selecting an LED as a light source for fiber optics system are : wavelength, spectral width, power, coupling, and current-voltage characteristics. Some LED could perform in the range of 800 nm to 1400 nm.

2.5.2 The Injection Laser Diode (ILD)

This type of light source is more preferable in the fiber-optic industry for their inherent ruggedness, extreme efficiency, and compact size. The ILD is capable of producing as much as 10 dB more power output than the LED. Other advantage of ILD compared to LED is that the light signal could be emitted at a much narrower numerical aperture thus could couple more power to the optical fiber. However, this requires an additional device when using ILD which increases the cost of operation. ILD provides a high-performance operation of fiber optic sensors and a long and a stable coherence length thus it is best fitted for Mach-Zehnder or Michelson interferometer.

2.6 Optical Detectors[6,7,8,9]

The optical detector is as important to any fiber-optic system as the optical fibers or the light source. The basic principle of reception of luminous flux by an electronic system is the conversion of photons into electrons. In a reverse-biased semiconductor PIN photodiode (Figure 2-30), incoming photons are absorbed, and electron hole carrier pairs are generated primarily in the depleted zone. The photogenerated carrier pairs are separated by the high electric field in the depletion region and are collected across the reverse-biased junction. As the carriers traverse the depletion zone, a displacement

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[6] Spillman, W.B., "Optical Detectors", Fiber Optic Sensors: An Introduction for Engineers and Scientists, pp. 69-97, John Wiley & Sons, Inc., 1991.
[7] Hecht, J., Understanding Fiber Optics, 2nd edition, Sams Publishing, 1993.
[8] Ungar, S., Fiber Optics: Theory and Applications, John Wiley & Sons, pp. 175-195, 1990.
[9] Daly, J.C., "Photodetectors", Fiber Optics, pp. 124-147, CRC Press, Inc., 1986.

current is induced at the load as the signal current. For a semiconductor with absorption coefficient α at the wavelength λ, the primary photo-current produced by the absorption of incident light of optical power P_0 is given by:

$$I_p = P_0 \frac{q(1-r)}{h\upsilon}(1 - e^{-\alpha_0 w}) \qquad (2.10)$$

where q is the electronic charge, $h\upsilon$ is the photon energy ($h\upsilon$ =1.24/ eV), r is the Fresnel reflection coefficient at the semiconductor-air interface, and w is the width of the absorption region. The quantum efficiency is defined as,

$$\begin{aligned} \eta &= \frac{(\textit{number} \text{ of carriers generated})}{(\text{number of incident photons})} \\ &= (I_p/q)/(P_o/h\upsilon) \qquad (2.11) \\ &= (1 - r)(1 - e^{-\alpha_0 w}) \end{aligned}$$

The responsivity R, often used to characterize the photodiode performance, is given by:

$$R = I_p / P_o = \eta q / h\upsilon \qquad (2.12)$$

For an ideal photodiode (η =1), R= λ/1.24 A/W, where λ is the wavelength in microns.

It is evident that the energy carried by the photon must be sufficient to permit a transition from the valence band to the conduction band; thus the forbidden bands should be made as narrow as possible :

$$hf \geq E_c - E_\upsilon = E_g \qquad (2.13)$$

where,

E_c is the energy of conduction band

E_υ is the energy of valence band

E_g is the energy of forbidden bands

where the critical wavelength[10] is

$$\lambda_c = \frac{hc}{E_g} \tag{2.14}$$

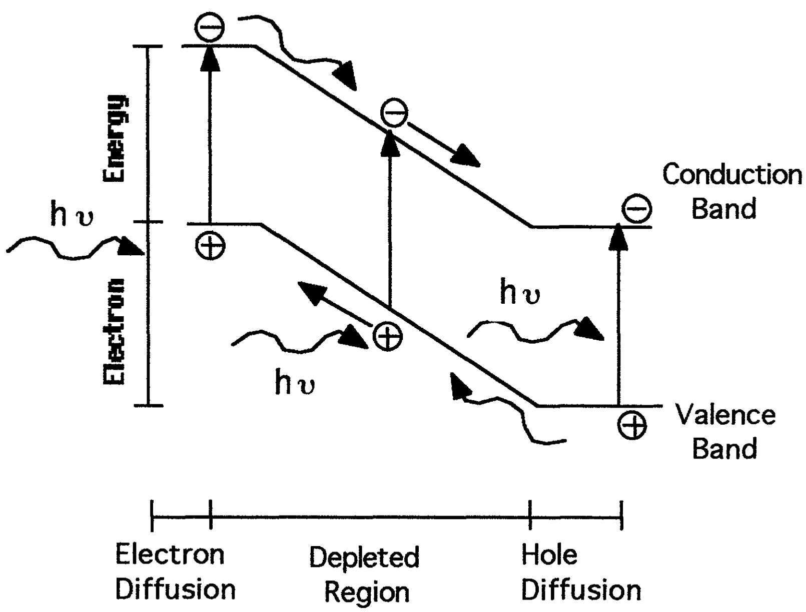

Figure 2-30: Absorption of photons

Figure 2-30 shows the principle of operation of an absorption of photons., incoming photons are absorbed, and electron-hole carrier pairs are generated primarily in the depleted intrinsic region. The three basic functional elements of an optical detector are as follows:

1. The detector (to receive signal from light source through optical fiber thus converts them into an electrical current).
2. Amplification stages (amplifying the signal and convert it into a form ready for processing).
3. Demodulation (to reproduce the original electronic signal).

[10] This is true if and only if $\lambda > \lambda_c$.

Two representative types of detectors which are used widely in fiber optic industry : the semiconductor photodiode and the avalanche photodiode (APD). Both detectors exhibit fast rise time and acceptable bandwidth parameter. APD is more expensive and requires an auxiliary power supply but it provides greater receiver sensitivity as well as signal amplification without sacrificing high-speed operation.

2.7 Multiplexing[11]

The use of fiber-optic sensors especially in civil engineering will be even better when its function can be extended the simultaneous measurements of several important properties of a structure. This is sometimes referred to as multiplexing. Multiplexing could measure simultaneously transmission of two or more information channels along a common path such as, strains, temperature, pressure, corrosion, chemical content or the void inside structures. By multiplexing several optical fiber sensors merged together to go through a single fiber, thus eliminating the use of multiple sensors which may create problems associated with shear multitude of connectors and access ports as described at Figure 2-31. A simple example of the use of multiplexing in civil engineering application is its ability to form a network of sensors in a large structure.

[11] Kersey, Alan D., "Distributed and Multiplexed Fiber Optic Sensors", Fiber Optic Sensor : An Introduction for Engineers and Scientists, Editors: Udd, John Wiley & Sons, Inc, 1990.

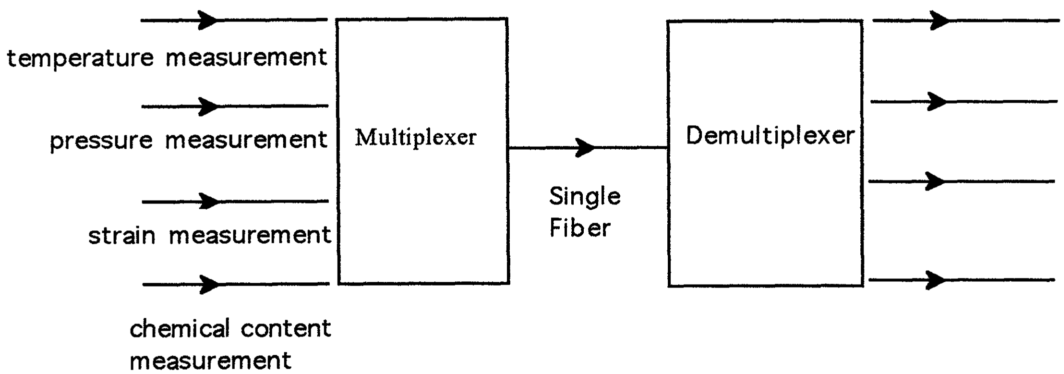

Figure 2-31: Multiplexing several optical fibers carried into a single optical fibers at different wavelength while signals will not interfere with each other and can be separated at the output end.

Optical wavelength-division multiplexing sends multiple signals down a fiber at different wavelengths, for instance, one signal at 1300 nm and the other at 1550 nm. This is possible because the signals will not interfere with each other and can be separated at the output end. This effectively doubles fiber capacity at the cost of extra transmitters, receivers, and optical components to combine and separate two or more signals. The multiplexing characteristic of optical fiber sensors helps to improve the performance of interferometric type of sensors.

Various types of multiplexed sensor systems that are commonly used include:

- *Time-Division Multiplexing (TDM):* Sensor information is allocated to a particular time slot within a repetitive transmission period.
- *Frequency-Division Multiplexing (FDM):* Sensor information is allocated to different frequencies in a broad-bandwidth analog signal.
- *Wavelength-Division Multiplexing (WDM):* Sensor information is allocated to different optical wavelengths to carry signals through the same optical fiber.

- *Coherence Multiplexing:* Sensor information is differentially encoded on components of the optical carrier which have different degree of mutual coherence with respect to some reference carrier.
- *Polarization-Division Multiplexing (PDM):* Sensor information is encoded on orthogonal polarization components of the optical carrier.

Chapter 3

Novel Applications of Fiber Optic Sensors : An Overview

3.1 Introduction

The emergence of fiber optic sensor technology not only has impacted the telecommunication industry but also has spread its usefulness into many engineering areas. The research has grown rapidly especially its role in infrastructures and buildings. This field which is the state of the art, promises to operate effectively in the future and could change the way engineer designs a structure. The monitoring and control of a civil infrastructure system have captured the attention of engineers and researchers from various disciplines. This may significantly accelerate the transfer of technology to civil engineering. Fiber-optic sensors based on "smart structure" concepts will definitely improve the efficiency and reliability of large structures [Masri, 1993].

The first part of this chapter deals with the types of sensors for sensing environmental changes and more attention is placed on the interferometric sensors. As it is not possible to review all the applications of optical fibers in this chapter, two previous work in strain sensing and crack opening measurement to illustrate the application of optical fiber sensors to monitor changes in mechanical properties in concrete structures. In the last part, real application in bridge structure is reported to demonstrate the transfer of technology into practical use in the field as well as the implantation of this technique with the help of computer technology.

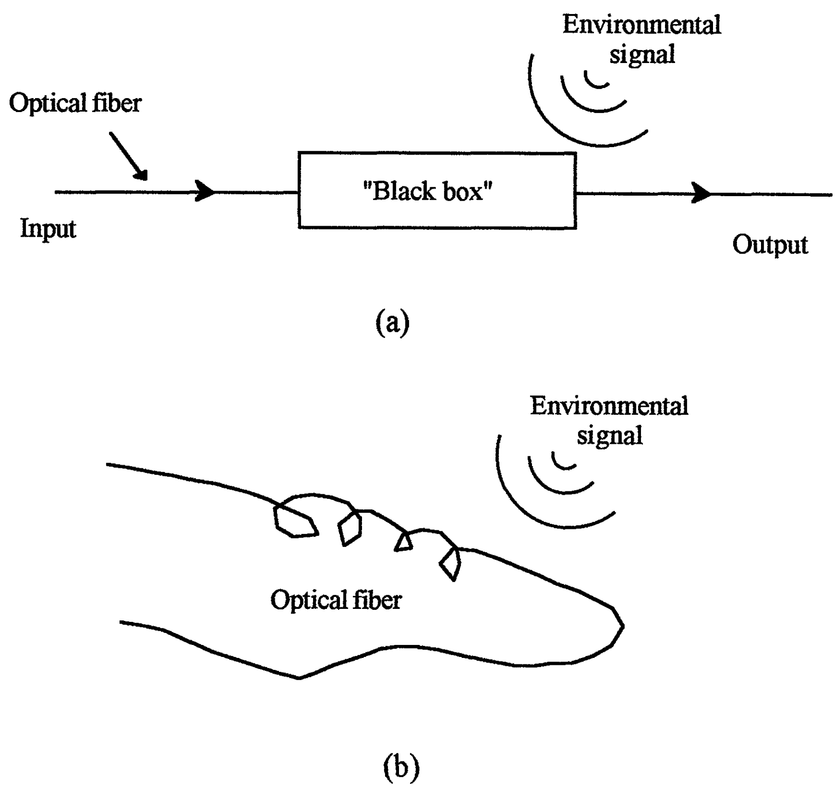

Figure 3-1: (a) Extrinsic or hybrid fiber optic sensor consisting of input and output fibers carrying light to and from a black box which modulates the light beam upon activation by an environmental signal; (b) intrinsic fiber optic sensor which the properties are modulated by an impacting environmental signal. (After Udd, 1993).

3.2 Types of Sensors

The classification of fiber optic sensors is basically divided into two major classes i.e. extrinsic and intrinsic sensors depending on how they work and the types of measurement needed. Figure 3-1 illustrates the difference between extrinsic and intrinsic sensors.

3.2.1 Extrinsic Sensors

The early development of fiber-optic sensors took advantage of the ability of small diameter optical fibers to transmit electrical signals that had been transformed into optical signals. Since the fibers are only employed for signal transmission purposes, the fibers are a passive component of the system. This class of sensors is termed extrinsic sensors, in which the sensing function is performed by exploiting a non-fiber-related phenomenon such as the interference of light beam or behavior associated with reflected light. The distinguishing characteristic of extrinsic fiber optic sensors is that sensing takes place in a region outside the fiber which can be described as a "black box" sensor. The fibers are employed to carry the optical information to the box and the data back, for instance, measuring property changes inside concrete structures.

3.2.2 Intrinsic Sensors

Subsequent development in fiber-optic technology were accountable for the evolution of a second class of optical sensors, termed intrinsic sensors, in which changes in the fiber properties due to external perturbation are the basis for measuring the characteristics of these external stimuli. In an intrinsic fiber optic sensor, the modulation of the optical carrier induced by the field disturbances occurs while light remains guided within the fiber. Since the transmission characteristics of optical fibers are dependent upon perturbation from a wide variety of stimuli, this sensitivity has resulted in the phenomenal growth of the field of intrinsic sensing. Indeed it has been anticipated that fiber-optic sensors will dominate the sensors market within the next decade for a very broad range of sensing applications. Some common intrinsic fiber optic sensors are microbend sensors, distributed sensors, blackbody sensors and interferometric sensors.

3.3 Fiber-Optic Sensor System

Several systems have been used to detect changes in structure. The simplest type of sensor used is the intensity sensor which only measures the changes in the intensity at the output relative to the input ends. In many fiber optic sensor applications, the fiber simply carries the light to the remote optical sensor at the end of fiber. The light is then modified and returned, typically through the same fiber; the fiber plays no role in the sensing mechanism. The basic principle behind the intensity sensor is that light comes from the light source and travels through the optical fiber to the optical sensor at the end of the fiber, in many instances leading to substantial optical intensity loss. One type of classification for the intensity sensors is the intrinsic type of sensor where sensing takes place within the fiber. Microbend sensor is one example of an intensity sensor; the system usually consists of a light source, optical detectors, and a data acquisition microcomputer as shown in Figure 3-2. The light source is controlled in order to acquire a signal representing information which is then transmitted through optical fiber from signal source to the receiver. The information is represented by optical signals feature distinct amplitude, phase, frequency, or polarization characteristics. Thus the combination of the light beam and the optical fiber is analogous to the more conventional information transmission systems involving electrical signals and copper wires. With a conventional fiber-optic system, an optical transmitter system is generally employed to create an appropriate light signal from an electrical signal by employing either a laser diode or light emitting diode[1]. The light signal is then conducted into the fiber and transmitted to an optical receiver system containing a photodiode which converts the light signal into an electrical signal prior to amplification and post processing.

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[1] The choice depends on what type of fiber is used. For example, single mode fiber usually needs a laser diode since the small core characteristic while multimode fibers could use the LED.

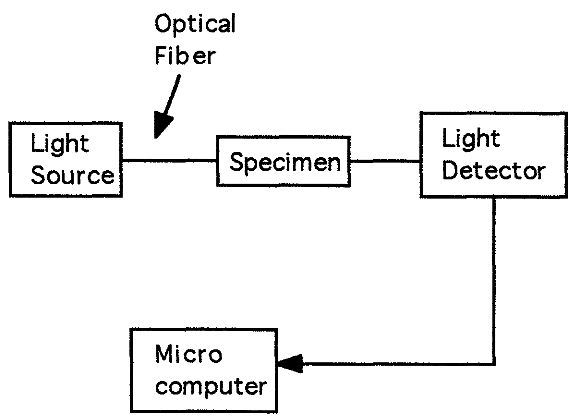

Figure 3-2: Typical fiber-optic Sensor system.

For more advanced, reliable and sensitive techniques, interferometric sensors are used particularly for the fiber-optic strain sensors. Examples of interferometric sensors include Michelson, Mach-Zehnder, Polarimetric and Fabry-Perot. Interferometric sensors allow the fiber to play a more critical role in the sensing mechanism, and the light is not required to leave the fiber at the sensor to interact with the field to be studied. In this type of device, the optical phase of the light passing through the fiber is modulated by the field to be detected. This phase modulation is then detected interferometrically, by comparing the phase of light in the signal fiber to that in a reference fiber. With interferometric sensors, one could expands the use of sensors into multiple measurand changes in structures which is sometimes called multiplexing. Changes such as temperature, pressure or strain could be simultaneously transmitted and analyzed by a computer. Another type of sensor which is the grating sensor which is mainly used as pressure sensors, hydrophones, strain sensors and vibration sensors.

3.4 Interferometric Sensors

Interferometric fiber optic sensors are based upon the principle that environmental perturbations shift the phase of light path which propagates through single-mode fibers. An important attribute of interferometric fiber sensors is its common applicability to sensing a broad range of environmental parameters. The measurement of properties such as strain in a large structure has become a major interest of civil engineers.

The possibility of using intrinsic optical fiber to measure temperature or strain was first suggested by Kingsley and Davies[2]; with sensing systems such as interferometric, Polarimetric, and modal interferomteric sensors. The discussion is only limited to interferometric system which is one of the primary interest in this review. The interferometric sensors have become the most popular type of sensors used in the telecommunication area due to its functionality. Its appearance in the structure monitoring area could help engineers detect mechanical changes in a more reliable manner. Interferometric sensors could be considered phase modulation sensors which generally requires coherent light sources and single-mode fibers. Their capabilities in providing accurate measurements and high degree of sensitivity (especially temperature and strain measurements) due to their nature prove to be effective for concrete structures. Interferometric sensors capitalize on the interference of two light beams in measuring the changes. With this class of sensors two coherent beams are created from a single light

[2] S.A. Kingsley and D.E.N. Davies, " The use of optical fibres as instrumentation transducer", 1976. Proc. Conference on Lasers and Electro-Optical Systems, San Diego, pp. 24-25.

beam by employing a beam splitting device, and these beams are then coupled into optical fibers which serve as the 'reference arm' and the 'sensing arm'. The sensing arm is subjected to deformation while the reference arm is generally isolated from the strain field or other external stimuli. However there are several drawbacks regarding this type of sensor: (1) as a phase detection system, typical output is sinusoidal and for maximum sensitivity and linearity a complex relationship is requisite between the sensing and reference phases, (2) it is difficult to ensure that coherent sources (particularly laser diodes) maintain adequate wavelength stability since a wavelength change could cause a change in phase, (3) in order to maintain coherency, single-mode fibers are required and these by their nature are difficult to couple to light sources, (4) the reference arm stability is crucial for high accuracy and it is difficult to protect this arm from all variables which can produce phase changes.

There are many forms of interferometric sensors available nowadays, however the discussion will be narrowed down to the three most common configurations that is Michelson, Mach-Zehnder, and Fabry-Perot interferometric sensors.

3.4.1 Mach-Zehnders Interferometric Sensor

The Mach Zehnder as well as Michelson interferometers are configured with two paths and the parameter to be measured alters the fiber length or the transit time of the light signal, thus changing the phase relationship with respect to reference path. The basic principle of Mach Zehnder interferometric sensor is based on two arms i.e. reference and sensing arms. The sensing arm is subjected to deformation while the reference arm is generally protected from strain field and other external perturbation. A schematic diagram is presented in Figure 3-3. In this figure, the signal is launched from the light source into beam splitters which send the light to the reference and sensing fibers. The sensing fiber is connected to the specimen which is subjected to deformation that reduces the signal while the reference fiber, the control, still receives the same signal from the light source.

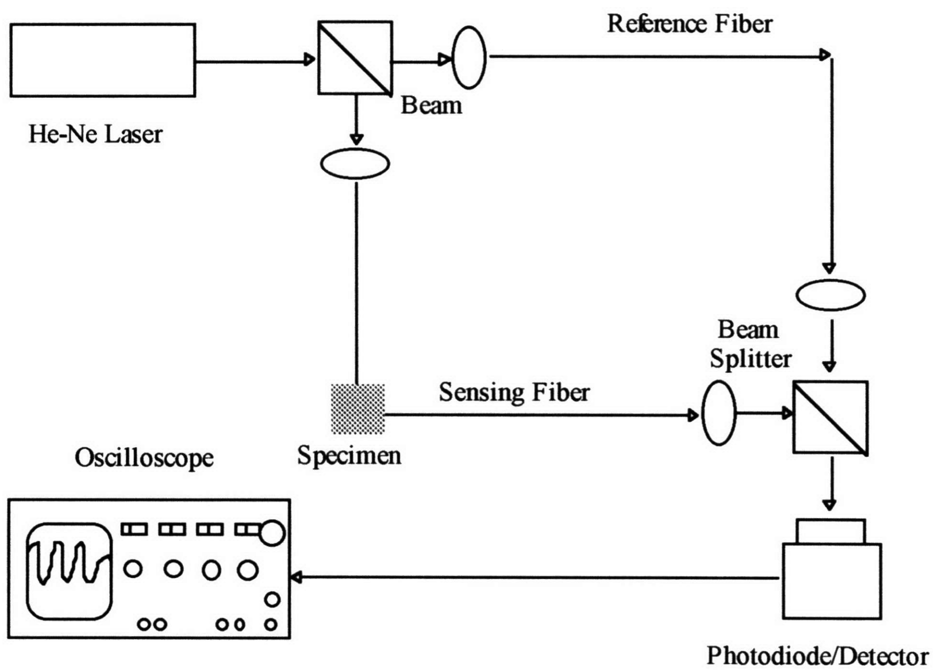

Figure 3-3: The schematic of typical Mach-Zehnder Interferometric.

The mechanism of this system depends on the change in length of transmission medium in response to mechanical or other deformations thus resulting in a change in the optical path length of the light beam. This variance in the optical path length of the two beams results in a relative phase shift between them which is detected by observing the shift in the fringe pattern upon integrating the two beams. A phase shift between the two signals results in constructive or destructive interference. Unfortunately, there are a few drawbacks regarding the use of two fibers which involves a physically larger sensor, two connecting leads, and the potential for greater noise due to dissimilar optical input paths.

3.4.2 Michelson Interferometric Sensor

The simplest fiber optic interferometer is the Michelson which schematic diagram is shown in Figure 3-4 (Corke et al., [1983]). The Michelson strain sensor comprises two optical fibers with reflective ends to reflect the light. This interferometric system as well as the Fabry-Perot interferometer furnish localized unidirectional sensing capabilities. One of the basic differences between the Michelson interferometer and the Mach-Zehnder interferometer is that while the latter system typically operates in two loops, and hence four optical fibers emerge from the structure, the former system features only two fibers emerging from the structure and each fiber accommodates light beams moving in opposite directions. This latter feature is accomplished because the ends of the fibers are mirrored to reflect the incident light path. The light beam consequently travels back along the fiber prior to being disassociated by the same unit that earlier connected it to the fiber. It is obvious that this arrangement is more efficient and reliable than the Mach-Zehnder interferometer. Another benefit of employing this system compared to Mach-Zehnder system is that the structural integrity of the host structural material is not affected by this arrangement[3] as much as the Mach-Zehnder system, and because the light path of a Michelson interferometer is twice as long as for the Mach-Zehnder interferometer thus the Michelson scheme is more sensitive. The only impediment which could arise both for Michelson and Mach-Zehnder systems is the sensor noise attributed to the difference in optical paths of these optical waveguides connected to the sensor regions.

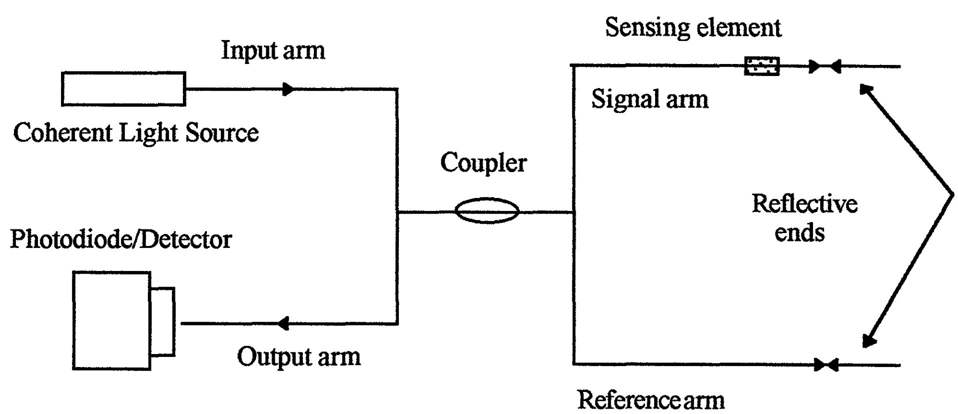

Figure 3-4: The schematic of typical Michelson Interferometer.

3.4.3 Fabry-Perot Interferometric Sensor

Lee et al. (1991) first demonstrated that intrinsic Fabry-Perot fiber optic sensors could be fabricated by sputtering titanium oxide on the ends of optical fibers, then fusion splicing two fibers together. Fabry-Perot interferometers are constructed of two reflectors on either side of an optically transparent medium and classified as an intrinsic sensor. Another type of this system has been modified and used more often i.e. the extrinsic Fabry-Perot. Figure 3-5(a) shows typical Fabry-Perot interferometer while Figure 3-5(b)

[3] It will be noted that this is not a great concern in concrete structure.

shows the schematic of the extrinsic Fabry-Perot system. With proper spacing of the reflectors, the transmission of interferometer is high and by changing the spacing causes the transmission to drop. With high-reflectivity reflectors, the transmittance is very sensitive to changes in wavelength or reflector spacing. Formerly, the invention of this type of sensor was utilized in temperature change measurements[4] however its use could be expanded to localize unidirectional sensing capabilities in strain sensor as well as pressure sensor.

Fabry-Perot interferometers are attractive for sensor applications because they can be easily coupled to the physical or chemical variable being sensed.

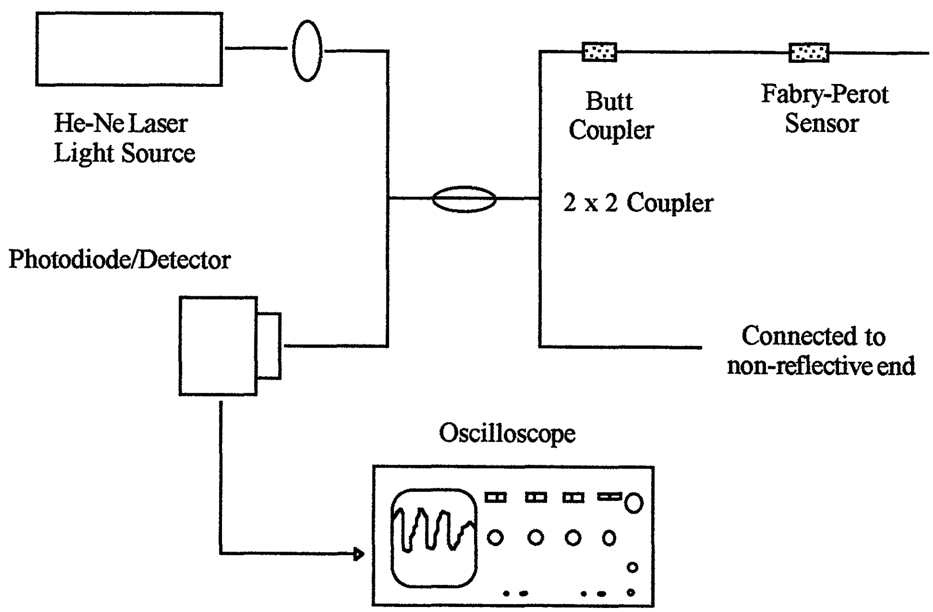

Figure 3-5 (a) : The schematic of typical Fiber-Perot Interferometric.

[4] Mitchell, G.L., "Intensity-Based and Fabry-Perot Interferometer Sensors", Fiber Optic Sensors: An Introduction for Engineers and Scientists, Edited by Udd, John Wiley & Sons, Inc., 1990.

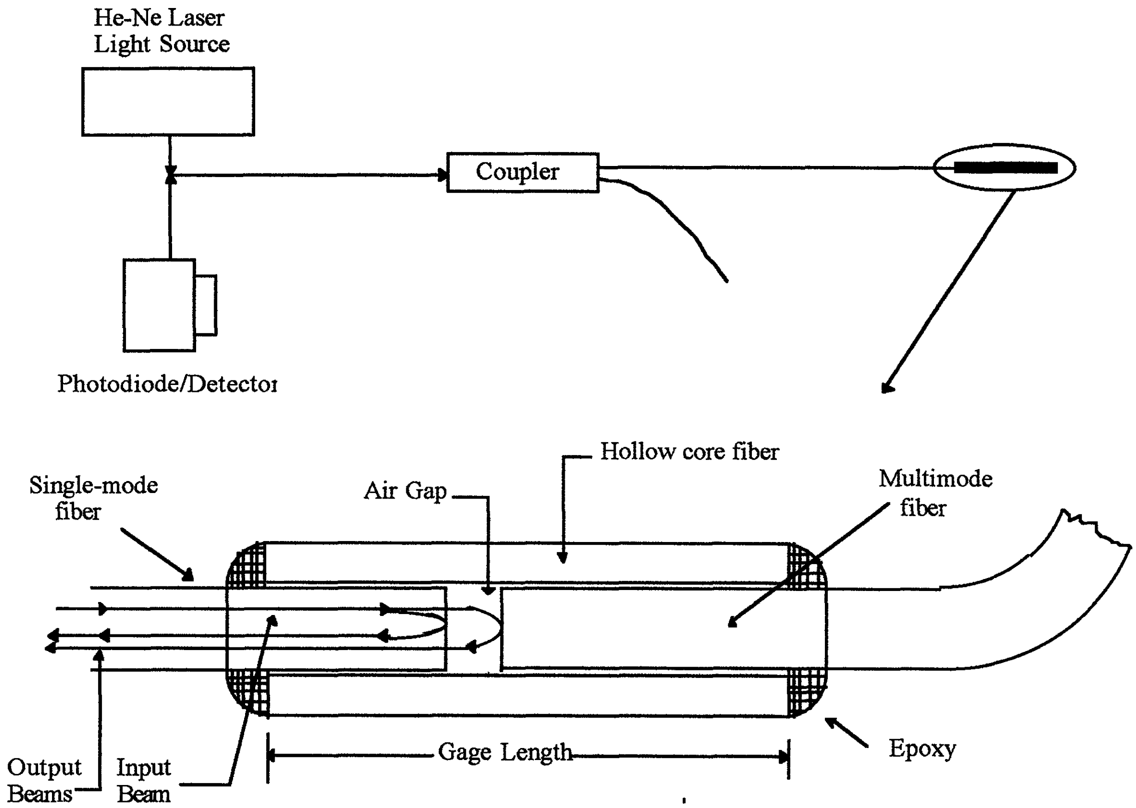

Figure 3-5 (b): The schematic of typical Extrinsic Fiber-Perot Interferometric (EFPI).

3.5 An Overview of Embedded Optical Fiber

Several activities have been undertaken by embedding optical fibers inside concrete structures to study the mechanical behavior of concrete structures[5,6,7]. FOS (Fiber Optic Sensor) provides dependable measurements because of the sensitive characteristic of optical fibers and also possibility of a real-time damage assessment of the structure. FOS

[5] Maher, M.H., Nawy, E.G., "Evaluation of Fiber Optic Grating Strain Sensor in High Strength Concrete Beams", Applications of fiber Optic Sensors in engineering Mechanics, Edited by Ansari, F., ASCE, 1993.
[6] Huston, D.R., Fuhr, P.L., Ambrose, T.P., "Dynamic Testing of Concrete with fiber Optic Sensors", Applications of Fiber Optic Sensors in Engineering Mechanics, edited by Farhad Ansari, ASCE, 1993.

technology could fit in both new and existing structures. For existing structures, the optical fibers could be mounted on the surfaces of the structures. However the drawbacks of this technique are significant since there may not be effective strain transfer between the external sensor and the structure. Furthermore, the sensors could be damaged since it is placed outside the structures. For new structures, optical fibers can be embedded inside the structure thus provide an intimate contact with the material itself. However, lack of information regarding the survivability of these optical fibers inside the concrete structures could pose a barrier to the successful implementation.

Two applications in laboratories are reported in this paper that dealt with the embeddment of optical fiber. The first of the application is the use of embedded fiber optic Bragg grating in concrete beam[8], and the second one is the determination of dynamic fracture parameters in fiber reinforced concrete.[9] Both of these applications show promise of utilizing optical fiber sensors in real structures.

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[7] Mendez, A., "Applications of Embedded Optical Fiber Sensors for Non-Destructive Testing of Concrete Element and Structures", Applications of Fiber Optic Sensors in Engineering Mechanics, edited by Farhad Ansari, ASCE, 1993.
[8] Maher, M.H., Nawy, E.G., "Evaluation of Fiber Optic Bragg Grating Strain Sensor in High Strength Concrete Beam", Applications of Fiber Optic Sensors in Engineering Mechanics, edited by Farhad Ansari, ASCE, 1993.
[9] Ansari,F.,"A Fiber Optic Sensor for the Determination of Dynamic Fracture Parameters in Fiber Reinforced Concrete", Applications of Fiber Optic Sensors in Engineering Mechanics, edited by Farhad Ansari, ASCE, 1993.

3.5.1 Fiber Optic Bragg Grating (FOBG) Strain Sensor

This type of optical fiber was first invented by Hill et al. [1978] in a standard telecommunication application. The FOBG is very capable for the quantitative measurement of load induced strain based on changes in grating spacings. This feature is certainly needed in measurement of civil engineering applications such as bridges. An exciting and relatively new development is the technique of directly utilizing photorefractive Bragg gratings within the core of a single-mode fiber[10]. The photorefractive Bragg fibers depend on glass composition to allow a large and stable refractive index change to be generated in the core of fiber. An interference pattern of ultraviolet light at around 240 nm is focused onto the core of a germanium-doped silica fiber. The gratings were simply formed by an optically induced refractive index shift generated by the interference of two counter propagating waves in the fiber. High sensitivity measurements of strain have been shown by monitoring the phase shift of the Bragg reflection when loading is applied.

An FOBG equipped with a longitudinal periodic variation of the index refraction in the core of an optical fiber as shown in Figure 3-6. The periodic variation is created at a wavelength corresponding to the interference pattern of the ultraviolet light. With the periodic Bragg grating, only light with a wavelength equal to twice the optical path (spacing) is reflected. As shown in equation 3.1.

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[10] Meltz, G., Morey, W.W., Glenn, W.H., "Formation of Bragg gratings in Optical Fibres by a Transverse Holographic Method", Optic Letters, vol. 14(15), pp. 823-825, 1989.

$$\lambda_{Bragg} = 2\ n\ D \tag{3.1}$$

where λ_{Bragg} is the reflected wavelength of the light; n is the average index of refraction in the core of the fiber; and D is the spacing of the periodic refractive index variation. The application of loading induces strain which caused the spacing which caused the spacing (D) to change, creating a shift in the Bragg wavelength reflected for an applied strain.

In the simplest configuration the spectral shift of the Bragg reflection corresponds to an applied strain or temperature change. Maher et al.[1993] performed this simple task by launching light from LED source at 1300 nm into a 3 dB coupler with one leg of the coupler connected to the fiber with the FOBG. The return leg of the coupler is then connected to a spectrum analyzer which monitors the spectral shift of the reflection band (Figure 3-7). Figure 3-8 shows schematically the system instrumentation which consists of light source, optical spectrum analyzer as the receiver, a 3 dB coupler and the grating strain sensor.

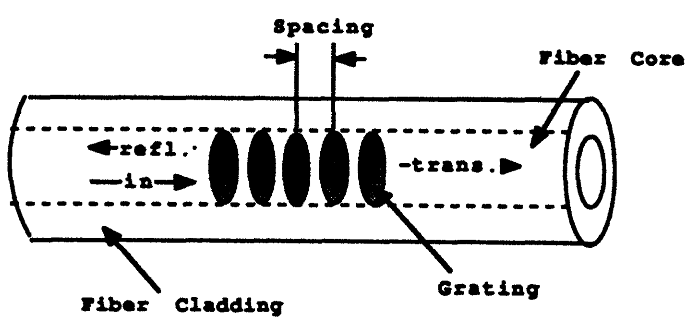

Figure 3-6: Schematic diagram of gratings in FOBG sensor.

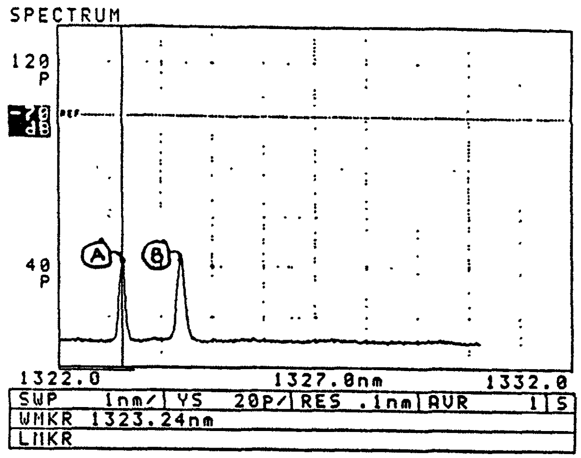

Figure 3-7: Typical spectral shift detected by FOBG from load induced strain or temperature change.

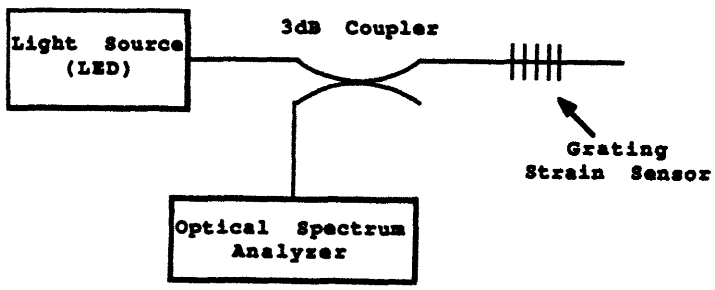

Figure 3-8: Schematics of instrumentation for FOBG sensor [Maher et al., 1992].

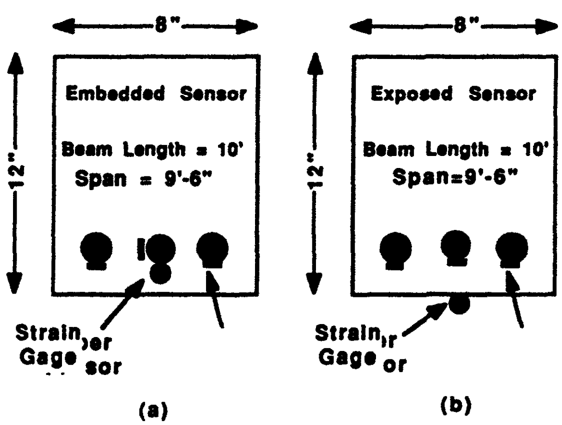

Figure 3-9: Schematic diagram of the concrete specimen cross-sections.

3.5.1.1 Experimental Work

In Maher et al. [1993], three-point bending tests were performed with FOBG embedded inside the reinforced concrete and bonded externally underside the specimens. Figure 3-9 shows the schematic diagram of the concrete specimen cross-sections and the measurements are compared with the strain gage measurement to get the correlation between these two sensors. The results of moment ratio vs. tensile strain for the embedding of fibers and externally bonded fibers were shown in the Figure 3-10 and Figure 3-11 respectively. Good agreements were observed between measurements obtained from the FOBG sensor with those obtained from electrical strain gages and with LVDT for the second test.

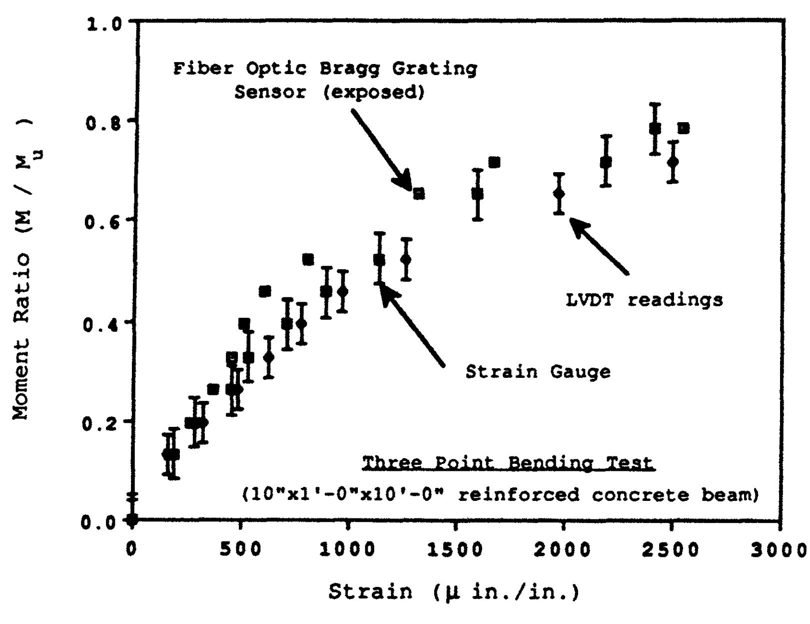

Figure 3-10: Moment Ratio vs. tensile strain on a FOBG sensor embedded in a large scale reinforced concrete beam.

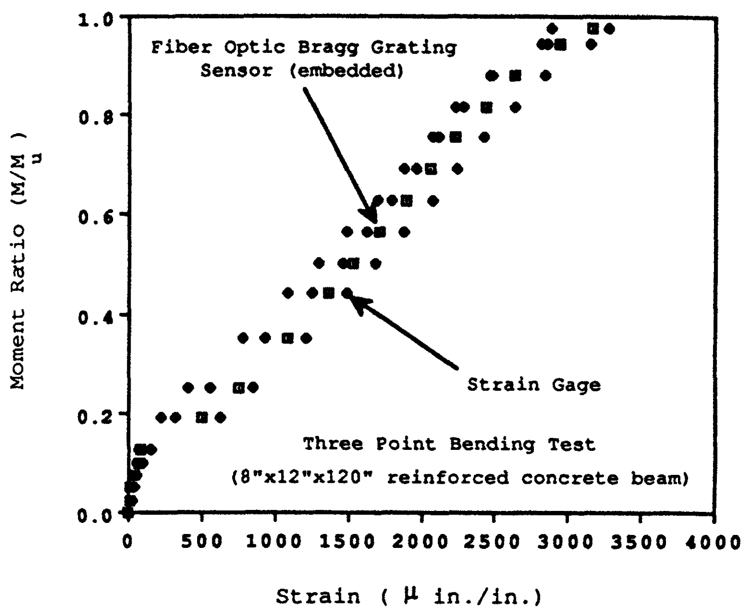

Figure 3-11: Moment Ratio vs. tensile strain on a FOBG sensor exposed on the underside of the large scale reinforced concrete beam.

3.5.2 Dynamic Fracture Mechanics

Development of sensors for detecting and quantifying the fracture process in concrete structures has been a continuing goal of researchers in the smart structure discipline. In one study done by Ansari [1993], the displacement measurement associated with opening cracks in cementitious composites was studied assuming the locations were known a priori. Although in real applications, cracks could occur in any possible location, this experiment does serve to demonstrate the feasibility of crack sensing in concrete structures with optical fiber sensors. Figure 3-12 describes the instrumentation involved in a typical fracture test by using intensity modulated fibers.

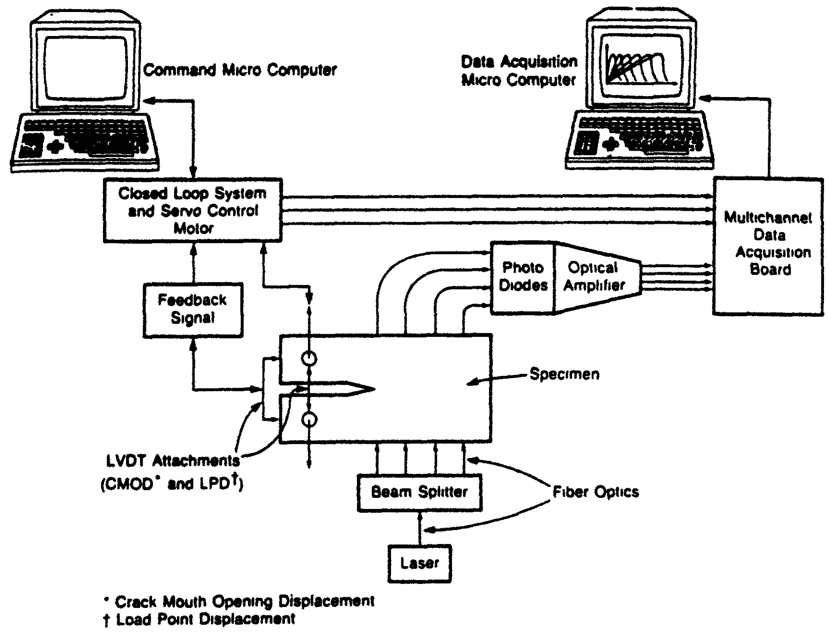

Figure 3-12: Instrumentation involved in a typical fracture test by intensity modulated fibers.

Determination of fracture mechanics parameters in concrete have been the subject of numerous investigations. One parameter of significant importance in determining fracture properties is the crack tip opening displacement (CTOD) which in this experiment is obtained by using embedded optical fibers. Figure 3-13 illustrates the behavior of the optical fiber inside the specimens.

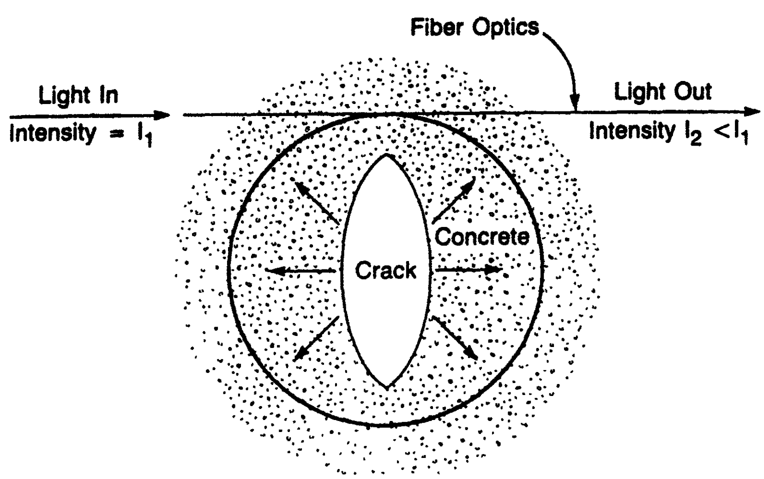

Figure 3-13: Fiber optic CTOD sensor for concrete.

3.5.2.1 Instrumentation and Experimental Work

In the experimental set-up of Ansari [1993], a 25 mW Helium-Neon (He-Ne) laser source provided the light source entering the optical fiber. Light intensity output is detected by a photodiode from the exit end of the optical fiber. Optical intensity is amplified and is converted to digital signals through a multichannel high speed waveform digitizer at a sampling rate of 1 MHz. The output of the digitizer is transferred to a microcomputer for analysis. A Tinium Olsen Charpy impact machine was modified and instrumented for testing FRC beams under three point bending load conditions.

The first step in this experimental work is to calibrate the correlation between the displacements and corresponding signal modulations. The calibration process is shown in Figure 3-14 which is simulated by the separation of cylinder halves.

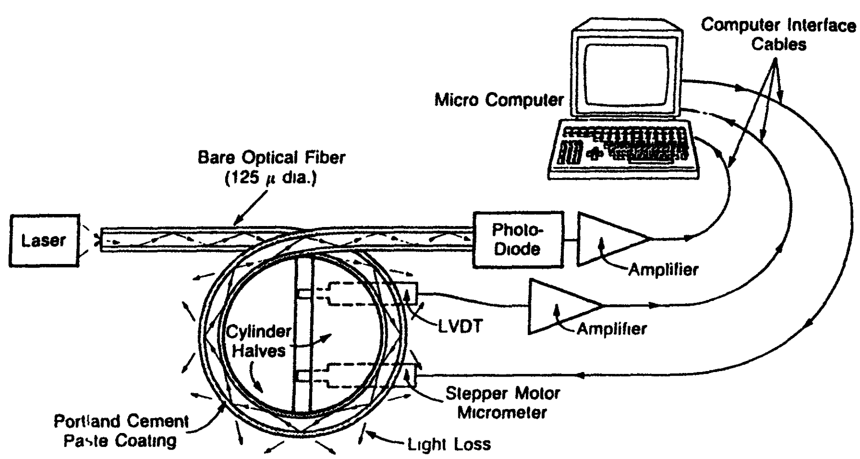

Figure 3-14: Instrumentation associated with the calibration of the fiber optic CTOD.

Figure 3-15: Placement of the fiber optic sensor in the concrete mold.

Figure 3-15 shows the placement of the sensing loop (25.4 mm in diameter) in the concrete mold. The loop introduces microbending in the system. Notches were cut in the middle of the beam to control the crack location. All specimens were tested under an impact velocity of 1.1m/s. Typical CTOD data for specimens with various amounts of fiber reinforcement are compared in Figure 3-16. It will be noted that addition of steel fibers results in lower CTOD values and longer fracture periods. Figure 3-17 describes the typical stress-CTOD curves for the four different types of specimens tested. Short conclusion can be drawn in this test i.e. under impulsive loading conditions, specimens containing larger quantities of steel fibers exhibited longer time durations to fracture and reduced CTOD.

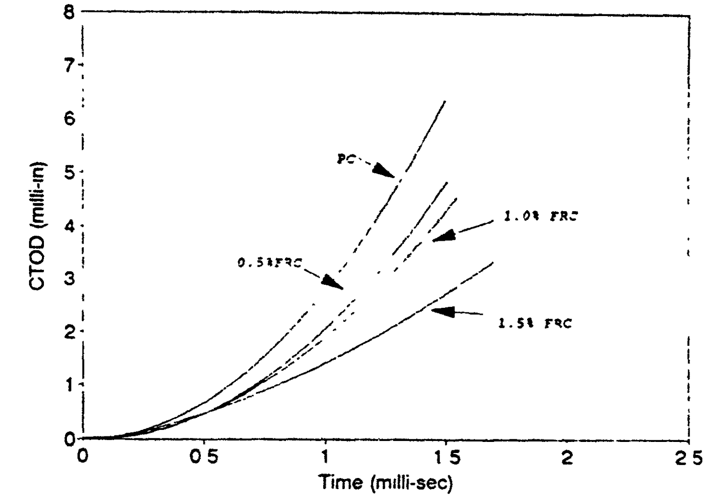

Figure 3-16 : Typical CTOD response for specimen with different amounts of fiber.

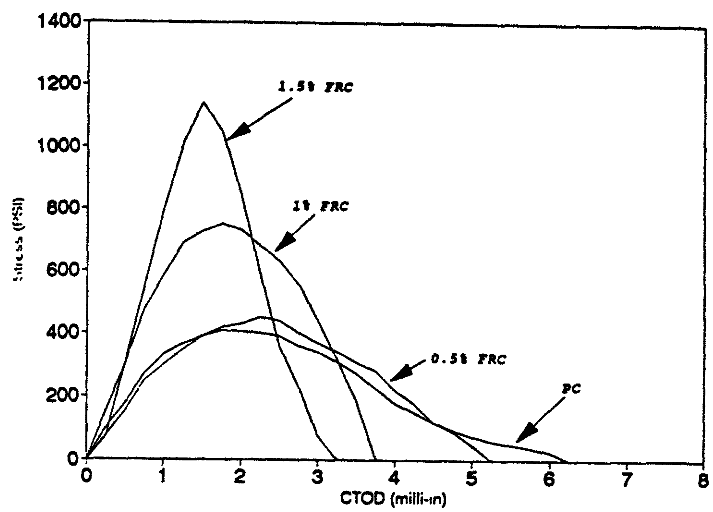

Figure 3-17: Typical stress-CTOD relations.

3.6 Technology Transfer

Since the initial demonstrations of various fiber optic sensing techniques in the laboratories, much progress has been made in creating practical sensors for use in real world applications. Although the technology of FOS has not reached the point where its applications could be considered practical in real structures, some in-situ implementation has been done to demonstrate the usefulness of this technique. An application of embedded optical fibers in concrete structures are presented here with respect to the monitoring of a prestressed concrete bridge in Leverkusen, Germany[11] .

3.6.1 Monitoring of Prestressed Concrete Structures

The bridge Schiessbergstrasse in Leverkusen presents a new advancement in structural engineering with the use of "intelligent tendons" for prestressing as well as other sensors for the monitoring of stress strain behavior of the concrete, temperature change, and chemical effects. Here, the discussion will not include the chemical sensor and will only focus on the stress strain and temperature change in the structure. Figure 3-18 shows the plan view and details of the bridge.

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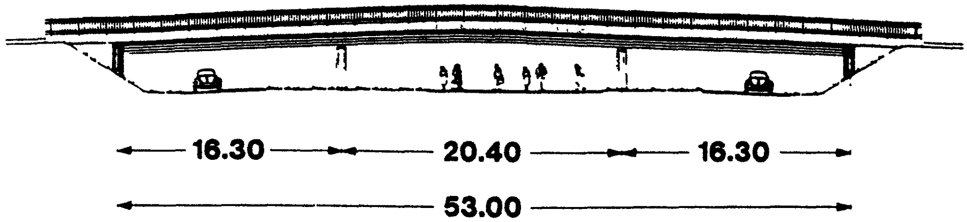
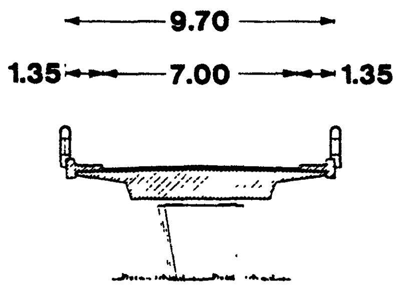
[11] Wolff,R., Miesseler,H-J., "Monitoring of prestressed concrete structures with optical fiber sensors", The 1st European Conference on Smart Structures and Materials, Glasgow 1992.



Plan view



Cross section

Technical data

Spans	L1=L3:L2=16.30:20.40
Slabs width	9.70m
Slabs thickness	1.12m
Clear height	3.00m
Load class (DIN 1072)	60/30
Degree of prestressing	Limited
Nature of the composites action	post-tensioning with subsequent bond

Figure 3-18: Plan view and technical data of the bridge.

3.6.2 Stress Strain and Temperature Measurements

The use of copper wire and optical fiber sensors facilitates a permanent control of the prestressing element over its entire length. The sensors are already integrated into the tendon during its fabrication hence each tendon can be continuously monitored individually.

The monitoring of the structure for this bridge only continued for the first two months after the construction. In the Schiessebergstrasse bridge, 3 prestressing tendons, each comprising of 19 individual bars, are equipped with copper wire sensors. One sensor module consists of 4 optical fiber sensors are placed on both the top and bottom part of the bridge. Figure 3-19 describes the longitudinal and cross sections of the bridge.

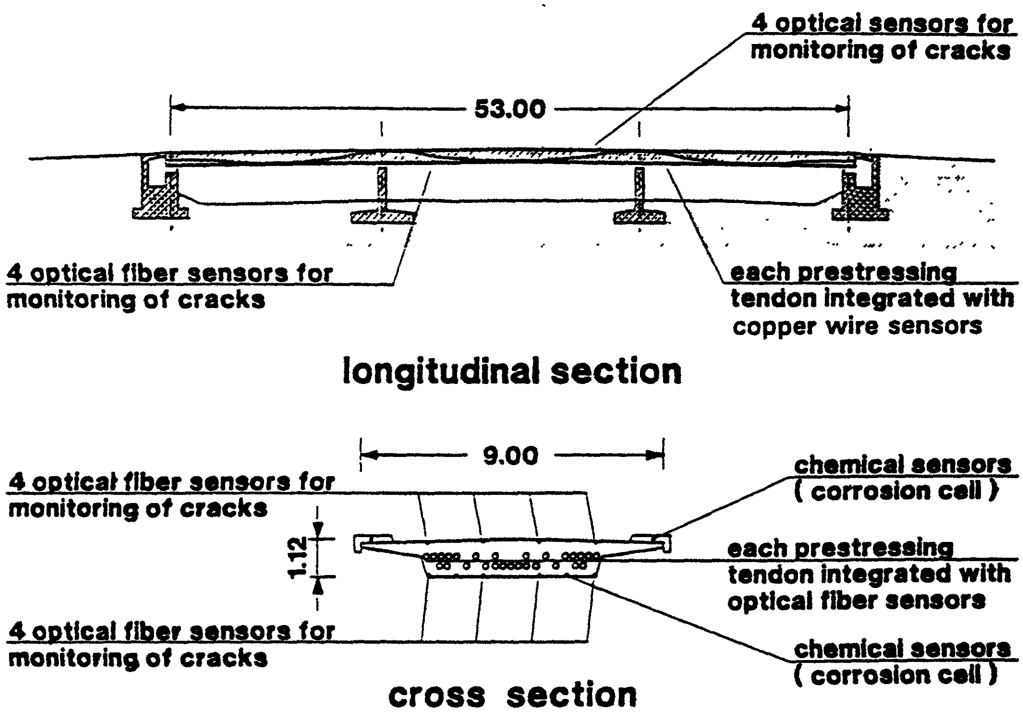


Figure 3-19: Arrangement of the optical fiber sensors and chemical sensors.

3.6.3 Results

The data processing is integral in monitoring the bridge continuously. The measured values are processed by a personal computer in a measuring chamber located near the pier with specially developed software. A phone line from the measurement chamber to the office of the client allows an inquiry and a storage of the measured values. An alert notification occurs when the difference between measured values and theoretical values exceeds a predetermined threshold value. This alert can help maintain safe conditions and reduce maintenance costs.

The sensor elongation during December and January 1992 as shown in Figure 3-20 were observed. In the tension zone of the middle span at the second pier, the sensors are 8 m in length. The sensor elongation was mainly influenced by temperature and creep since the bridge was not open to traffic at this time. The information regarding deformation of the structure are permanently recorded by a computer in the measurement chamber in the bridge and then running via phone line to the laboratory of SICOM[12].

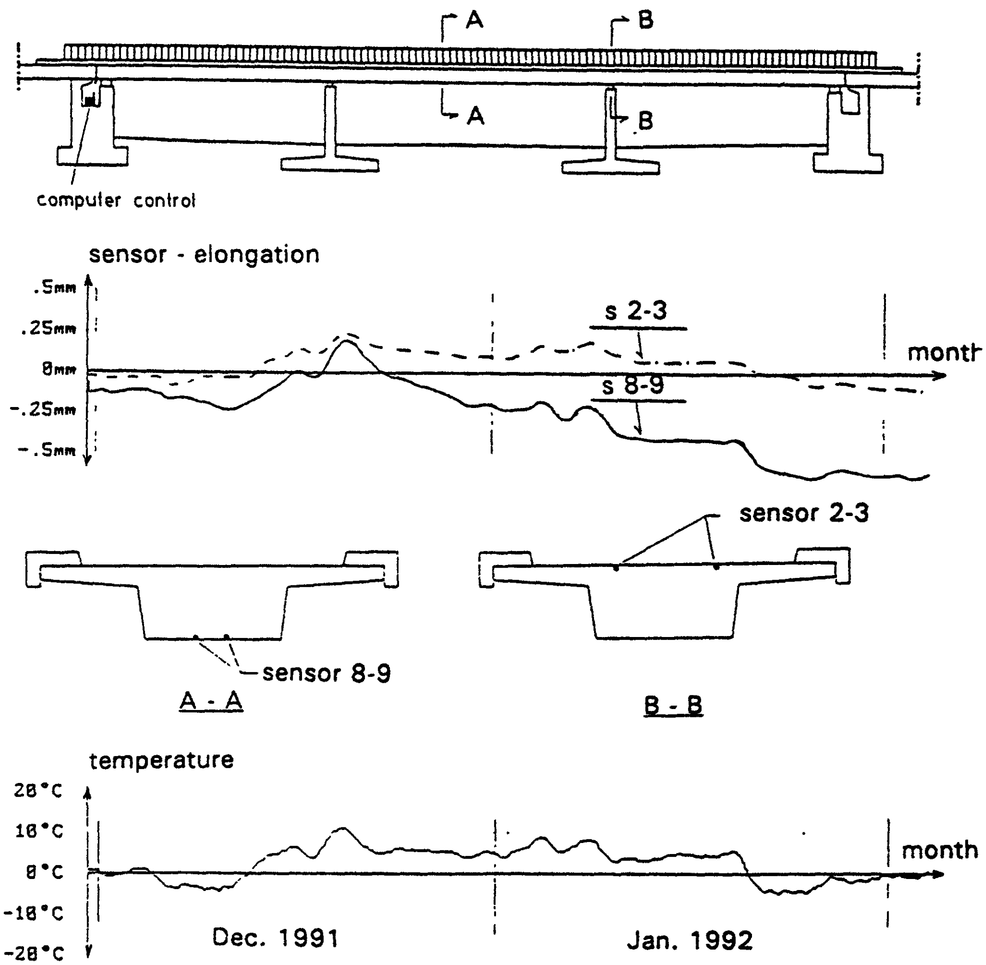


Figure 3-20: Measurement results of Bridge Schiessbergstrasse.

[12] SICOM is the name of company where the authors are presently working.

Chapter 4

Experimental Preparation

Good experimental preparation is essential for consistent data. Certain aspects of the experiment require special attention. First, due to the heterogeneous behavior of the cement paste, it is very difficult to make uniform specimens. A second problem encountered is that the optical fibers are brittle and easily damaged in the concrete matrix. Third, the calibration of test equipment is tedious and requires periodic examination. This chapter will cover all the steps for specimen preparation as well as all the testing and observation procedures, including optical fiber pull-out, SEM (Scanning Electron Microscope), and optical fiber measurement of crack openings. In addition, the equipment and materials used for the tests will be discussed.

4.1 Materials

There were two elements used in the experiments, cement paste and optical fibers. The cement paste consisted of type III (high early strength) Portland cement, water and mortar sand. For both the SEM and pull-out specimens, the sand[1] was sifted with a number 25 sieve while the cement passed a number 200 sieve. For part of the crack opening study, acrylate-coated optical fibers with total diameter equal to 250 μm was used. Three different types of optical fibers were employed in the durability study i.e. SEM study and pull-out tests, they are as follows:

1. Acrylate-coated fibers (core diameter = 125 μm and total diameter =250 ± 20 μm)
2. Polyimide-coated fibers (core diameter =100 mm and total diameter = 400 ± 30 μm)[2]
3. Teftzel-silicone-coated fibers (core diameter = 104 mm and total diameter = 120 ± 7 μm)[3]

4.2 Pull-OutTests

4.2.1 Specimen Preparation

The dimensions of the pull-out specimen were 1" (25.4 mm) by 1/2" (12.7 mm) by 3/8" (9.5 mm) thick. All three optical fibers were cut to length 22 mm and then inserted into Plexiglas blocks with 10 mm protruding out.

The molds were made of brass and consist of six sections, each section with an internal area of one inch square (Figure 4-1). The Plexiglas blocks that hold the optical fibers have the same dimensions as the specimens. To ease specimen separation from the

[1] The sand is manufactured by Walbro, Massachusetts.
[2] The total diameter includes core, cladding, and buffer jacket. The tolerance is established by the manufacturer.
[3] Both polyimide and teftzel-silicone optical fibers were provided by Polymicro Technologies, Inc., Arizona.

molds, form releasing oil was applied to all sides of the Plexiglas except near the hole where the optical fiber was inserted. The inside surface of the mold was also coated with form releasing oil in order to reduce damage when the specimens were removed. The hole in the Plexiglas block was originally designed for a 0.5 mm diameter fiber. Since the optical fibers have a smaller diameter, a small amount of clay was placed inside the hole to better accommodate the smaller size of the fiber. Another benefit of putting the clay was to avoid mortar being trapped inside the hole. After the Plexiglas blocks were placed in the molds the cement paste was poured into the other half so that the optical fibers were embedded in the matrix (Figure 4-2). Table 4.1 displays the specifications for the experimental schedule.

Table 4.1 Pull-Out Specimen Specifications

Pull-Out Tests Schedules	
Different Periods :	1 Month[4]
The optical fibers are embedded inside the cement paste	3 Month[5]
Different Cycles :	30 cycles[6]
Freeze-Thaw Cycles	60 cycles[7]
Different Cycles :	20 cycles[8]
Wet-Dry Cycles	40 cycles[9]

[4] 1-Month period consists of 28 days in a water bath.
[5] 3-Month period consists of 84 days in a water bath.
[6] 30 freeze-thaw cycles consists of 14 days curing inside a water tank and 30 cycles each 12 hours/day of freezing and thawing, for a total of 44 days. The specimens were stored in a refrigerator.
[7] 60 freeze-thaw cycles consists of 14 days curing inside a water tank and 60 cycles each 12 hours/day of freezing and thawing, for a total of 74 days.
[8] 20 wet-dry cycles consists of 14 days curing inside a water tank and 20 cycles each 12 hours/day of wetting and drying, for a total of 34 days.
[9] 40 wet-dry cycles consists of 14 days curing inside a water tank and 40 cycles each 12 hours/day of wetting and drying, for a total of 54 days.

For the mortar mixing, a Kitchen Aid Model K5SS mixer was used. The mixer consists of six adjustable speeds which are manually controlled, a mixing paddle and a removable stainless steel bowl. The mortar mixing procedure follows:

1. Weigh 200 grams of mortar sand which has been sifted with a # 25 sieve , 100 grams of type III cement which has passed a # 20 or finer sieve (in this test sieve # 200 was used), and 50 grams of tap water. The final composition of the concrete is 1 : 2 : 4 (Water : Cement : Fine Aggregate) or w/c = 0.5.
2. Blend the cement and sand for three minutes at level 2 to achieve a good mixture. Next add one third of the water and mix at level 4 for 2 minutes. Then add another third of the water and mix for another two minutes at the same level. Finally add the remaining third of water and mix for 2 minutes at level 5.
3. Mild vibration is applied for a three minute period while pouring the mortar into the molds. Longer periods of vibration should be avoided since segregation/bleeding might occur. The paste is tapped with a small diameter rod to release the entrapped air.
4. Cover the specimens with plastic wrap to keep the specimens moist. The specimens are then allowed to cure for 24 hours before placing them in the curing tank.

4.2.2 Testing Procedures

The pull-out machine used to draw out the optical fibers was designed by Yiping Geng, for two directional fiber pull-out(Figure 4-3). In this particular test, only uni-directional load is applied for fiber pull-out. The apparatus consists of a hardened steel rod, a ball bearing block[10], a fiber grip, a 50-lb load cell, a "L" shaped bracket, a metal plate where the "L" shaped bracket is mounted, and a LVDT holder. The load cell was calibrated by applying known tensile loads and taking the corresponding voltage readings. The change in voltage was plotted against the known load and a calibration factor was determined. The load cell needs an external power supply of 3.0 volts. The LVDT (Linear Variable Differential Transducer) also needed to be calibrated along with the analog transducer amplifier (ATA) which is specially designed for the excitation, amplification and demodulation of AC-operated LVDT-type transducers. The LVDT is calibrated with the aid of a micrometer and the data acquisition system. In this test, an MHR-250 type LVDT was used in the pull-out test. The LVDT has an internal power supply which generates 3.0 volts. The pull-out tests were conducted at a monotonic crack opening displacement of roughly 6.615 μm/sec using a 30 teeth gear; each test lasted approximately 14.167 minutes. The experimental procedure follows:

1. Before mounting the specimen to the fiber grip, one must sand the contact surfaces of the specimen to avoid uneven surfaces which would cause improper attachment to the "L" shape bracket. A fine grade of sand paper was used in this case.
2. For acrylate and teftzel-silicone coated optical fibers, two layers of tape were wrapped around the fiber in order to avoid direct contact between the fiber and the grip. These layers provide a buffer layer thus making the fiber less susceptible to breakage.

[10] In this test, one should not tighten the screws on the bearing block, the block was previously designed for mix-mode pull-out.

3. The fiber was first placed into the fiber grip groove. The fiber grip was then tightened to prevent fiber slippage and a set screw located at the bottom of the grip was tightened to further clamp the fiber in position. Due to the smaller diameter and brittleness of optical fibers, two strips of tape each approximately 0.5 cm are used to support the weight of the specimen by attachment to the top of the fiber grip. The grip was then mounted onto the end of the pull rod by four screws located on four corners of the grip.
4. A moveable metal plate was mounted perpendicular to the main axis of the pull-out direction. The "L" shaped bracket was then attached to the metal plate.
5. The 5-minute epoxy was mixed and applied to the contact surfaces of the "L" shaped bracket and the specimen.
6. The pull rod and the movable metal plate were slid towards each other to firmly hold the specimen in place.
7. The motor was oriented such that the gears of the motor and pull rod were properly meshed. Once in position, the motor was secured into position by tightening the thumb screws.
8. The LVDT holder was attached to the back of the "L" shaped bracket. Once fixed into position the LVDT barrel was inserted in the upper hole of the holder and secured. Next the LVDT core, which was attached to the LVDT target, was inserted and located so that it was in its range (i.e. between -10 volts and +10 volts). The author found it best to operate in the plus or minus 7.0 volts to ensure the linearity of the displacement reading is ensured (Figure 4- 4).

9. The motor was started simultaneously with the data acquisition system.

4.3 Scanning Electron Microscope Studies

Wooden molds which consist of five sections each at the dimension of 1" (25.4 mm) by 1" (25.4 mm) by 3/8" (9.5 mm) thick (Figure 4-5). The molds are symmetric about both axes with a hole placed on one side at the mid-height of the block. This was to accommodate the insertion of the optical fiber. The author found that it was only possible to prepare two sets of molds at one time since more than two molds were uncontrollable on the vibrating table. The inside surfaces of the mold were covered with form releasing oil in order to easily remove the specimens without damaging them. Approximately 6 in. of optical fiber was inserted through the hole. The procedure of mortar preparation was the same as the one in the pull-out test (Section 4.2.1). One exception was that after pouring the mortar in the molds, a razor blade covered with form releasing oil was embedded in close proximity to the optical fiber (extreme care was taken to avoid touching the fiber). The purpose of the razor blade was to ease the process of taking out the optical fiber from the cured mortar. After 24 hours the specimens were extracted from the molds, the razor blades removed and the specimens were then placed in curing tanks.

To test the optical fiber durability, they were subjected to five different environments as shown in Table 4.2. Observation in the SEM (Figure 4-6) was carried out to see physical evidences of deterioration. Some of the optical fibers needed two different magnifications in order to observe in detail the surface profile of the optical fibers. To carry out the SEM, it was necessary to first glue them to circular mounts and have them gold coated. Careful attention in handling the optical fibers was taken since they are very brittle and "bruises" or "dents" are easily introduced. The application of liquid graphite on the mount help to provide a better conductivity . One needs to make sure that the fibers are free of moisture before its placement in the vacuum chamber for electron scanning (Figure 4-7).

Table 4.2 SEM Studies

Scanning Electron Microscope (SEM) Studies	
Different Periods :	1 Week
1. Inside the Water Tank	2 Week
2. Inside the Calcium Hydroxide Solution	3 Week
where pH = 13.0 and	1 Month
3. Inside the mortar	3 Month
Different Cycles :	30 cycles
Freeze-Thaw Cycles	60 cycles
Different Cycles :	20 cycles
Wet-Dry Cycles	40 cycles

4.4 Crack-Opening Test

4.4.1 Specimen Preparation

Fibers with three inclinations were embedded inside the cement paste (15°, 30° and 45°). The molds were made from brass with the inside dimension of 2" (50.8 mm) by 2" (50.8 mm) by 3/8" (9.5 mm) thick (Figure 4-8). A thin acetate film was inserted in the middle of each mold. Two sides of the mold were drilled with three different holes to allow the optical fiber to pass through at an angle inclination of 15°, 30° and 45°. All surfaces of the mold and film were coated with form releasing oil. A small hole was cut in the middle of the thin acetate film to let the optical fiber pass through. Clay material was applied near and inside the hole as mentioned previously. Each fiber was cut approximately to a 5 ft (1.52 m) length to allow for easy connection to both the detector and light source. The experimental procedure for the preparation of the crack opening measurement consists of the following steps:

1. Weigh 3000 grams of mortar sand (sifted with a # 25 sieve), 1500 grams cement type III (sieve # 45 was used throughout the tests), and 750 grams of tap water. Thus the composition of the material was 1 : 2 : 4 (Water : Cement : Fine Aggregate) or w/c = 0.5.
2. Blend the cement and sand for three minutes at level 2 to achieve a good mixture. Next add one third of the water and mix at level 4 for 2 minutes. Then add another third of

the water and mix for another two minutes at the same level. Finally add the remaining third of water and mix for 2 minutes at level 5.

3. Six specimens can be made for each mixing which gave 2 specimens for each angles.
4. Three PVC cylinders, 3" x 6" in dimension, were used to cast three cylinders to determine the compressive strength and modulus of elasticity of the specimens. The final modulus and compressive strength were found from the average of the three cylinders.
5. Mild vibration is applied for a three minute period while pouring the mortar into the molds. Longer periods of vibration should be avoided since segregation/bleeding might occur. A small diameter rod is used to release the entrapped air.
6. Cover the specimens with plastic wrap to keep the specimens moist. The specimens are then allowed to cure for 24 hours before placing them in the curing tank.

4.4.2 Experimental Procedure

The tests were performed at the Lightwave Technology Laboratory, Brown University. Instrumentation set up (Figure 4-9) consisted of a stabilized light source MG94B (Anritsu model) single-mode fiber laser diode at 850 nm wavelength (Figure 4-10). The photodiode detector Hewlett Packard 81520A optical head 450-1020 nm was used (Figure 4-11) in conjunction with a Hewlett Packard 8153A lightwave multimeter for the temperature control circuit to reduce the noise (Figure 4-12). The light-multimeter was then connected to a data acquisition system which utilized LabView Graphical

Programming for Instrumentation version 3.1. A special cleaver was used to prepare the fiber for proper connection to the light source and detector (Figure 4-13).

The pull-out apparatus designed by Noah G. Olson, is similar to the aforementioned pull-out machine. One major exception is the ability to measure the optical fiber intensity loss while the specimen is opened. This is possible due to the different specimen geometry in which the fiber is totally embedded in the matrix at both sides of the crack. In addition the LVDT is mounted directly onto the specimen which avoids any discrepancies in displacement measurement due to slippage. Hydrostone was used to cover the rough surface of the specimen. It was important to tighten all holding screws in the specimen clamp to avoid slippage (Figure 4-14). The crack-opening tests were conducted at a monotonic crack opening displacement of roughly 2.65 μm/sec using the 12 teeth gear, each test lasted approximately 12.5 to 15 minutes.

4.4.3 Compressive Strength and Elastic Modulus Determination

The determination of compressive strength and elastic modulus of the specimens were undertaken. The cylindrical specimens which were cured inside a curing tank were tested on the same day the crack opening specimens were tested. The concrete cylinders were prepared with the same mix used to cast the crack opening specimens (Figure 4-15). The concrete cylinders were capped with hydrostone to provide a smooth surface while loaded in the machine. The testing employed a 60 Kip Baldwin Machine which subjects the concrete 3" x 6" cylinders to continuous loading until failure. The loading rate of 0.1507 MPa/sec was employed to load the cylinders continuously without introducing any shock stresses. The range of the results shows that f'_c may vary from 39.3888 MPa to 45.5836 MPa. The load values are taken from the load cell reading as they were considered more accurate than those from the machine dial. Furthermore, the data acquisition system recorded the loading time and magnitudes every second.

For the measurement of the modulus of elasticity, the stress and strain ratio will be used to determine the slope which represents the Young's modulus of elasticity. The apparatus used for testing was the 60 Kip Baldwin Machine (Figure 4-16). Each specimen then is connected to a yoke assembly and two linear variable differential transducers (LVDT) placed opposite to each other (Figure 4- 17) . Calibration of the LVDTs needed to be done before testing the concrete cylinders. The length used was 2 in., a value measured when the yoke assembly was placed at the mid-height of the cylinder. The range of the results shows that E_c may vary from 3449.0 ksi to 3710.3 ksi. Table 4.3 summarizes both the compressive strength and modulus of elasticity.

Table 4.3 : Material Properties of Crack Opening Tests

10 Days Strength of Concrete Cylinders		
Cylinder	**Compressive Strength**	**Modulus of Elasticity (E_c)**
1	41.4148 MPa (6.005 ksi)	24390.3 MPa (3536.6 ksi)
2	39.3888 MPa (5.711 ksi)	23786.2 MPa (3449.0 ksi)
3	45.5836 MPa (6.609 ksi)	25588.3 MPa (3710.3 ksi)
Mean :	42.1290 MPa (6.109 ksi)	24588.3 MPa (3565.3 ksi)

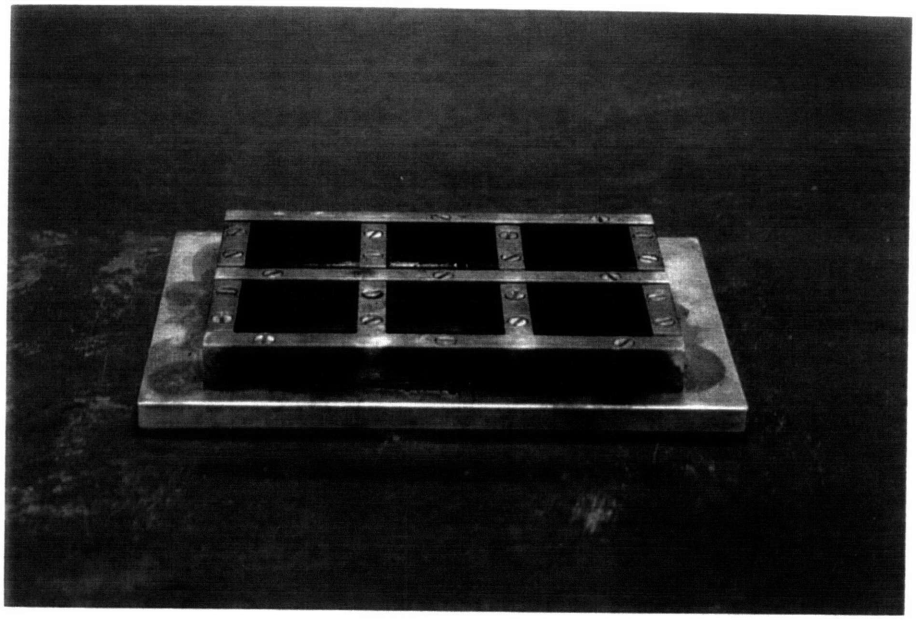


Figure 4-1: Brass mold used to cast specimens (notice the six sections).

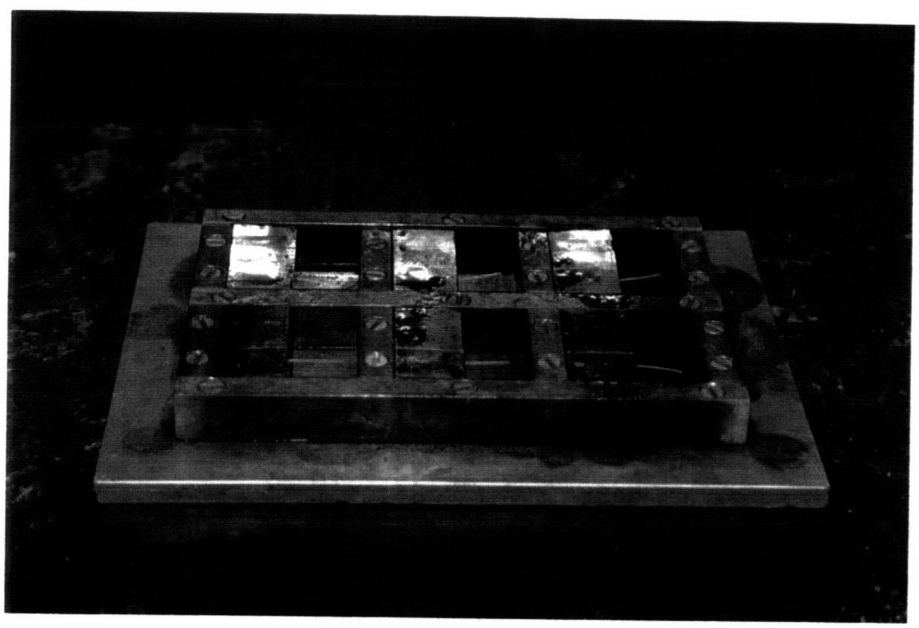


Figure 4-2: Mold with Plexiglas blocks inserted - ready for specimen casting.

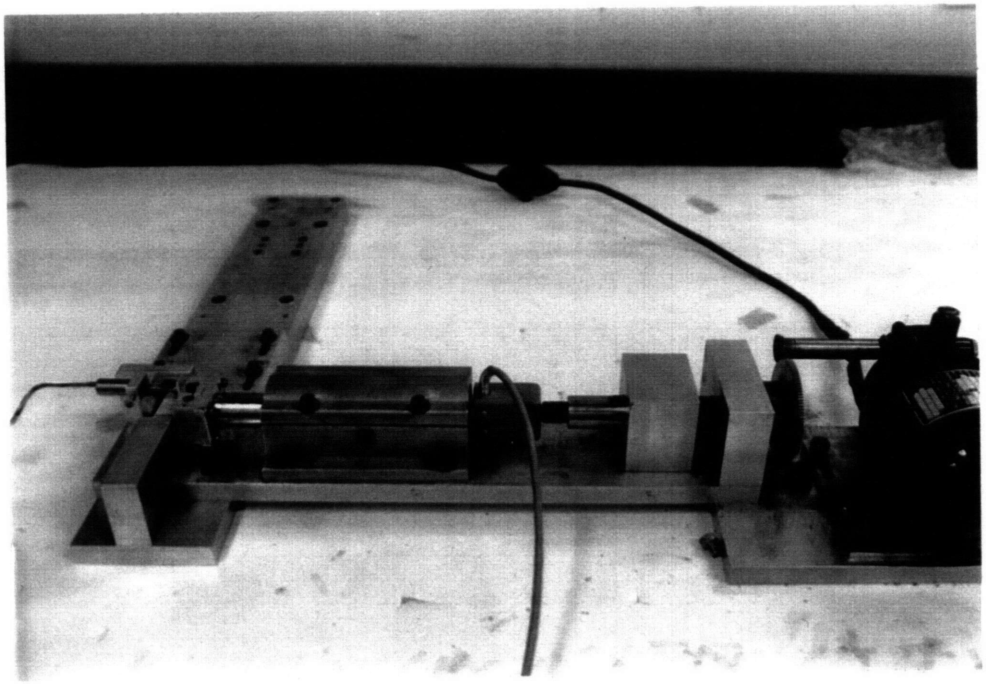


Figure 4-3: Pull-out Test apparatus.

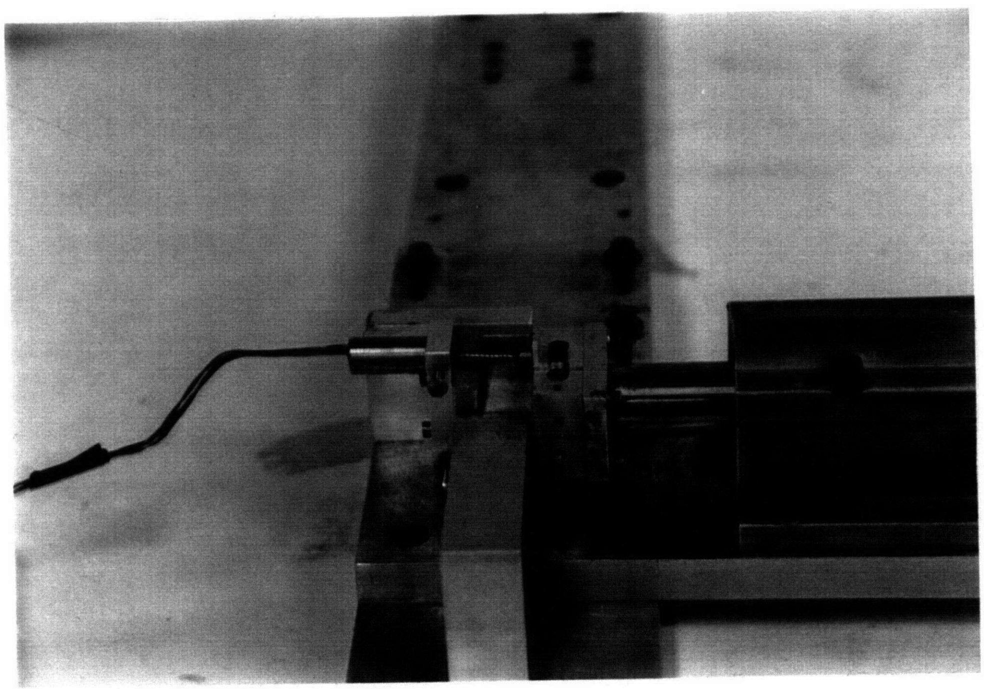


Figure 4-4: Close-up view of the fiber grip and "L" shaped bracket (notice how the LVDT core touches the target on the top of the fiber grip).

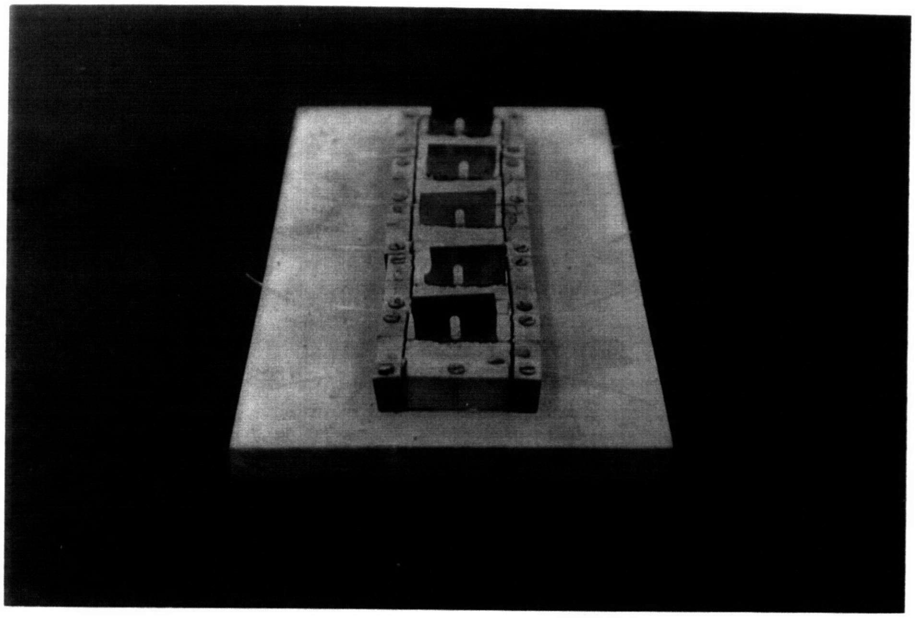


Figure 4-5: Wooden mold for SEM studies.

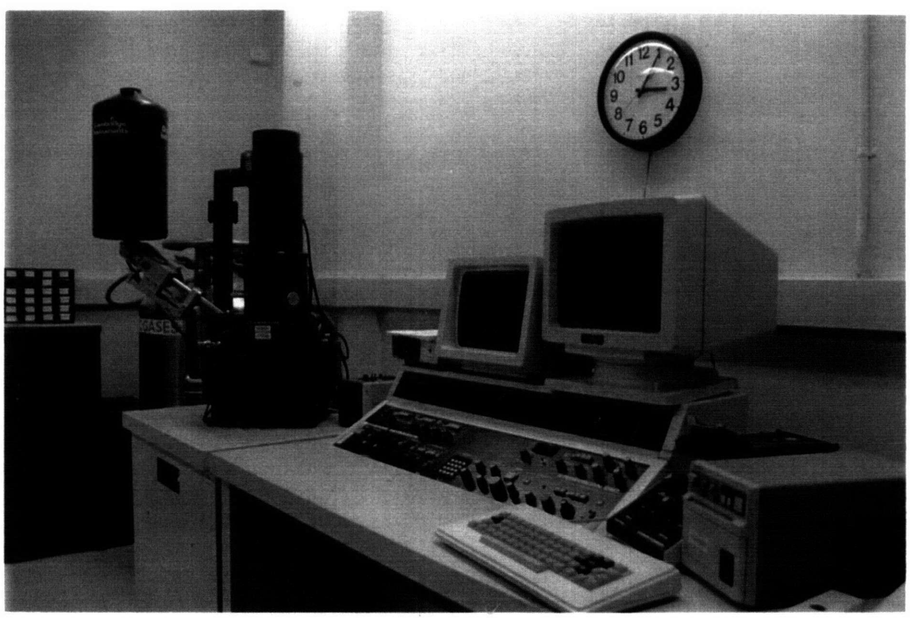


Figure 4-6: Control Panel of the Scanning Electron Microscope.

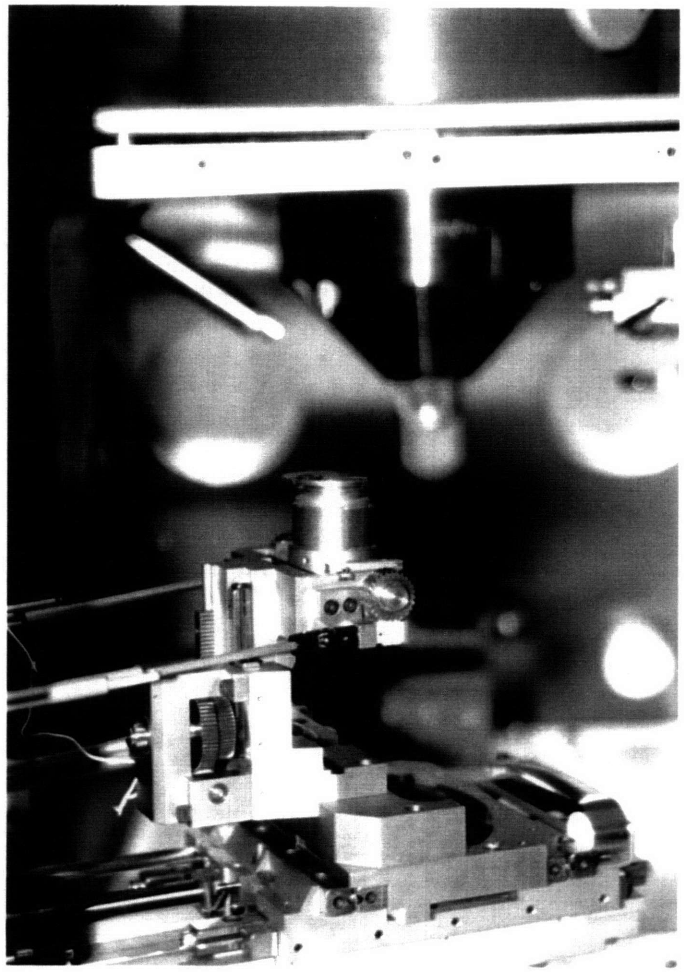


Figure 4-7: The Scanning Electron Microscope vacuum chamber.

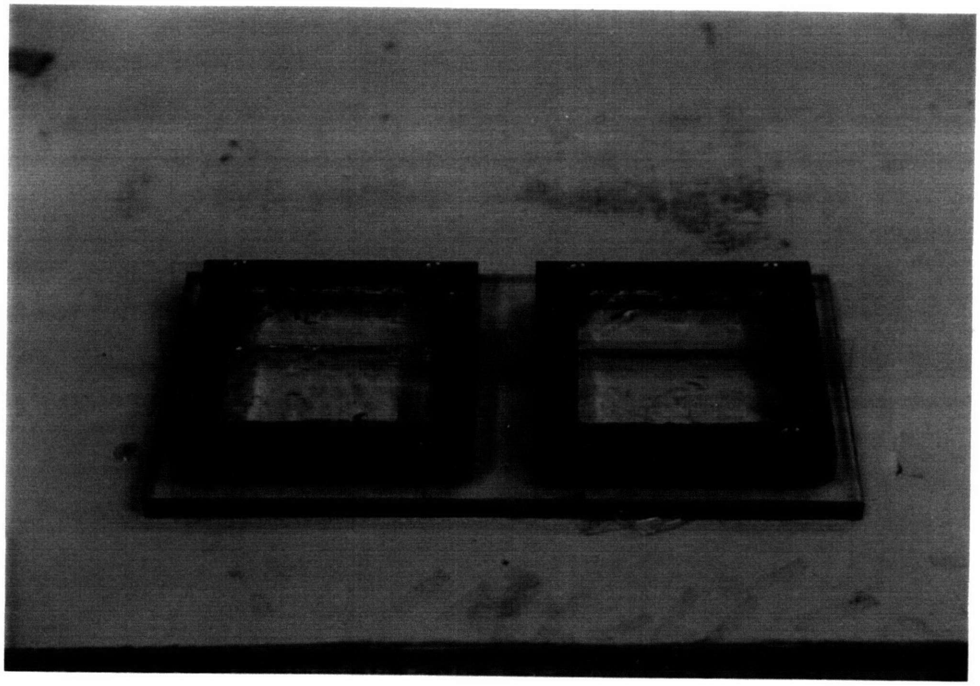


Figure 4-8: Brass mold used to cast crack opening specimens.

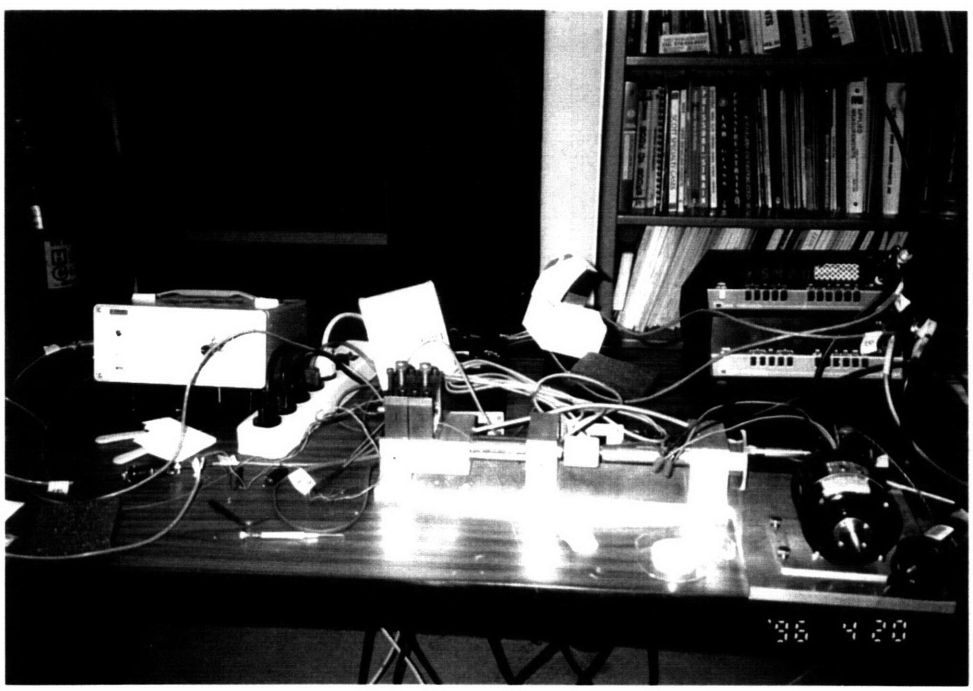


Figure 4-9: Crack Opening Test Apparatus.

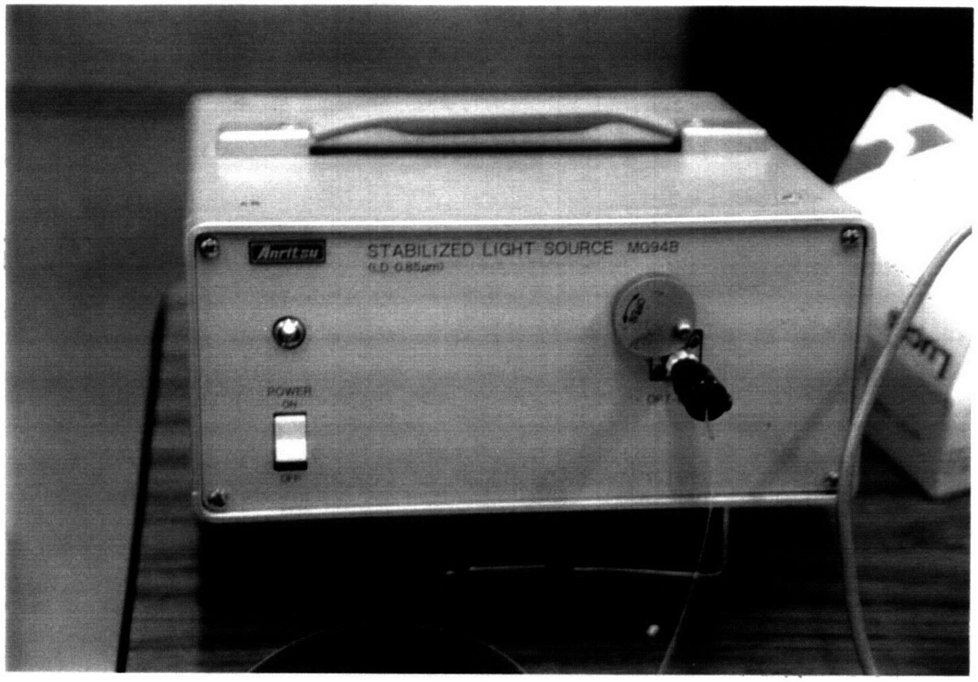


Figure 4-10: Stabilized Light Source MG94B (LD 0.85 μm).

Figure 4-11: Photodiode detector Hewlett Packard 81520A optical head 450-1020 nm.

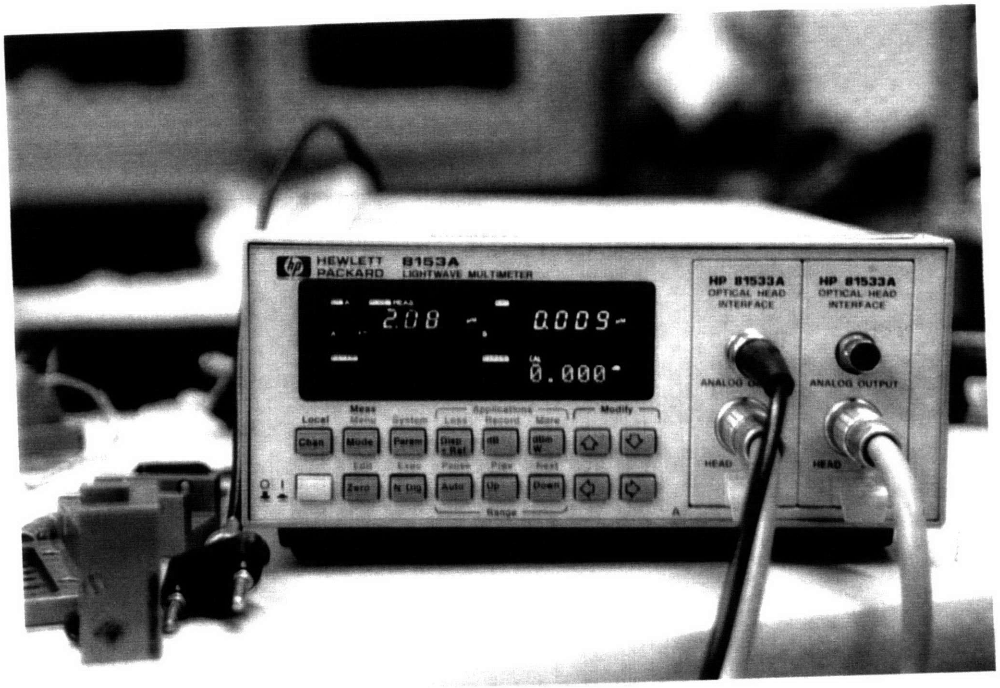


Figure 4-12: Lightwave multimeter Hewlett Packard 8153A.

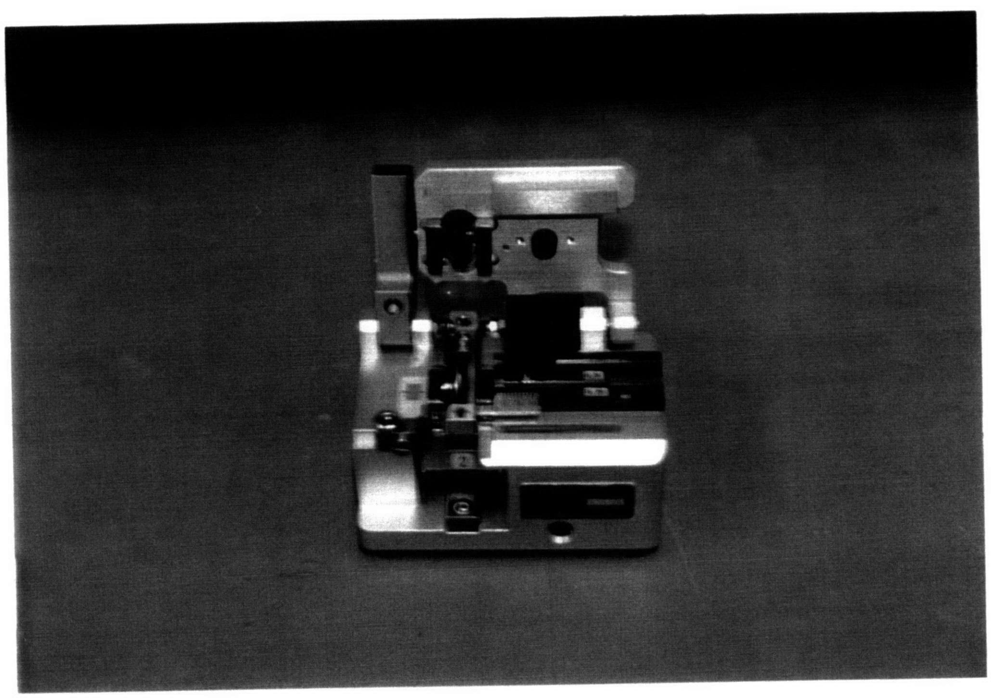


Figure 4-13: Special cleaver for trimming the optical fiber.

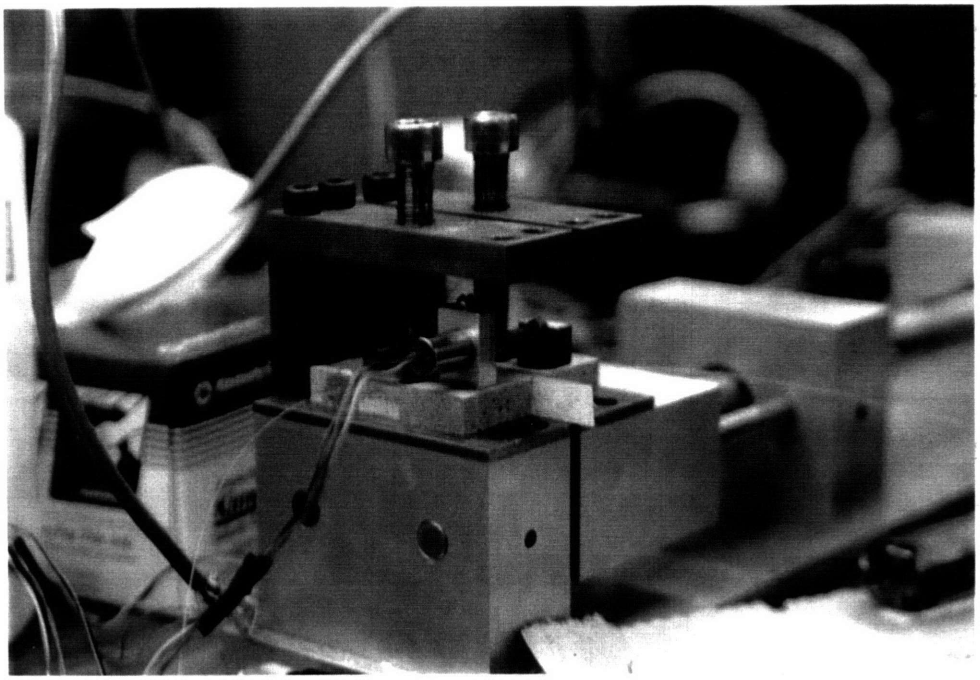


Figure 4-14: Close-up look at the crack opening test.

Figure 4-15: Concrete cylinders capped with hydrostone.

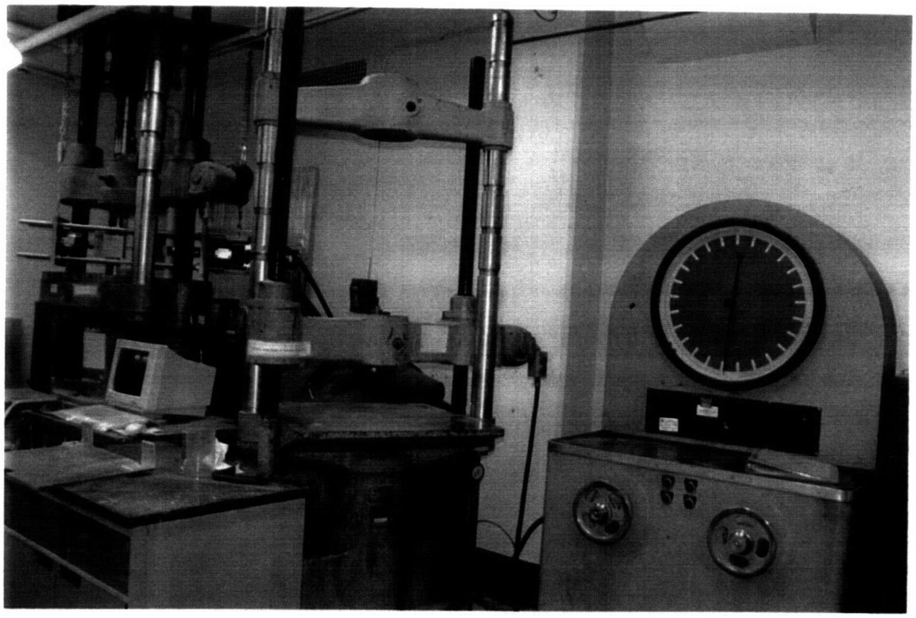


Figure 4-16: 60 Kip Baldwin Machine.

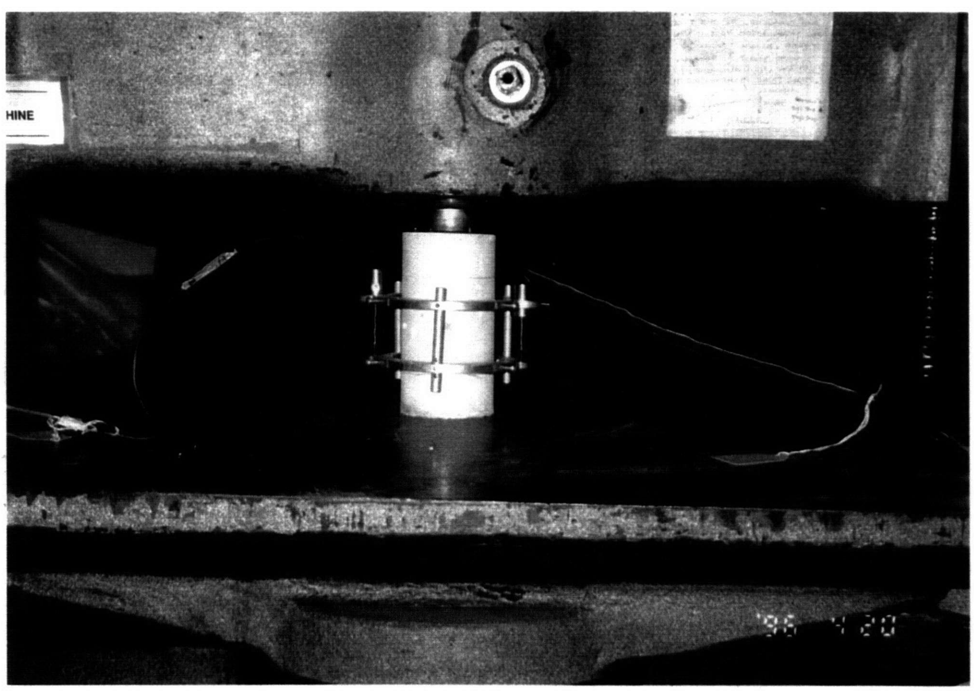


Figure 4-17: The Compressive Strength and Young's modulus test set-up.

Chapter 5

Feasibility Study of FOS

This chapter consists of two independent parts of studies; the first part of the study will focus on the feasibility of the new innovative optical fiber sensors technology in the construction market. Several models of innovation are presented to look at the behavior of the technology. The study of implementation process is also discussed to see if the technology could be transferred smoothly by diffusion process in the future. The last part of discussion focuses on the market of the FOS. Discussion on who will benefit from this innovation and who should have responsibility to foster the innovation will conclude the first part of the chapter. The second part will present preliminary experimental results to show the feasibility of FOS technology in quantifying the crack growth in concrete structures.

5.1 Facts About Concrete Structures

According to NSF studies in 1990[1], the world invests about US $ 1,430 billion annually in the construction of structures, including: buildings (residential, commercial, industrial, etc.), civil works, and utilities (such as highway, railroads, etc.). 80 percent of structures that are built in the world use concrete as primary materials. The deterioration of concrete structures especially in the infrastructures has been recognized as major concerns in most part of the U.S. as well as other parts of the world, thus the demand of a high reliability structure has become a critical aspect since some major accidents have ruined infrastructures as well as buildings.

In 1994, the government showed its concern regarding building better structures in the proposal entitled "White House Task Force Proposed Industry Targets for Innovation"[2]. Several objectives targeted for the beginning of the 21st century were put forth. Two of the objectives relate closely to the development in the area of smart structures i.e. 50 percent lower operations/maintenance costs and 50 percent fewer building-related accidents.

In order to solve the deficiency of structures, a first approach by the construction industry is to strengthen the structures. Codes only intend to protect structures from collapsing without acquiring important history data of structures. If an economically

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[1] Chong, K.P., Scalzi, J.B., Dillon, O.W., "Overview of Nondestructive Evaluation Projects and Initiative at NSF", Intelligent Structures, Editors : Chong, K.P., Liu, S.C., Li, J.C., Proceedings of International Workshop on Intelligent Structures, Taiwan, 23-26 July, 1990, Elsevier Applied Science.

[2] Civil Engineering Research Foundation. National Construction Goals: A Construction Industry Perspective. Washington DC: Civil Engineering Research Foundation, 1995.

feasible and technical system can be developed to continuously monitor the performance of structures, proper maintenance can be accomplished in the early stage and failure of structures and particularly loss of human lives may be avoided or minimized. According to a recent study, 40 percent of the nation's busiest bridges (those carrying 15,000 or more vehicles a day) are structurally or functionally deficient. It is only a matter of time before the nation's economy which so dependent on good transportation begins to suffer. The society awareness regarding these issues will surely trigger business opportunity for construction companies with interest in providing solutions to these problems, as the improvement of technology and science is relatively connected with the business side. One alternative to minimize the problems is the use of Fiber Optic Sensor (FOS) which could provide a good quality control during early process of construction as well as monitoring the structures until the end of their service life.

5.2 Innovation in Construction

The advancement of technology will be useless if its use could not be translated into marketing the product. Moreover, construction industry influences the productivity of other sectors of the economy because of its core role in the nation's infrastructure thus the market study of FOS should be undertaken.

It seems that innovation in the area of construction is heading in a backward direction. The US Government only spent 12 percent of the total GDP (Gross Domestic Product) into construction which is rather small compared to Japan or western European countries[3]. As much as 60 percent of the estimated expenditures are consumed in repairing and maintaining of existing structures. Given this condition, only a small portion of the budget will be left for R&D. Thus the biggest problem here lies in repairing and maintaining the infrastructures. As mentioned earlier, concerning the fiber optic technology which promises the reduction of spending, one needs to pay attention to how this innovation can survive in the construction market. Figure 5-1 describes one of the process of innovation which takes place in most of the product or process innovation.

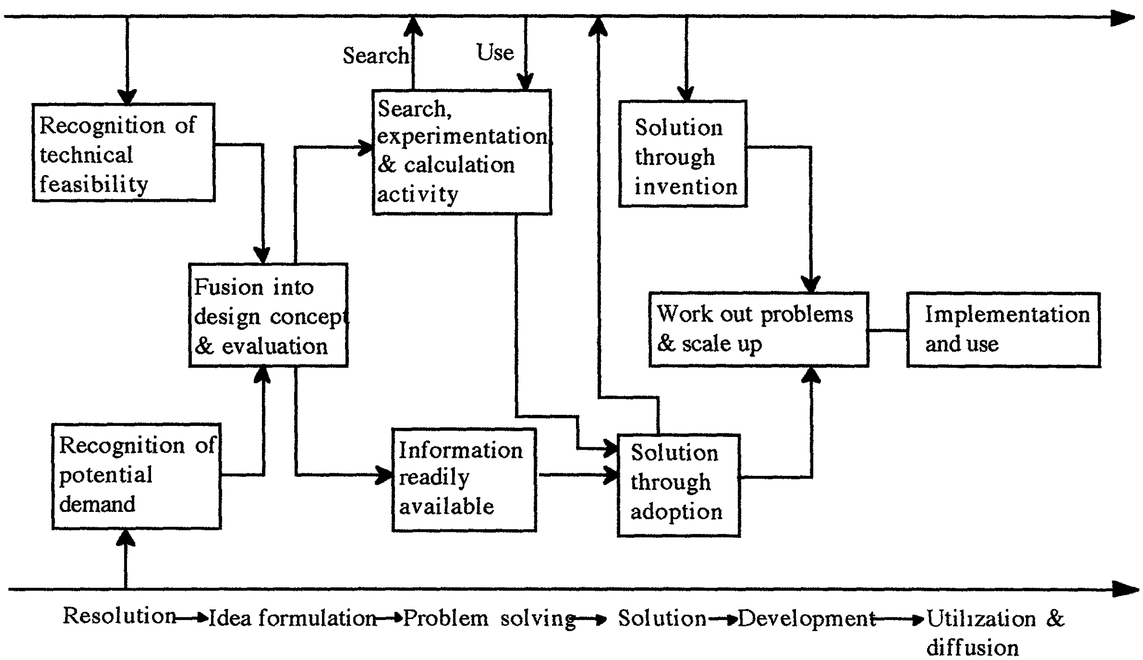

Figure 5-1: Model of the process of innovation (After Marquis, 1969).

[3] Lerner, A.C., Dibner, D.R., The Role of Public Agencies in Fostering New technology and Innovation in Building, pp. 31-46, National Academy Press Washington, D.C., 1992.

5.3 FOS: Innovation vs. Invention

It is a subtle matter to differentiate between innovation and invention of FOS technology. According to Schmookler, an invention is a new combination of technology given pre-existing knowledge which fulfills the demands of customers. On the other hand innovation refers to technical changes in products or processes. The question of whether the FOS is invention or innovation needs to be studied carefully.

As an invention, FOS fulfills the requirement of the new combination of several technologies i.e. material coatings, sensor technology, optical-glass quality, laser technology, and concrete technology which are combined to form a new innovation i.e. optical fiber sensor technology. As an innovation, FOS provides technical changes in using optical fibers as structural monitors as compared to its original purpose for transferring telecommunication signals. Thus FOS could be considered to occupy both positions as innovation as well as invention. It could be tracked down that FOS is recognized first as an invention for its application in the telecommunication area but changes its status into innovation when technical changes are introduced in its applications, thus the invention now is part of the process of innovation. One could consider that the FOS innovation fell into the "generic technology". Almost no agencies outside the government are willing to put their investment in this type of technology due to its innovation natures i.e. risky, long-term commitment of R&D and its primary purpose not directly into a commercialization of product or process. FOS technology could also be categorized as a nonmarket innovation where its orientation is subtle since the motivation is not based on monetary profit rather than the advancement of technology.

5.4 Perspective Market of FOS

In order for the FOS to become a feasible solution in monitoring structures (with obvious advantages over other techniques) this sensor needs to fulfill certain criteria. In this regard it is probably advantageous for a sensor to feature a single-ended configuration which exploits a reflective rather than transmissive transmission. Such arrangement would ensure an easier installation procedure with less connections. It would also be advantageous if the sensing system could be easily installed by individuals without any specialized knowledge in fiber-optic technology. This system should fit to both existing structures as well as new ones, by installing it in two ways i.e. embedment or attachment. The trained and experienced scientists should be supported to continuously fostering the innovation and finally, sensor should possess a dynamic range commensurable with the anticipated properties of the measurements, while possessing adequate resolution and sensitivity for accurately capturing the characteristics of the measurement field.

The use of optical sensor could be extended to develop a structure or material which contains their own sensors, actuators, and computational/control capabilities. At this moment, the research work merely considered optical fibers as a means of monitoring system states, however this area of research will surely mature and expand into the implementation into adaptive structures which possess actuators that enable the alteration of system states in a controlled manner. Clearly, the innovation of adaptive structure is still far from the reality in term of commercialization in construction industry. However, this technology could finally blended into the adaptive structure[4], which is the ultimate goal of this system.

5.5 Models of Innovation

There are many models proposed in the innovation area to study the behavior of a product or a process in the market environment. In order to analyze FOS technology, one could use models of innovation for market environment with some modification towards the analysis. Since the nature of the innovation is a nonmarket environment, the analysis of the operative values relating to acceptance or rejection of an innovation is difficult and sometimes not clear in terms of profit orientation. Four models will be presented in order to analyze the technology of optical fiber sensors especially in construction market (i.e. Marquis model, Trajectory and Paradigm, S-Curve and External and Internal models). Using each of the model, one can identify where the FOS technology lies in the current and future market and probably could deduce the best suited model in predicting the market of FOS.

[4] The term adaptive structure is interchangeably used with smart structure/material.

5.5.1 Marquis' Model[5]

According to Marquis' model, there are three distinct types of innovations in the industry i.e. radical breakthrough, complex system and incremental. The radical breakthrough is described as the type of innovation which turns out to change the whole character of an industry. This type of innovation is quite scarce and unpredictable, and is predominantly the product of independent inventors or of research by firms outside the industry ultimately influencing the innovation. The complex system is identified by the long-term commitment of researches and an excessive spending of funds for R&D to accomplish. It is not a common type of innovation in most industrial firms simply because the risk is enormously high. The incremental or "nuts and bolts" is the type of innovation which is mostly driven by economic factors and absolutely critical for the average firm's survival.

FOS technology is not only categorized as the radical breakthrough which changes the way people think about the construction industry but also could serve as the complex system innovation since achieving the economical innovation needs a long period of commitment in R&D. One should notice that the technology of optical fiber has previously started in the area of telecommunication. This technology has matured to at the point where technology transfer is not the critical problem. However its presence in concrete construction is very new and little researches have been undertaken in this area.

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[5] Marquis, D.G., "The Anatomy of Successful Innovations", Reading in the Management of Innovation, Editors : Tushman, M.L., and Moore, W.L., second edition, Harper Business, 1988.

Clearly, it is not an easy task to use the technology directly, plenty of modifications are required to suit its implementation in the construction industry.

The radical breakthrough probably introduces a reluctant perception in industry regarding this technique at the start due to the incompatibility natures between optical fibers and concrete. On one hand, optical fibers are small and weak and at the other end, concrete present a massive and strong nature. However, once the material science technology catches up by producing good quality coatings and the basic systems have been set up, the risk will be reduced and the innovation slowly will become an incremental innovation (i.e. "nuts and bolts"). Later innovation fosters more innovations by improving reliability and effectiveness in concrete structures.

5.5.2 Trajectory and Paradigm Model[6,7,8]

Most of the innovations could be categorized either as "demand pull" or "technology push". Recognition of demand is a more frequent factor in successful innovations rather than recognition of technical potential especially in the U.S. construction industry which is designated by high costs and long completion periods. In addition to the nature of construction industry, there are lesser spending of government's capital in this area from

[6] Dosi, G., "Technological paradigms and Technological Trajectories", Research Policy 11(1982) 147-162.
[7] Abernathy, W.J., Utterback, J.M., "Pattern of Industrial Innovation", Reading in the Management of Innovation, Editors : Tushman, M.L., and Moore, W.L., second edition, Harper Business, 1988.
[8] Nelson, R.R., Winter, S.G., "In Search of a Useful Theory of Innovation", Research Policy 6(1977) 36-76.

year to year thus demand pull characterized this industry rather than the technology push.

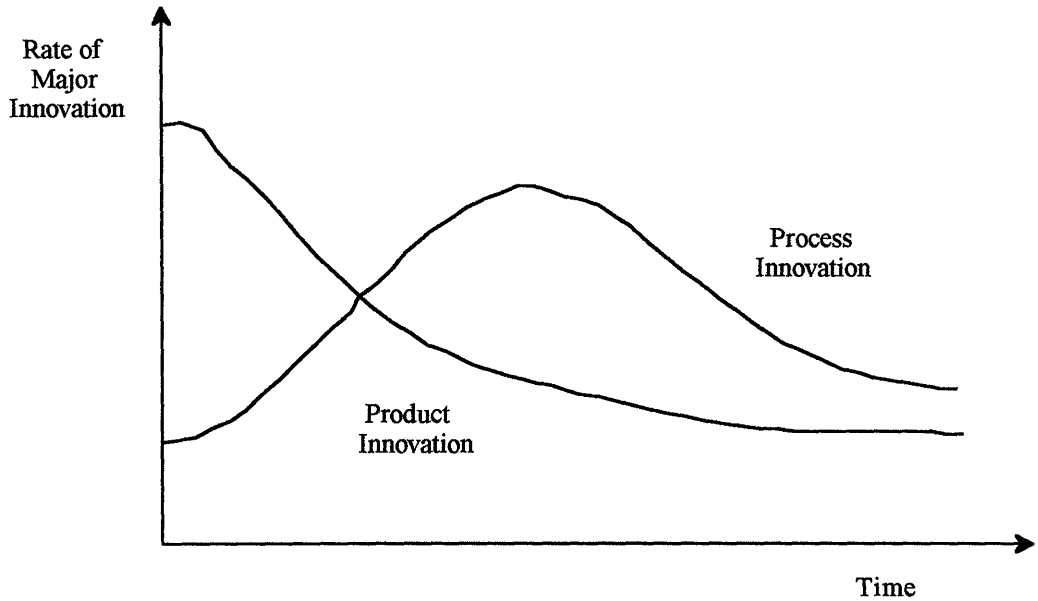

Figure 5-2: The product innovation prevails the process innovation in the early stage however the process innovation will catch up to improve the performance of the innovation.(After Bernathy and Utterback).

In the demand pull theory, the stages of product and process innovations are different. Most of the time the needs of solution regarding obstacles in the initial process does not consider cost as the primary reason. This is due to the interest of the developer to extend a new technology. After the demands have been fulfilled, the incremental technical changes take place and one can realize that the product innovation precedes the process innovation (Figure 5-2). This assumption regarding product and process innovation and demand pull theory only holds in the initial stage of innovation. However, relying on the demand pull model itself does not provide enough information regarding the future of the technology due to several limitations regarding this theory [Dosi, 1982].

The introduction of new model which could identify the direction of demands is certainly needed in this analysis.

The introduction of technological paradigm inside an innovation could help in characterizing the innovation starting from initial process until its final stage. Along this paradigm lies several possible technological trajectories which sometimes change the direction of the paradigm. In many cases the promising trajectories or strategies for technological advance, within a paradigm, are associated with improvements of major components or aspects of the innovation. There are two possibilities of conditions at the end of a paradigm and trajectories i.e. frontier of achievable capabilities or decay stage. A frontier is described as a condition which is confined by physical, biological, or other constraints. If an innovation frontier lies towards the end of the paradigm, it means the nature of this innovation is not efficient since it dissipates time and costs for false paradigm's direction. Once the frontier barriers are broken, new trajectories could arise thus shift the direction of the overall paradigm (Figure 5-3).

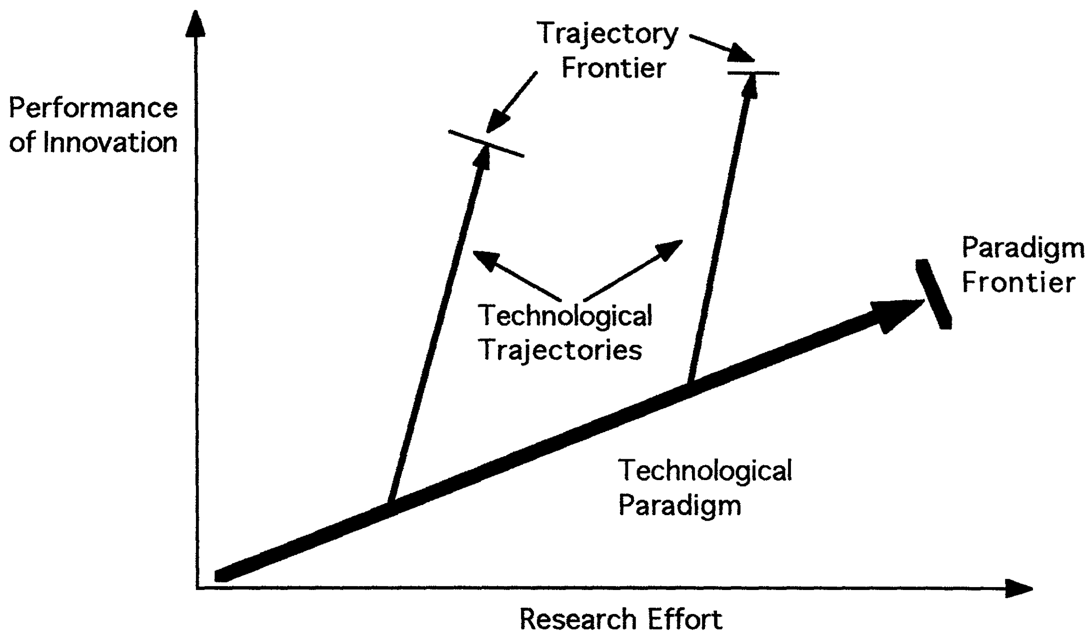

Figure 5-3: Technological Paradigm consists of several trajectories includes with their frontiers.

The trajectory of FOS technology could be changed when new technologies or systems are invented. Previously, the optical fiber technology has been aimed at the improvement of low-loss medium to transfer the input signals in the telecommunication area. Nonetheless a new trajectory has been established due to the effectiveness of the optical fibers as a means of sensor. In this new trajectory itself lies several alternative trajectories which could again change the direction of the innovation. Some technical changes that could alter the trajectory into another dimensions of trajectories are the improvement of coating materials which enable successful performance in concrete environment or the possibility of multiplexing[9] in the sensor system applied in real structures. Once the coating material is invented or multiplexing is introduced to the system, the progress in the real applications will take place in infrastructures and buildings. Other trajectories can be formed if the distributed sensing and the idea of smart structure can be combined to provide extensive data needed by engineers.

From this model, many of trajectories could occur during the process of innovation until the end of innovation. Each trajectory introduced in innovation could lead into another trajectory which sometimes have different orientation with the previous paradigm.

5.5.3 S-Curve Model[10]

There seems no reliable solution in continuously monitoring behavior of structures. The presence of FOS technology in this area creates a competition among several immature techniques. There has not been a solid system implemented in this area yet, thus making it easier for this technology to penetrate the market and taking advantage of it. One must consider the practical technological limit i.e. coatings of optical fiber which in a sense create technical potential in the state of innovation. Other technological limit is the combination of FOS with other innovation to establish the primary innovation i.e. the

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[9] Multiplexing is a technique that could measure several mechanical changes in the structure via single optical fiber.

[10] Foster, R.N., "Timing Technological Transitions", Reading in the Management of Innovation, Editors : Tushman, M.L., and Moore, W.L., second edition, Harper Business, 1988.

smart structure. Another issue such as technical discontinuities could threaten the survivability of this technology from other monitoring systems of structure. In order to avoid this problem, the need of improving the product should be undertaken. However, the process will probably take several years to mature the goal, thus the FOS technology still lies in the bottom of the S-curve (Figure 5-4). If one can relate between the role of technology in corporate strategy and technological potential, one can see that FOS technology offers a "high" technological potential which means that the state of the art is still remote from the technical limit which could classify as a "high-tech" industry and a chance of improvement opens wide.

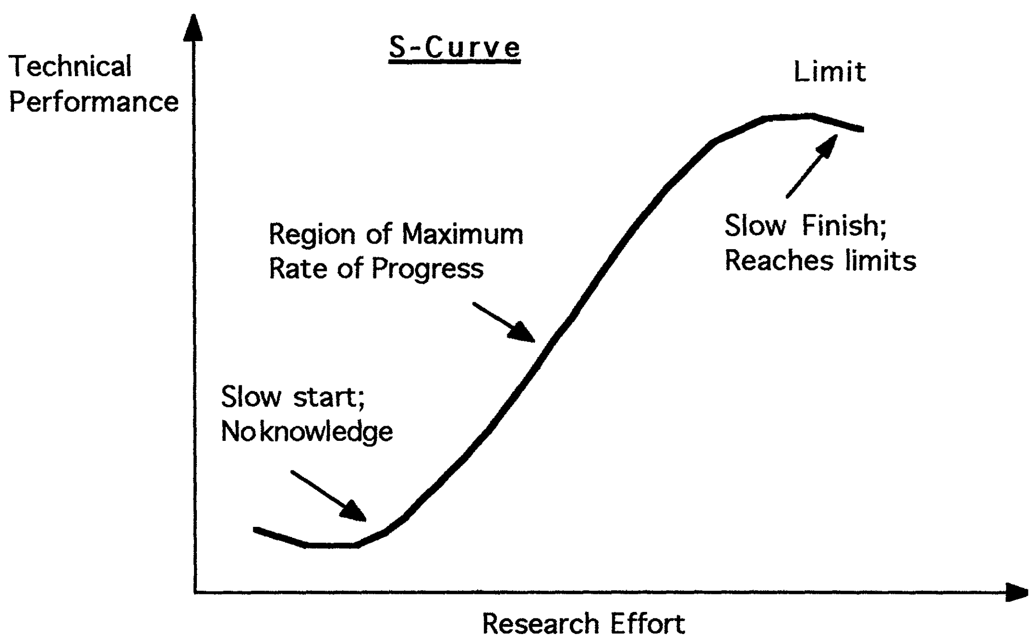

Figure 5-4: The S-curve Phenomenon (After Foster, 1986).

In the S-curve model, the three critical points in curve define as (1) a starting point which is characterized with a slow start with little knowledge of innovation, (2) the next stage is the maximum progress of innovation which is excelled due to the breaking of the barrier (technological limits), and (3) the final stage is recognized with decay stage where the curve reaches a constant slope of the innovation thus slow finish will prevail in this stage. For the FOS technology, one can see the that the growth of this technology is still at the bottom of the curve which is still collecting opportunities to expand and establish in the sensing area in construction. At this moment, the innovation relies on the available type of optical fibers used in telecommunication industry to fulfill their performance in monitoring structures, however once the new concepts and new coating types designed specifically for construction application are available, the process will either repeat itself or discontinue. At the same time, different S-curves from different technologies plays critical role to establish the new curve in FOS technology.

There is no way to maximize the use of FOS in civil engineering applications without improving the whole details/minor weakness in the system. The challenge from outside attackers (new techniques) surely present challenges for this innovation thus improvement or transition into another S-curves could help the innovation of FOS to survive in the competitions. The discontinuing of innovation would not happen probably for several years due to the early stage of this innovation unless changes in policy by government agency result in cutting construction expenditures. The timing in this innovation is critical due to necessary action needed to be taken in order to create a better solution of safer structures. Parallel efforts from other part of innovations are imperative to excel the technology into a mature stage.

A question might arise regarding the position of the FOS technology in the construction industry. Has FOS technology misread the market signal ? The answer is no, since the demands and needs of safer structures have increased ever since it deals with the life of people and the timing is perfect due to the fast advancement in computer technology as well as laser technology which can be coupled with smaller size of optical fibers to provide solutions to achieve this innovation.

5.5.4 External and Internal Technology Model[11]

Before touching the issue of external and internal sources of technology, an innovation can be categorized as a successful one, if both factors i.e. time and cost of innovation could be minimized to certain levels. Innovation time is defined as the length of time needed from starting of applied research until the first commercialization of the innovation while innovation cost is defined as all costs spent for the innovation until the introduction of the product or process to the market. Thus, a careful planning regarding the direction of the innovation is essential to establish a marketable product/process.

As the progress of this technology is previously brought into existence in the telecommunication industry, one cannot deny that most of the innovation come from external sources. While the technology has a solid foundation, the take off of this technology in the sensor area in construction is easier than other competitors which may

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[11] Mansfield, E., 'The Speed and Cost of Industrial Innovation in Japan and The United States: External vs. Internal Technology", The Institute of Management Sciences, 1988.

need to start from the beginning. The comparison studies between Japanese and American counterparts by Mansfield shown that Japanese companies maximize the uses of external technologies to reduce time and cost of innovation. For FOS technology, similar actions should be considerably taken and certainly could spur the establishment of this new technology in the construction area in shorter time thus avoid this innovation from other attackers (i.e. impact echo, radar imaging, etc.). Although other competitors as mentioned earlier have the same advantages of having solid technology, the flexibility that optical fibers offer as a monitoring device could be demonstrated more effectively by real application in prototype structures.

The internal sources of technology in this area basically are the extensive information regarding the concrete material characteristic and its interaction with glass-type of material. The contribution from external sources are more dominant compared to the internal one, thus surely reducing the time and cost of innovations.

In order to progress quickly in the establishing of this kind of technology, government sponsorship is necessary to spur R&D in the parallel fields of the FOS technology such as the fiber coating materials or the study of interaction between concrete and optical fibers. The process of innovation could be slow down if one of the area of researches could not cope with the improvement of this technology. A closed links between the industry, research institutes as well as among the researchers in different parts of innovation should be maintained in order to transfer the technology into commercialization or practical applications.

5.6 Implementation

The next process of innovation of the FOS technology is the implementation of this technology into real applications which could create market opportunities to reinforce the progress of innovation. The terms diffusion and implementation process are sometimes interchangeable between each other depending on the position of the technology players i.e. source or user. In the implementation process, the innovator should apply this technology into a limited use of case studies to learn the market sensitivity and technological success of the innovation. The technology should be tested in several categories to make sure the next transition i.e. diffusion will be the unruffled one. Categories such as the social impact in the community, effectiveness of the technology, profit market of the technology and the management strategy will be the measurement for successful implementation of this technology in the future.

The discussion on implementation is focused on an organizational behavior either by private or government agency to adopt this new innovation. Implementation could be considered as a process which occurs during the decision time to translate a tool, technique, or other object into some utilization and bounded by the adoption decision and institutionalization[12]. Using the process approach introduced by Goodman, which consists of five critical processes, the implementation of optical fiber sensors is studied.

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[12] Goodman, P.S., Griffith, T.L., " A process approach to the implementation of new technology", Journal of Engineering and Technology Management, 8 (1991) 261-285.

The five processes provide step by step processes starting from the beginning of implementing the technology until the final transfer which diffuse the technology into other users. The five processes are defined as follows:

(1) Socialization - In this early process of finding the suitable technology which could fulfill the goal of the organization, the user tends to acquire the information either from internal or external sources on this subject area. In the case of FOS, the user for instance government agency could identify the necessity of this technology from scientists or experts, public opinion regarding higher safety codes or supplier which provides new state of the art technique in dealing with the study of structures. Using these inputs, government agency could generate the demand of public as well as technology push to reason the practicality of the innovation. In this stage, the user decides which is the most effective method to solve the problem. If the user is a private-owned company, the investigation of the risk of technology and the profit margin will be the tests to approve the adoption.

(2) Commitment - The next step deals with more seriousness regarding decisions to adopt the technology. It is acknowledged that during this process, the user will find out the discrepancy between actual and the expected benefits. For the embedded sensors, the user might find out that this technique might not work in the harsh environment however, due to the commitment of the users, they might be willing to foster the research until the technological hurdles are overcome. Another alternative of this technology is by embedding optical fibers into thin polymeric films which could probably provide better

protection as well as easier installation of the sensors. Modification of the technology will soon convert to an acceptable benefit.

(3) Reward Allocation - The reward allocation of this technique is usually separated into two different types of rewards i.e. manifest and latent rewards. Manifest rewards for this technique can clearly be recognized as reducing cost of maintenance, accurately detecting changes in structure or increase the safety factor of infrastructures. Latent rewards could be explained as factors that are unexpected during the implementation and these rewards could be benefits as well as costs. The unforeseen rewards might be the period of implementation of this technology which could be reduced by eliminating barriers or the use of sensor which could be expanded into active control provided a real-time control of structure. However, the cost rewards might disturb or stop the continuation of implementation of this technology. In this stage, the user should carefully analyze of this technology before stepping into the next step.

(4) Feedback and redesign - The idea behind this process is to identify the progress of the innovation and how it is fitted particularly to the demand. As it is mentioned earlier, the users will consider costs secondary at the initial introduction of the technology. However, as the commitment is taken the unnecessary spending should be minimized. The redesign of innovation soon will take place to reduce unintended costs of the technology. For the FOS, the redesign of the process depends on the efforts by innovators to foster the technology. The innovator (i.e. the government agencies) should work closely with potential users according to their expectation of the technology in order to stay competitive in the market. The feedback and redesign process would take long period of

time to adjust the technology and there is still a chance to abandon the technology once the costs exceeds the benefits of this technology.

(5) Diffusion - The final stage which will be discussed in detailed later, is the stage where the implementation is ready to be shifted into other users or industries. By this time, the FOS has been recognized as an effective solution for condition assessment of structures. Thus, the larger the user group the more feedback in improving the technology thus relieving the burden of government in terms of supporting the technology alone. During this stage, the technology has been transformed into a market driven oriented one thus stimulating the private sector to foster the technology since it is assumed that adoption cost or uncertainty of the innovation will decline through time.

5.7 Diffusion

Although the diffusion of optical fiber sensor technology has not reached at the point where the technology could be transferred into the market, several models of diffusion are introduced to show its trend in the future. The term diffusion could be defined as the dissemination of technology throughout population or lead users. Three types of diffusion models are presented : (1) Traditional Diffusion (2) Modified-Traditional Diffusion (3) Evolutionary Diffusion.

5.7.1 Traditional Diffusion

Traditional diffusion presents a state of diffusion where the source of technology is disseminated toward certain homogenous users. Most of the users are in the same field of the new technology; in term of optical fiber sensors, it can be classified as a source in the area of construction. However, the fact that this technology itself mutated from different discipline i.e. telecommunication and aerospace community, made this model unsuitable for FOS technology.

Nonetheless, one needs to examine the behavior of this technology according to the traditional model which sometimes provides trends which other models could not furnish. The traditional model strictly relates the innovation with the size and time of the innovation. The FOS technology R&D is proposed by government to establish a better quality of structure. The size of participating company plays crucial roles since this technology is expensive and high risk. Larger sized firms will provide internal R&D which will surely reduce the time for product entry into the market. The technology advancement of FOS should be undertaken by several sectors of government agencies thus push this innovation faster if compared with single-private owned organization with only specific interest to run the R&D. The users of the technology might probably start from different departments of the government. Another assumption of the traditional diffusion is the method to disseminate the idea by interfirm i.e. the technology is used in the closed link of specific interest of innovation and no mutation should be taking place during the transfer of technology from source and users. However, this assumption does not apply to FOS due to the nature of technology which is clearly dependent on the feedback of several different users in the different area. The first introduction of technology has already started inside universities or institutes. Several universities and government agencies have been collaborating by embedding the sensors into public structures to monitor the systems. By taking advantage of these exhibitions, the experts (i.e. researchers in the sensor community) could convince private sectors to join in the R&D funding. However, the real market of this technology should wait until the system proves to be reliable and effective. Since this technology has not been developed there are many opportunities for entrepreneurs.

5.7.2 Modified-Traditional Diffusion

The next model will adjust the traditional model with different types of users in terms of the interaction between sources and users. The assumption that the technology could mutate and translate into another field, country, or industries is so called the intrafirm. The FOS technology needs to have an intrafirm diffusion since the nature of the innovation is complex. The technology itself has been implemented in R&D department among several nations, i.e. U.S., Germany, and Japan. The contribution of each country could reduce significantly time and investment especially in the era of globalization where the information superhighway could help the introduction of this innovation faster. Government agencies could use this diversification to reduce the risk thus gives long term commitment to the universities and institutes. The rate of diffusion of FOS in the initial stage shows increasing tendencies towards another trajectories. A set of completion target needs to be reinforced in order to re-evaluate the effectiveness of the technology. In terms of diffusion rates of different industries, FOS could create unexpected market which is totally different from the original target market (e.g. new fiber material which could be applied in other sector of industries outside construction).

5.7.3 Evolutionary Diffusion[13]

Evolutionary diffusion model shows the modification/mutation of technology occurred during the transfer of technology from sources to the users. This set of modification leads to other sub-sources which customized the new innovation differently than the previous one. The FOS technology is shared among different disciplines and the mutation of the technology could not be avoided thus the knowledge regarding the technology becomes more abroad and introduces new technical changes; the changes are mutually influenced and continuously redefined. Although it is recognized that the size of firms and market structure have roles in pushing the diffusion of the technology, other factors such as localized search of potential user could be more efficient in finding appropriate users who are willing to share the risks; it might be small material supplier companies that could produce a certain optical fiber sensing film which could be easily attached to the structure or small firm which is specialized in generating data from the

[13] Cainarca, G.C., Colombo, M.G., Marotti, S., "An evolutionary pattern of innovation diffusion. The case of Flexible automation", Research Policy 18 (1989) 59-86.

sensors and develop a user friendly software that could be learned easily by inspectors. Another characteristic of the evolutionary diffusion is to establish system integration which put together the innovators position as designers and manufacturers. In order to establish this pattern, a good organizational structure needs to be developed which allows the horizontal information flows and close interaction with customers and suppliers. This step is necessary, considering how complex this innovation would be. The management of organization should help link the technology to a feasible market.

5.8 Attributes of Success

The discussion on every stages of improvement of the technology can always be studied from its attributes of success. Any innovations could be analyzed in term of their success. There are five parts of attributes of success described herein :

(1). Technical - From technical point of view, fiber optic sensors are still under improvement. The span of this technical stage could probably take 5 to 10 years until the technology could remove the barriers for this technology. Technically speaking, the idea of using optical fibers in telecommunication area has been modified into its use as sensors in structures, further research needs to be carried out to provide solid technical solutions for this innovation.

(2). System and compatibility - Although technical stage has shown its way of applying this technology, major compatibility problem between the optical fiber and the host matrix has not been resolved. Thus, this technology probably should wait 3 to 5 years for it to mature and move into another step.

(3). Business - In term of business, deteriorating structures will always exist and increase thus the possibility of profit market is high. At this moment, the commercial use has not attracted private sector to take advantage of this system innovation (i.e. long period and a great deal of funding). However, once the initial or basic researches have shown some successes the adoption of this innovation will start.

(4). Strategic - The strategy that could be applied in this technology is that government should lead the way at the beginning part of the innovation and slowly transfers the risk to private sectors by establishing joint ventures between government and private sectors. Fostering the innovation in the early stages facilitates adoption by the private sector.

(5). Social Impact - this last attribute is technically the most important compares to other attributes mentioned before, however these attributes are sometimes overlooked thus resulting failure to the innovation which may be catastrophic. Government intervention will be further discussed in the next section.

5.9 Government Policy[14,15]

Government intervention is part of the process from the early stage of the innovation until the technology is implemented to show that it can stay competitive and profitable. Government agencies control both the innovations done by government itself and the private sector innovation. The goal is to protect public users from environmental hazards and safety towards the using of the new technology.

FOS technology could be classified as procurement-related R&D since government was heavily involved as a user-demander of the technology. The "spillover" of the knowledge thus transferred to the civilian technology in terms of public domain information. However, this type of policy usually only confines to the early stages of FOS technology development and the support only continues when the FOS shows its effectiveness.

It has been shown that intervention of the Federal Government sometimes creates both positive and negative effects. From the positive side, the government intervention is necessary to establish certain guidelines especially in decisions that are closely related to the public issues. Since the nature of innovation is complex, probably only government agencies could support the R&D of this technology. The negative issue of the intervention could pose threat of a slower growth of innovation due to restriction in

[14] Nelson, R.R., Langlois, R.N., "Industrial Innovation Policy: Lessons from American History", Reading in the Management of Innovation, Editors : Tushman, M.L., and Moore, W.L., second edition, Harper Business, 1988.

codes. Many critics seem to blame government action rather than observe that the role is important to lead this country to advance in international competition. The consideration of using the FOS technology needs to be prioritized since disasters in structures have increased lately due to unpredictable mother nature. The seriousness of government policy for this technology affects the factor of successful implementation of the technology. Low R&D funding could cause the innovation to fall significantly behind the best technologies and practices necessary to ensure their success in an increasingly competitive market. The higher expectancy in rate of return could also pose a barrier to advancement of technology. Thus, government agencies needs to consider the importance of innovation rather than merely the costs in order to decide whether to discard or adopt the innovation.

Several strategies could be implemented by government in order to foster the FOS in the years to come. One alternative is BOT (Build Operate Transfer) term which stimulate private sectors such as contractor or developer to take parts in the innovation thus the process of adoption will consequently be taking place. BOT term could diffuse the technology from one user into others and could help users use the new technology thus equipping them with competitive advantages over other competitors. Another way to implement this technology is that government should take an action by becoming the first user thus reducing the uncertainties within other users. Other strategy is to establish a special institution which could be mutually funded by suppliers, owners, contractors

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[15] Brooks, H., " Emerging Technologies: Consequences for Economic Growth, Structural Change, and Employment", Symposium 1981, Editor: Herbert Giersch, J.C.B. Mohr (Paul Siebeck) Tubingen.

recruiting researchers and experts to work closely in figuring out where the technology path should be oriented. It is possible since this innovation deals with the primary needs of community. Establishing an international consortium is one way to help spreading the risks and spur the technology. In the case of low R&D, the government could sacrifice this innovation by letting other countries to step ahead farther thus the risk will be lowered, however the profit market will surely shift into countries which pay for the risks.

5.10 Who Will Benefit ?

Unlike other innovations which should be patented due to necessity of the innovators to get their investment back, FOS innovation is invented to solve degradation problem of structures which mostly relate to the public demands. At this moment, government is the only agency which supports this technology. However, owners of private buildings or general contractor should have responsibilities to help this technology to mature by implementing or applying this idea into their buildings thus reduce the cost of insurance for the buildings and also provide safer structures for the future.

In terms of benefits, first it should go to the society as a general and of course the government could cut the cost of maintaining the infrastructures and later it will translate into the industry as a whole where part of the expenditures could be used for either other funding for economic growth or probably be focused on other sector of construction innovations. Material suppliers could also benefit from this technology, probably by inventing certain techniques to place the sensors in the structures easily and safely. Computer technology firm could also benefit from the FOS technology by maintaining the systems of information of buildings.

5.11 Part I Conclusion

After studying the four models of innovation, one can conclude that the position of the FOS technology is still in the early stage of innovation process which is crucial for the innovator to direct the innovation in the future. Unlike other innovations which are created for commercial uses, FOS technology is supported by government for their own needs thus government agency should carefully organize this idea since most of the innovation sources are coming from outside. Organization which consists of several areas of researches should simultaneously move in the same direction towards the technology. The process of innovation could be delayed if one of the area of research could not cope with the improvement of this technology. The organization players should work closely together to pass the information quickly and efficiently.

A sensory system may possess sensors for health monitoring, but possess no actuators. Conversely, an active system may possess actuator for a controlled deployment, but have no sensors. The combination of these two will be the desired system in the future which is called “smart” structures, those with both sensors and actuators in a feedback architecture for the purpose of actively controlling system states. A more advance system could be the active structure which contains sensor and actuators that are highly integrated into the structure and have structural functionality in addition to control functionality. The active structure is sometimes called the intelligent structure, which is the ultimate goal of the technology.

The commitment of the government and closely linked disciplines should be pushed into the parallel goal of the innovation. The innovator should also consider competitors which could present threat to the continuation of technology. The saturation point of the FOS could possibly occur in two ways : (1) If another method proves more reliable and cost-effective, the trajectory will directly shift into other innovation. (2) The short of investment due to the unpredictable market of the technology.

Finally, the complex innovation such as FOS should be considered carefully in the early part of the process. The success of this innovation depends on government regulation, availability of the market in the future, the willingness of users to try this new idea and good organizational management. Once the technology is transferred into private owners the rate of innovation as well as diffusion will increase since the intention of the private sectors is to maximize the profit.

5.12 Preliminary Results

In this second part of the thesis, experiments were conducted to show the effectiveness of the optical fibers in the in detecting crack opening structure. The pre-crack matrix was loaded in the pull-out apparatus[16] while monitoring the optical fiber intensity loss. The results are shown in Table 5.1 regarding the sensitivity of acrylate-coated optical fibers at three different angle orientations inside the cement paste.

By varying the fiber orientation, it is possible to optimize the sensor sensitivity (see Table 5.1). Nonetheless, at this level only one crack can be monitored. With the OTDR (Optical Time Domain Reflectometer) system, one may be able to simultaneously monitor several crack openings in a structure. The OTDR system, first developed in 1976, is classified as a distributed fiber sensor which is based on Rayleigh back-scattered light.

Signal losses at 2.0 mm and 0.5 mm crack openings were measured for each case. For the 15 degree angle the intensity loss ranges from 1.170 dBm to 2.100 dBm at 2.0 mm and 0.458 dBm to 0.473 dBm at 0.5 mm (Figure 5-5(a)&(b)). For the 30 degree angle, the intensity loss drops even more. It ranges from 5.198 dBm to 5.961 dBm for 2.0 mm while at 0.5 mm the intensity loss ranges from 2.549 dBm to 2.817 dBm (Figure 5-6(a)&(b)). For the 45 degree angle, the data was not consistent due to possible experimental error.

[16] The pull-out apparatus used in these experiments was designed by Noah G. Olson.

Intensity loss ranges from 8.290 dBm to 13.745 dBm at 2.0 mm and ranges from 2.000 dBm to 6 489 dBm at 0.5 mm (Figure 5-7(a)&(b)). The results are tabulated in Table 5 1.

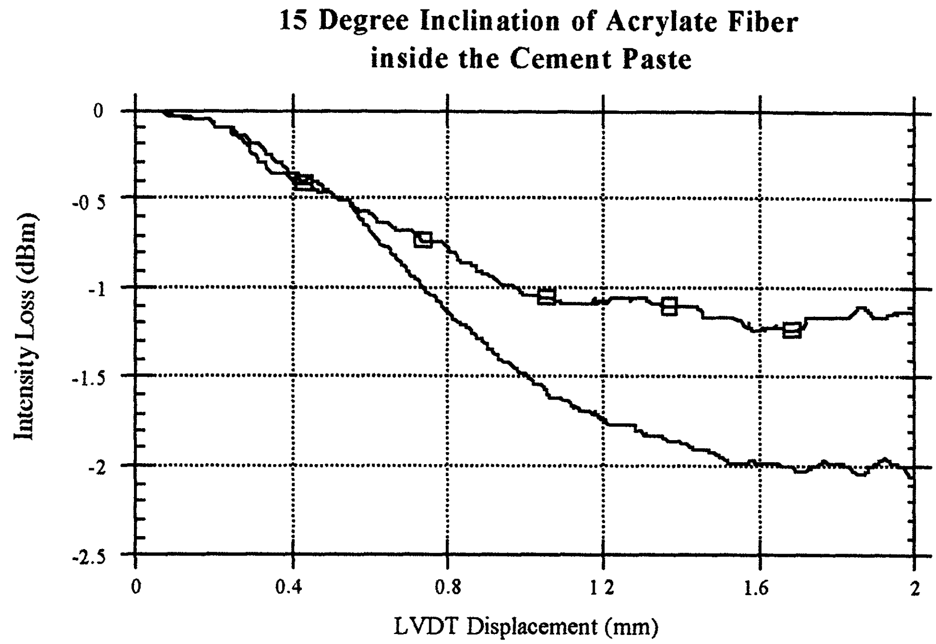

Figure 5-5(a): The 15 degree angle of inclination inside the cement paste.

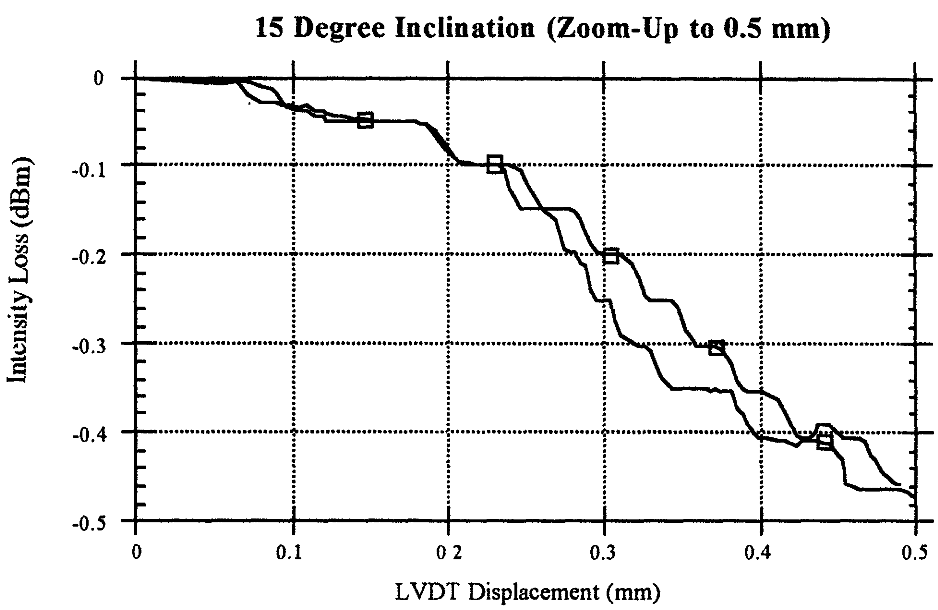

Figure 5-5(b): The 15 degree angle of inclination (Zoom-Up to 0.5 mm) inside the cement paste.

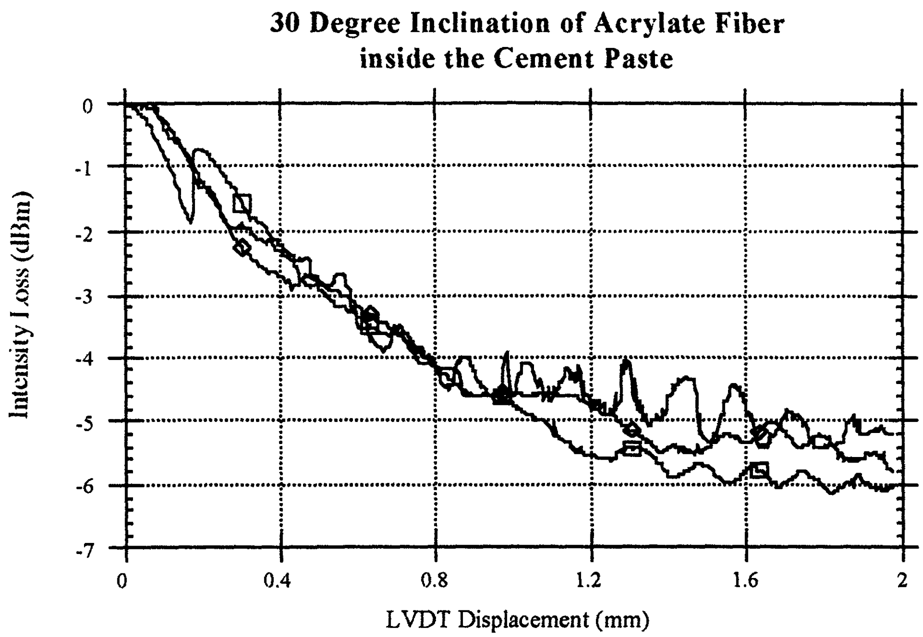

Figure 5-6(a): The 30 degree angle of inclination inside the cement paste.

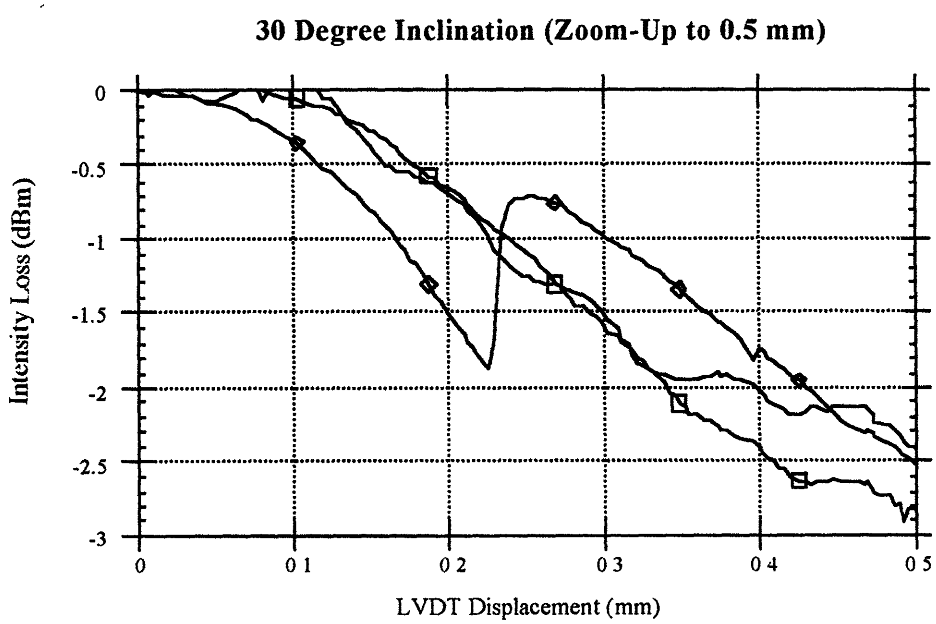

Figure 5-6(b): The 30 degree angle of inclination (Zoom-Up to 0.5 mm) inside the cement paste.

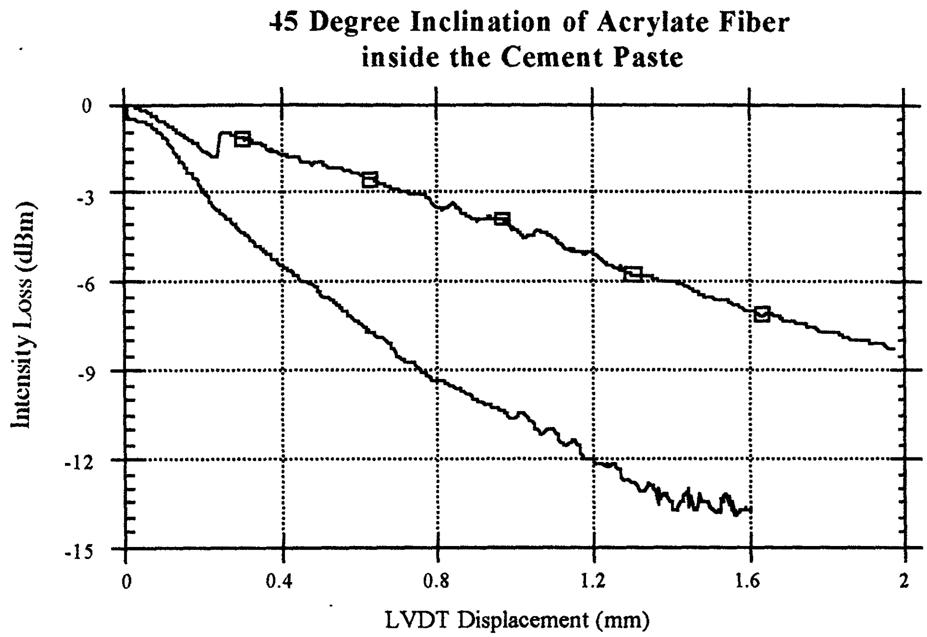

Figure 5-7(a): The 45 degree angle of inclination inside the cement paste.

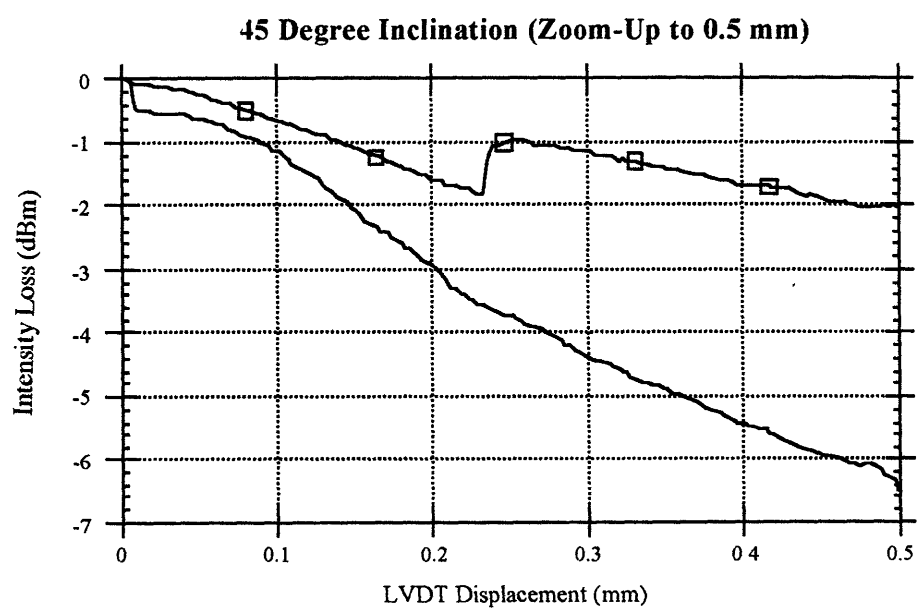

Figure 5-7(b): The 45 degree angle of inclination (Zoom-Up to 0.5 mm) inside the cement paste.

Table 5.1: Summary of the Crack-Opening Measurements

Crack-Opening of Acrylate Fibers inside the Cement Paste			
Angles (degree)	Specimen	Intensity Loss (0.5 mm)	Intensity Loss (2.0 mm)
15	1	0.473 dBm	1.170 dBm
	2	0.458 dBm	2.100 dBm
30	1	2.817 dBm	5.198 dBm[17]
	2	2.549 dBm	5.961 dBm
	3	2.764 dBm	5.760 dBm
45	1	2.000 dBm	8.290 dBm[18]
	2	6.489 dBm	13.745 dBm[19]

5.13 Part II Discussion and Conclusion

Three results obtained from this experiments shows ranges of intensity loss with respect to the crack opening displacement. Within each set different losses are observed. This is probably due to several reasons; (1) small bending occurs during the process of making the specimens, (2) pores may exist around the fiber due to imperfect compaction, (3) low dynamic range could cause the flattened shape at the end of curves.

The experimental results show that microbending of fibers inclined to cracks can induce measurable losses at very small openings. Although extensive research is still needed, the feasibility of crack monitoring with inclined embedded fibers has been demonstrated.

[17] The actual displacement recorded for this specimen is 1.9161 mm.
[18] The actual displacement recorded for this specimen is 1.9670 mm.
[19] The actual displacement recorded for this specimen is 1.6380 mm.

Chapter 6

Durability Studies

6.1 Introduction

The sensor must be compatible with the materials which form the structure. In particular the sensor must withstand the mechanical and environmental excursions for which the structure is designed for. The concrete environment is not friendly to optical fibers. The objective of this chapter is to find the ideal optical fiber coating for concrete crack sensors.

The durability studies consist of two parts: pull-out tests and SEM of optical fibers cured for different periods of time inside the cement paste. Also, the effect of freezing and thawing cycles (30 and 60 cycles) and wetting/drying cycles (20 and 40 cycles) were studied.

6.2 Durability of Optical Fibers[1,2,3,4]

An important parameter that concerns researchers in this area is the durability of optical fibers in hostile environment especially when it's embedded inside the concrete structure. Reports related to excellent performance of fiber optics in telecommunication area sometimes misled engineers to believe this material as a potential one for concrete structures as well, although the requirements may be contrary[5] to ones for telecommunication application.

An optical fiber consists of core and cladding and protected by buffer coating. The uses of coatings in the telecommunication area are to reduce microbending losses in the fibers, to ensure mechanical flexibility, long life at high temperatures, optical property preservation as well as preserving waveguide strength. The coatings currently in common use are polyimide, acrylate, teftzel-silicone, thermoplastic polyesters, nylons, urethanes and polyvinyls coatings. However, there is not any specific coatings that are specially designed for sensor applications in concrete structures.

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[1] Habel,W.R., Polster,H., "The Influence of Cementitious Building Materials on Polymeric Surfaces of Embedded Optical Fibers for Sensors", Journal of Lightwave Technology, Vol. 13, No.7, July 1995.
[2] Miller,R.A., "An Overview of Optical Waveguide Coatings", Fiber Optic Advances in Research and Development, Conference on the Physics of Fiber Optic, pp. 77-103, University of Rhode Island, 1978.
[3] Mehta, P.K., Monteiro, P., Concrete: structure, properties, and materials, Second Edition, Prentice-Hall, Inc., New Jersey 1986.
[4] Escobar, O., Gusmeroli, V., Matinelli, M., "Fiber-optic interferometric sensors for concrete structures", The 1st European Conference on Smart Structures and Materials, Glasgow 1992.
[5] For telecommunication purposes, one needs an optical fiber that could minimize microbending loss thus could transmit the light signal more efficiently, however when the purpose is not only sending a signal i.e. perform as sensors, microbending loss becomes critical in order to identify any change in the specimen. The strength design of optical fiber not specifically to survive in concrete environment.

Being exposed to the severe environment in concrete, coatings that are useful to protect the fibers for telecommunication may become useless. Two common attacks i.e. chemical and mechanical attacks may be present. Chemical attacks occur during the whole life-span of structure. In a well-hydrated Portland cement paste, the solid phase, which is composed primarily of relatively insoluble hydrates of calcium (such as C-S-H, CH, and C-A-S-H), exist in a state of stable equilibrium with high pH pore fluid. Large concentrations of Na^+, K^+, and OH^- ions account for the high pH value, 12.5 to 13.5, of the pore fluid in Portland cement pastes. On the other hand, mechanical attacks take place starting in the early process of the construction until the end of life of a structure. Defects due to mechanical attacks could be caused by aggregates during pouring of the fresh concrete as well as deposition of hydration reaction product onto the fiber surfaces during the settling process or unpredictable external loads on the structure.

Both attacks certainly affect the performance of the coatings in order to fulfill its purpose i.e. to protect the glass from attacks. An extreme careful handling of the sensors should be taken during the first stage of construction,; once the sensors are embedded inside the structure, there is no way to repair the fibers except to do it all over again .

Research programs have recently been undertaken to investigate the role of fiber coatings on the strength and sensitivity characteristic of fiber-optic sensors embedded in concrete structure as well as their bonding with the host materials and their function as protective layer of the glass core [Habel, 1995] and [Escobar, 1992]. Another chemical attack could arise from the presence of OH^- which could cause the coating to swell and later, will penetrate inside the glass to destroy the integrity of fiber.

6.3 Pull-Out Test

The intention of the fiber pull-out test is to study the change in bond properties between the fiber coating and matrix due to various aging and environment effects. To reflect the change in bond properties, four parameters are measured and tabulated. These include (i) the peak pull-out load, (ii) the displacement at peak pull-out load, (iii) the proportionality limit load, where the initial rising slope of the curve suddenly undergoes a change (which may be a drop or a significant decrease in rate of increase) and (iv) the displacement at proportionality constant. The proportionality limit load is based on subjective judgment, but is of engineering interest because it reflects the load (on a given length of fiber) when stress versus strain ceases to follow the initial slope. The stress transfer between matrix and fiber and the "calibration" of the sensor may then change.

The pull-out curve of the optical fibers are found to exhibit different trends. They can be classified into six different failure modes as shown in Figure 6-1. Type A represents pull-out trends which have a steep gradient and then the curve could either: (1) dramatically decrease in unit force with concave down fashion, (2) slowly decrease in unit force in concave up position or, (3) fluctuate in wave-like manner due to slip relaxation between fiber and matrix. The type B trend is a gradually increasing curve which never reaches peak value[6]. within the distance pulled. Type C is a variation of type A where its peak value is achieved later than A. Type D is another type A variation where the post peak trend quickly levels off to an average constant force. Type E once again is type

[6] The pull-out test in this study was limited only to the first 5.5 mm of the total length (10 mm).

A variation where the post peak trend decreases and then increases to a lower peak value. Type F represents pull-out curves which have a quasi-parabolic trend. The curve was nearly symmetric about the peak value. Table 6.1 to Table 6.3 tabulates the results for the pull-out tests.

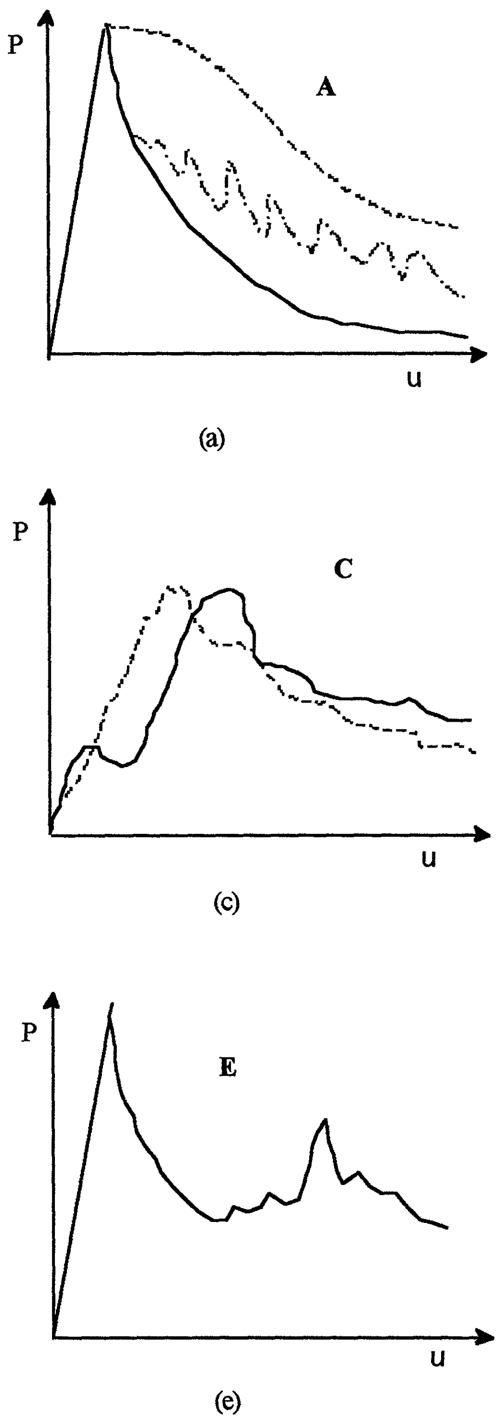


Figure 6-1: Five pull-out trends found in the optical fibers tests: (a). Type A, (b). Type B, (c). Type C, (d). Type D, (e). Type E and (f). Type F.

6.3.1 Acrylate-coated Optical Fibers

The performance of acrylate-coated optical fibers are examined in this sub-section. During the first month of the test period inside the cement paste, the failure modes are either type A or E. In this period, peak loads were the same as the proportionality limit loads. The peak loads ranged from 1010 mN up to 1058 mN. For the three month period inside the cement paste, three types of failure modes, A, B, and E appeared in the tests. For B type results, the proportionality limit value did not represent the peak value. At three months, the peak loads ranged from 631 mN to 1397 mN. Some of the specimens had the same or higher peak loads as the one month period. Others showed significant interfacial strength loss compared to results at one month. However, if one compares the proportionality limit loads, the values are consistently lower at three months. For 20 wet-dry cycles, the acrylate fibers have not shown a decrease in interfacial strength. The peak loads ranged from 1066 mN up to 1168 mN. The failure modes are either A/E[7], A, or D. For 40 wet-dry cycles, the interfacial strength showed an increase in value when compared to the results at 20 cycles. All specimens showed type A failure mode. The peak loads extended from 1337 mN up to 2309 mN. For 30 freeze-thaw cycles, the tendency was a decrease in interfacial strength. The failure modes were dominated by types A and D. The peak loads ranged from 687 up to 855 mN. For 60 freeze-thaw cycles, a more apparent loss of interfacial strength was shown with decreasing peak load

[7] It is sometimes hard to differentiate pull-out curves result based only single trend, some of the results could be represent by two or even three types of trends.

values which extended from 233 mN up to 286 mN. Some of the specimens showed no strength at all. The failure modes for this condition could be either A, D/E, or D.

6.3.2 Polyimide-coated Optical Fibers

The performance of polyimide-coated optical fibers are examined in this subsection. During the first month of the period inside the cement paste, the fibers exhibited failure modes A, E, A/E and B. The proportionality limit loads ranged from 828 mN up to 2284 mN while its peak loads ranged from 1363 mN up to 2284 mN. At three months failure modes are represented by types A, E, and A/E. At this period, pull-out specimens exhibit the higher peak values compared to the first month period. The highest peak value recorded was 6408 mN while the lowest one was 2321 mN. For 20 wet-dry cycles, the polyimide fibers have displayed a decrease in strength when compared to the previous conditions. The peak loads ranged from 615 mN up to 1098 mN. The failure modes are either A/E, B/D, or D. For 40 wet-dry cycles, there is no further decrease in peak load compared to the 20 cycle case. The failure modes in this case were A, F, and D. The peak values varied from 783 mN up to 1196 mN. For 30 freeze-thaw cycles, there was a propensity to exhibit an increase in interfacial strength. The observed failure modes were types A and D. The peak values ranged from 1827 up to 4380 mN. For 60 freeze-thaw cycles, polyimide fibers still displayed high interfacial strength. Nevertheless, the peak load slightly decreased compared to the 30 freeze-thaw cycles. The failure modes for this condition could be either A, B, D/E, E, or D. The peak value reaches as high as 3682 mN while the lowest peak value was 1297 mN.

6.3.3 Teftzel-Silicone-coated Optical Fibers

The performance of teftzel-silicone-coated optical fibers are studieds. After one month inside the cement paste, type B failure was displayed. The proportionality limit loads ranged from 483 mN up to 530 mN while the peak loads ranged from 1410 mN up to 2123 mN. After three months inside the cement paste, failure modes were represented by A type. At this period, some fibers reached higher peak loads compared to the first month period. The highest peak load value recorded was 4331 mN and the lowest one is 1278 mN. For 20 wet-dry cycles, the fibers exhibited a fairly high strength in peak load values. The peak loads ranged from 1041 mN up to 1997 mN. Type A failure mode dominated in this condition. For 40 wet-dry cycles, the peak loads do not show a decrease in values if matched to the previous one. Type A failure mode also appeared in this situation. The peak values ranged from 1921 mN up to 1961 mN. For 30 freeze-thaw cycles, the a dramatic increase in peak load is observed. The failure modes were types A, C/A, and D/F . The peak values ranged from 2423 up to 7065 mN. For 60 freeze-thaw cycles, teftzel-silicone coated fibers still displayed high interfacial strength. The failure modes for this circumstance could be either A, D, or F types. The peak value reached a high of 7179 mN while the lowest peak value was 2371 mN.

6.4 SEM Studies

Five different groups of specimens, as described in Table 5.2 are studied in the SEM. The first group consist of optical fibers stored in the water tank. The second group consists of optical fibers stored in Calcium Hydroxide solution with pH = 13.0. The third group consists of optical fibers embedded inside the cement paste. The fourth group consists of optical fibers treated under wet-dry environment and the fifth group consists of optical fibers treated under freeze-thaw environment. The results will be compared with the pull-out tests behavior of the optical fibers.

6.4.1 Fibers Inside the Water Tank

During the early period of time i.e. one, two, three, and four weeks stored inside the water tank, the acrylate-coated optical fibers show good performance without much damage. However, after three months the degradation of the fibers started to take place. As it can be seen in Figures 6-54 and 6-55, thin-hair cracks have appeared on the surface of the fibers. For polyimide-coated optical fibers, excellent surface conditions is observed for both early periods as well as three-month period. There is no significant damage on the surface, the longitudinal scratches may be the result of handling or due to contact with aggregates in the matrix. For the teftzel silicone-coated optical fibers, the dents and bruises are probably due to the mishandling of the fibers. It is difficult to avoid these problems due to the small diameter of the fibers, making them difficult to handle.

6.4.2 Fibers Inside the Calcium Hydroxide Solution

For the acrylate-coated optical fibers, the accumulation of the calcium hydroxide crystals on the surface makes observation impossible to be taken. However for the three weeks period (Figure 6-67), the surface could be seen and there seems to be no sign of degradation of the fibers. Both polyimide and teftzel silicone coated-optical fibers exhibit excellent surface conditions in this environment.

6.4.3 Fibers Embedded Inside the Cement Paste

There are three different periods of embedding the optical fibers (two weeks, one month, and three months) before SEM is carried out. After two weeks acrylate-coated fibers start to show degradation inthe form of thin-hair cracks seen on most of the surfaces. For one month and three months periods, the situations become worse where the cracks growth significantly and there are several big cracks appeared along the surfaces. Both polyimide and teftzel-silicone-coated optical fibers, perform well. Only longitudinal scratches are present. These scratches may be formed during the extraction of the fibers from the cement paste. For teftzel-silicone fibers, the bonding seems to be excellent, the author when found difficulties in removing fibers from the cement paste.

6.4.4 Wet-Dry Cycles Effect

Two different cycles are studied i.e. twenty cycles as well as forty cycles. The acrylate-coated optical fibers showed cracks all over the surface. Figures 6-93 and 6-94 exhibit cracks for 20 wet-dry cycles while Figures 6-97 till 6-99 display significant fiber degradation. Both polyimide and teftzel-silicone-coated optical fibers perform well. Only longitudinal scratches appear.

6.4.5 Freeze-Thaw Cycles Effect

Two different cycles are studied i.e. thirty cycles as well as sixty cycles. For the first thirty cycles, acrylate-coated optical fibers perform well in this condition. However, the condition become worse once longer cycles are introduced to the fibers. However, the cracking is not as significant as that in specimens under wet-dry cycles. Both polyimide and teftzel-silicone-coated optical fibers perform well. Only longitudinal scratches can be observed.

Table 6.1: Pull-Out Test Results of Acrylate-coated Optical Fibers

Acrylate-coated Optical Fibers					
Conditions	Failure Mode	Proportionality Limit Load (mN)	Proportionality Limit Displacement (mm)	Peak Load (mN)	Peak Displacement (mm)
1 Month					
Specimen #1	E	1036	0.1723	1036	0.1723
Specimen #2	A	1058	0.0168	1058	0.0168
Specimen #3	A	1010	0.1423	1010	0.1423
Specimen #4	E	1044	0.1481	1044	0.1481
3 Month					
Specimen #1	B	446	0.1539	1076	5.236
Specimen #2	A	631	0.1439	631	0.1439
Specimen #3	B	618	0.0439	1460	3.7056
Specimen #4	E	716	0.4206	716	0.4206
Specimen #5	B	660	0.2769	1397	4.6294
Specimen #6	B	674	0.3338	1130	4.9446
Specimen #7	E	666	0.0711	666	0.0711
Specimen #8	A	657	0.0522	657	0.0522
20 Wet-Dry cycles					
Specimen #1	A/E	1168	0.0763	1168	0.0763
Specimen #2	D	1276	0.3255	1276	0.3255
Specimen #3	A	1066	0.0564	1066	0.0564

Table 6.1: (Continued)

Conditions	Failure Mode	Proportionality Limit Load (mN)	Proportionality Limit Displacement (mm)	Peak Load (mN)	Peak Displacement (mm)
40 Wet-Dry cycles					
Specimen #1	A	1337	0.0483	1337	0.0483
Specimen #2	A	1494	0.0671	1494	0.0671
Specimen #3	A	1734	0.0659	1734	0.0659
Specimen #4	A	2276	0.0724	2276	0.0724
Specimen #5	A	2238	0.1438	2772	0.6588
Specimen #6	A	1953	0.1038	1953	0.1038
Specimen #7	A	2309	0.0305	2309	0.0305
30 Freeze-Thaw cycles					
Specimen #1	A	855	0.0266	855	0.0266
Specimen #2	D	687	0.0452	687	0.0452
Specimen #3	D	776	0.1268	776	0.1268
60 Freeze-Thaw cycles					
Specimen #1	D	207	0.3663	233	3.6403
Specimen #2	D/E	286	0.0513	286	0.0513
Specimen #3	A	429	0.1830	429	0.1830

Table 6.2: Pull-Out Test Results of Polyimide-coated Optical Fibers

Polyimide-coated Optical Fibers					
Conditions	Failure Mode	Proportionality Limit Load (mN)	Proportionality Limit Displacement (mm)	Peak Load (mN)	Peak Displacement (mm)
1 Month					
Specimen #1	A	2284	0.2023	2284	0.2023
Specimen #2	A/E	1894	0.1048	1906	0.2252
Specimen #3	E	1516	0.0926	1516	0.0926
Specimen #4	E	957	0.1150	1363	0.3230
Specimen #5	B	828	0.6074	1567	4.5961
Specimen #6	B	1023	0.3548	2062	5.2270
3 Month					
Specimen #1	A	2739	0.0609	2739	0.0609
Specimen #2	E	2809	0.0663	2809	0.0663
Specimen #3	A	2811	0.0980	2811	0.0980
Specimen #4	A/E	2321	0.0879	2321	0.0879
Specimen #5	A	2361	0.1338	2361	0.1338
Specimen #6	A	4709	0.1096	4709	0.1096
Specimen #7	A	5022	0.1611	5022	0.1611
Specimen #8	A	6408	0.1326	6408	0.1326

Table 6.2: (Continued)

Conditions	Failure Mode	Proportionality Limit Load (mN)	Proportionality Limit Displacement (mm)	Peak Load (mN)	Peak Displacement (mm)
20 Wet-Dry cycles					
Specimen #1	A/E	792	0.0220	843	0.2354
Specimen #2	B/D	615	0.1911	1001	0.7133
Specimen #3	D	1018	0.0297	1018	0.0297
Specimen #4	A/E	752	0.1893	752	0.1893
Specimen #5	D	978	0.2643	978	0.2643
40 Wet-Dry cycles					
Specimen #1	A	783	0.1682	783	0.1682
Specimen #2	A	800	0.0484	871	0.3963
Specimen #3	F	824	0.3012	1031	1.2174
Specimen #4	F	813	0.1845	1286	4.7954
Specimen #5	D	1196	0.3953	1342	0.8685

Table 6.2: (Continued)

Conditions	Failure Mode	Proportionality Limit Load (mN)	Proportionality Limit Displacement (mm)	Peak Load (mN)	Peak Displacement (mm)
30 Freeze-Thaw cycles					
Specimen #1	D	1849	0.1449	1913	0.2364
Specimen #2	D	1879	0.3905	1879	0.3905
Specimen #3	A	1827	0.4600	1827	0.4600
Specimen #4	D	4380	0.1459	4380	0.1459
Specimen #5	A	4073	0.1385	4073	0.1385
Specimen #6	D	3450	0.1215	3450	0.1215
60 Freeze-Thaw cycles					
Specimen #1	B	1881	0.3161	3682	5.4371
Specimen #2	D/E	1023	0.1615	1287	0.4214
Specimen #3	A	2133	0.1793	2133	0.1793
Specimen #4	E	1810	0.0735	2145	0.3368
Specimen #5	D	1086	0.0657	1453	0.4620
Specimen #6	D/E	1426	0.4446	1426	0.4446

Table 6.3 Pull-Out Test Results of Teftzel-Silicone-coated Optical Fibers

Teftzel-Silicone-coated Optical Fibers					
Conditions	Failure Mode	Proportionality Limit Load (mN)	Proportionality Limit Displacement (mm)	Peak Load (mN)	Peak Displacement (mm)
1 Month					
Specimen #1	B	483	0.0337	1410	4.3577
Specimen #2	B	530	0.0753	2123	5.1941
3 Month					
Specimen #1	A	1287	0.1378	1287	0.1378
Specimen #2	A	1300	0.1611	1300	0.1611
Specimen #3	A	1494	0.2275	1494	0.2275
Specimen #4	A	1838	0.2388	1838	0.2388
Specimen #5	A	2322	0.1073	2322	0.1073
Specimen #6	A	4199	1.7321	4199	1.7321
Specimen #7	A	4284	1.3979	4284	1.3979
Specimen #8	A	4331	0.5163	4331	0.5163
20 Wet-Dry cycles					
Specimen #1	A	1041	0.0813	1041	0.0813
Specimen #2	A	1235	0.0982	1235	0.0982
Specimen #3	A	1894	0.2099	1894	0.2099
Specimen #4	A	1997	0.0675	1997	0.0675

Table 6.3: (Continued)

Conditions	Failure Mode	Proportionality Limit Load (mN)	Proportionality Limit Displacement (mm)	Peak Load (mN)	Peak Displacement (mm)
40 Wet-Dry cycles					
Specimen #1	A	1961	0.0961	1961	0.0961
Specimen #2	A	1921	0.0739	1921	0.0739
30 Freeze-Thaw cycles					
Specimen #1	F	2423	2.2645	2423	2.2645
Specimen #2	D/F	1609	0.1433	2389	0.9774
Specimen #3	C/A	6272	1.5254	6272	1.5254
Specimen #4	A	3932	0.2327	3932	0.2327
Specimen #5	A	2676	0.0403	7065	0.5997
60 Freeze-Thaw cycles					
Specimen #1	F	2142	0.2060	2371	2.8926
Specimen #2	F	2244	0.0420	5421	2.9720
Specimen #3	A	7179	0.5930	7179	0.5930
Specimen #4	D	2610	0.0928	2610	0.0928
Specimen #5	F	3975	0.6299	4939	2.8767
Specimen #6	A	2597	0.3103	2597	0.3103

Table 6.4: The Summary of SEM Studies

Scanning Electron Microscope (SEM) Remarks				
Stored inside the water tank	Period	Acrylate	Polyimide	Teftzel-Silicone
	1-Week	Good	Good	Good[1]
	2-Week	Good	Good	Good
	3-Week	Good	Good	Good
	1-Month	Good	Good	Good
	3-Month	Thin-hair cracks	Good	Good
Stored inside the Calcium Hydroxide pH=13.0	Period	Acrylate	Polyimide	Teftzel-Silicone
	1-Week	N/A[2]	Good	Good[3]
	2-Week	N/A	Good	Good
	3-Week	Good[4]	Good	Good
	1-Month	Good	Good	Good
	3-Month	Good	Good	Good
Embedded inside the cement paste	Period	Acrylate	Polyimide	Teftzel-Silicone
	2-Week	Thin-hair cracks	Good	Good
	1-month	significant cracks	Good	Good
	3-month	significant cracks	Good	Good
Wet-Dry cycles	Cycles	Acrylate	Polyimide	Teftzel-Silicone
	20-cycles	Bad (cracks)	Good	Good
	40-cycles	Bad (cracks)	Good	Good
Freeze-Thaw cycles	Cycles	Acrylate	Polyimide	Teftzel-Silicone
	30-cycles	Good	Good	Good
	60-cycles	Bad (cracks)	Good	Good

[1] Some dents or bruises appear on the surfaces, however these damage may be caused by mishandled of the optical fibers.
[2] Due to the accumulations of calcium hydroxide on the surface of the fibers, the author could not determine the surface conditions.
[3] Bruises similar to the fibers stored inside the water appeared.
[4] For this period, the accumulation lessens thus the condition of the surfaces could be studied or seen.

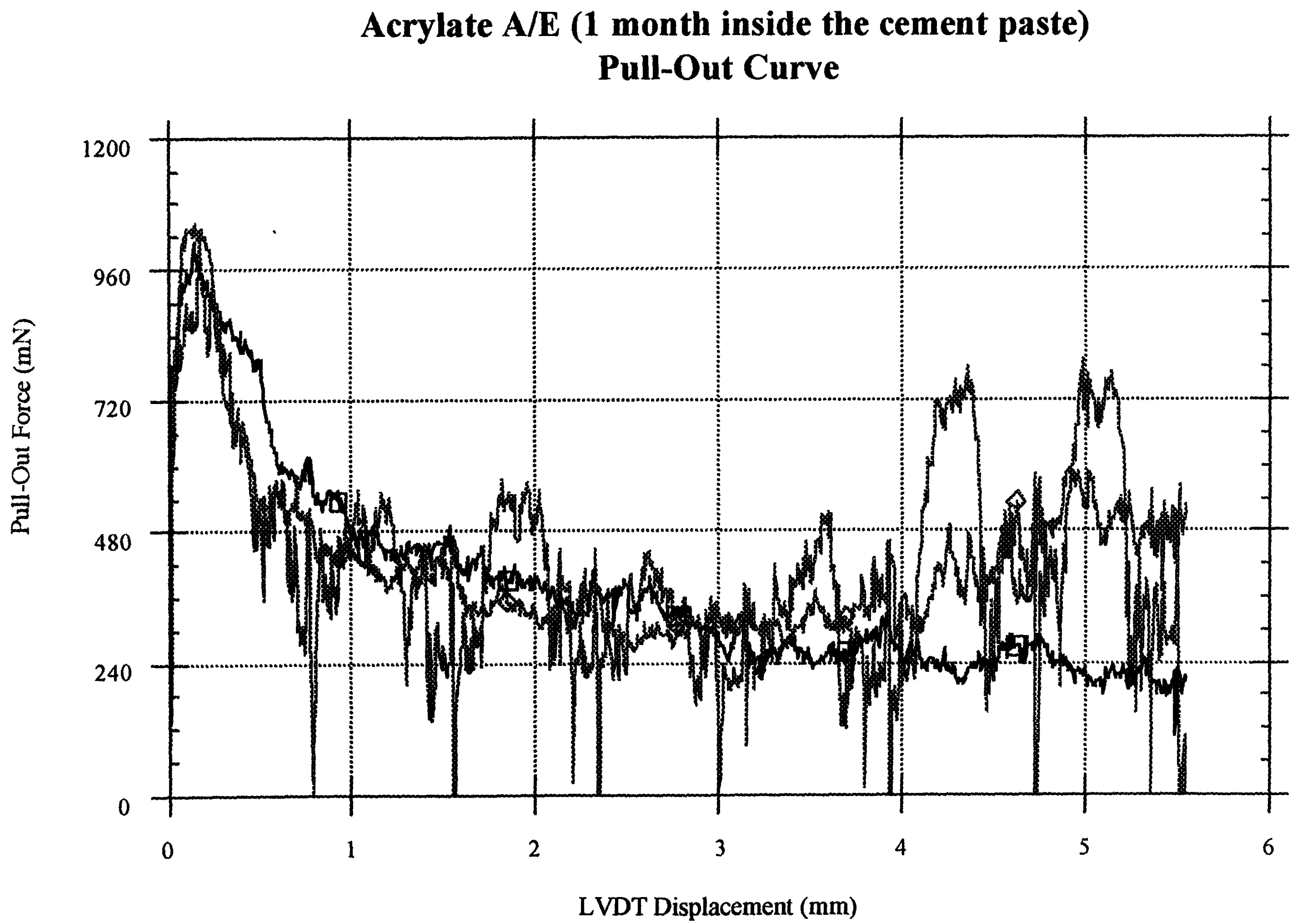


Figure 6-2: The pull-out curve of acrylate-coated optical fibers A/E-types (1 month inside the cement paste).

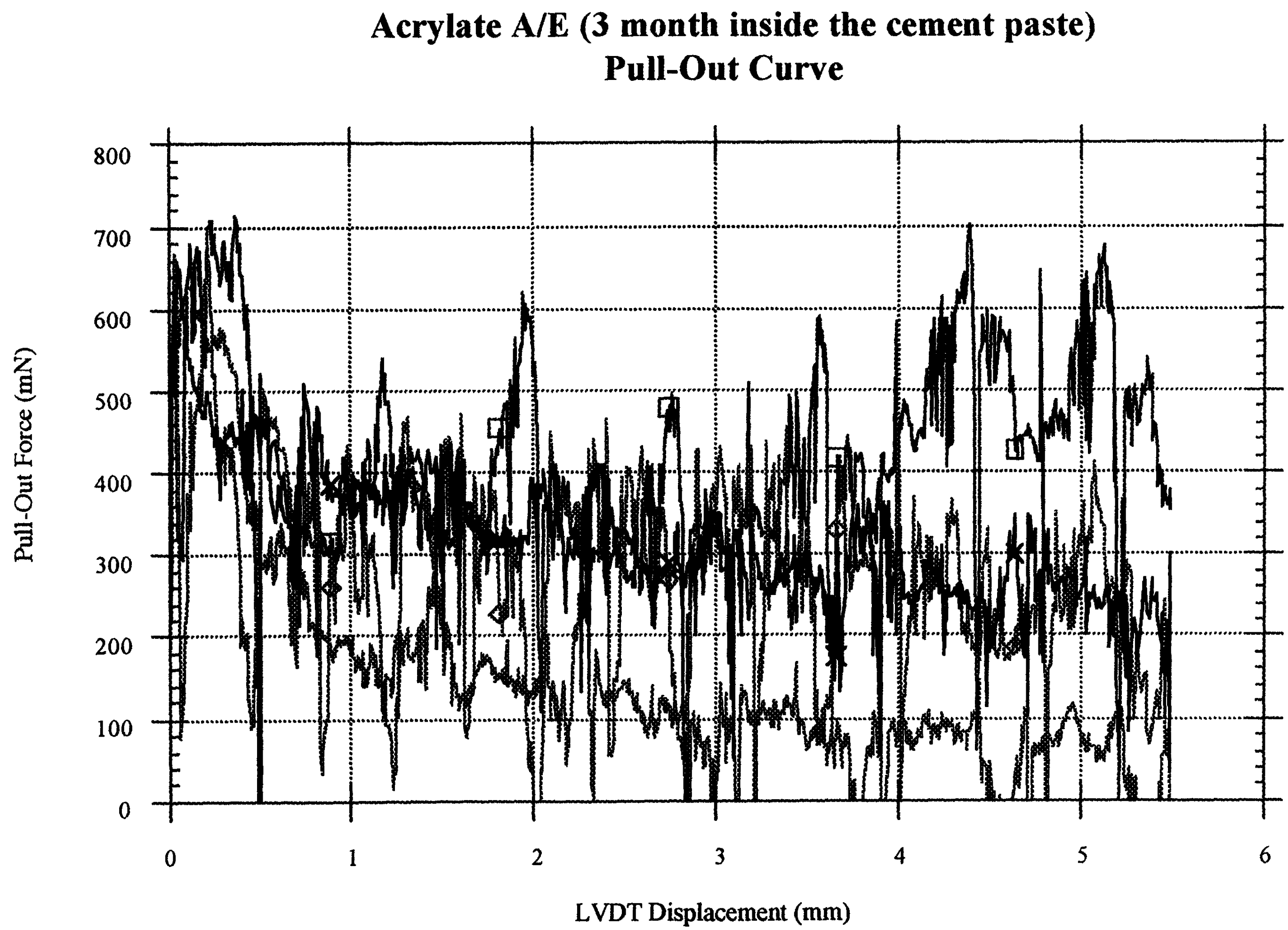


Figure 6-3: The pull-out curve of acrylate-coated optical fibers A/E-types (3month inside the cement paste).

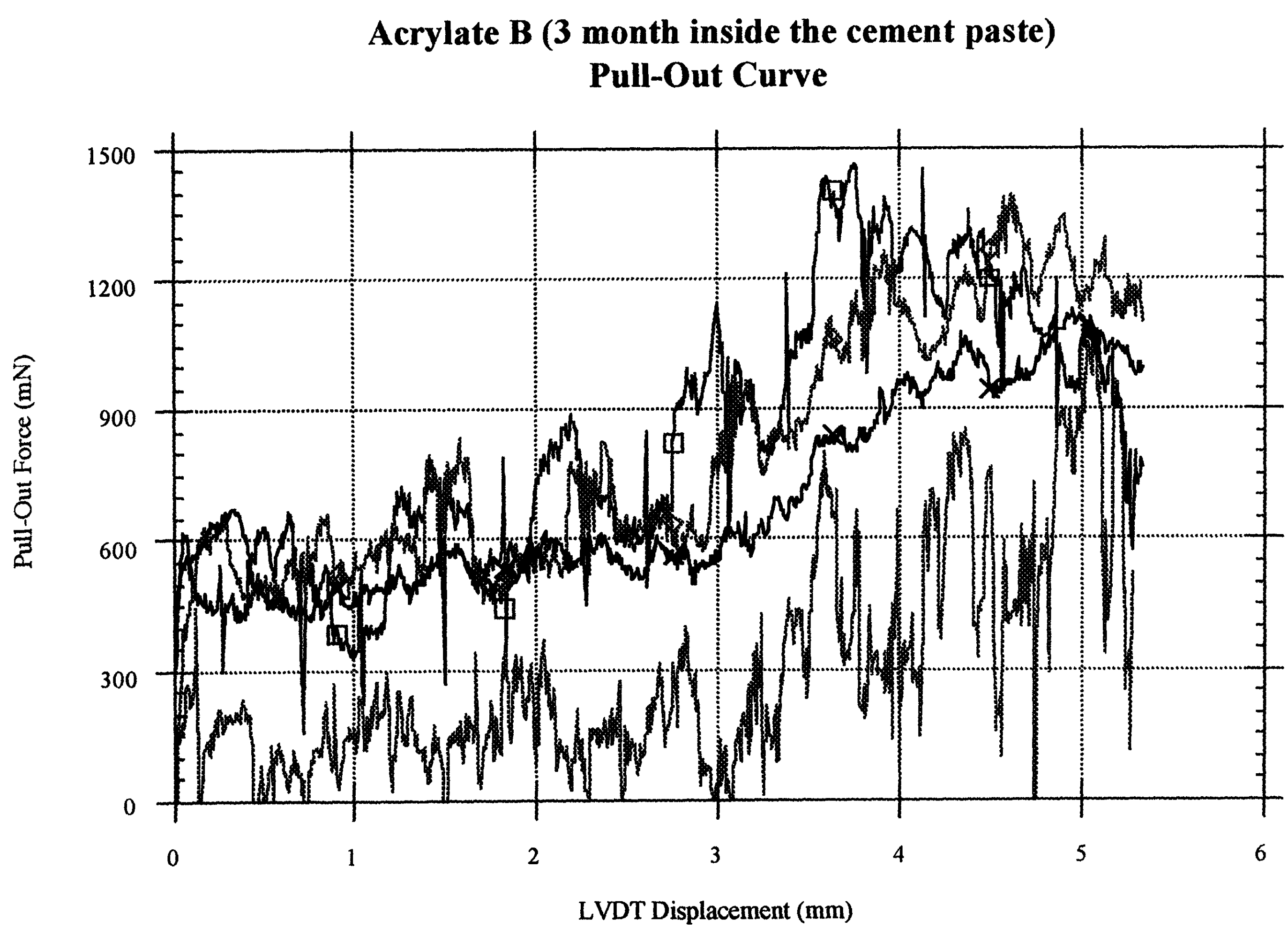


Figure 6-4: The pull-out curve of acrylate-coated optical fibers B-type (3 month inside the cement paste).

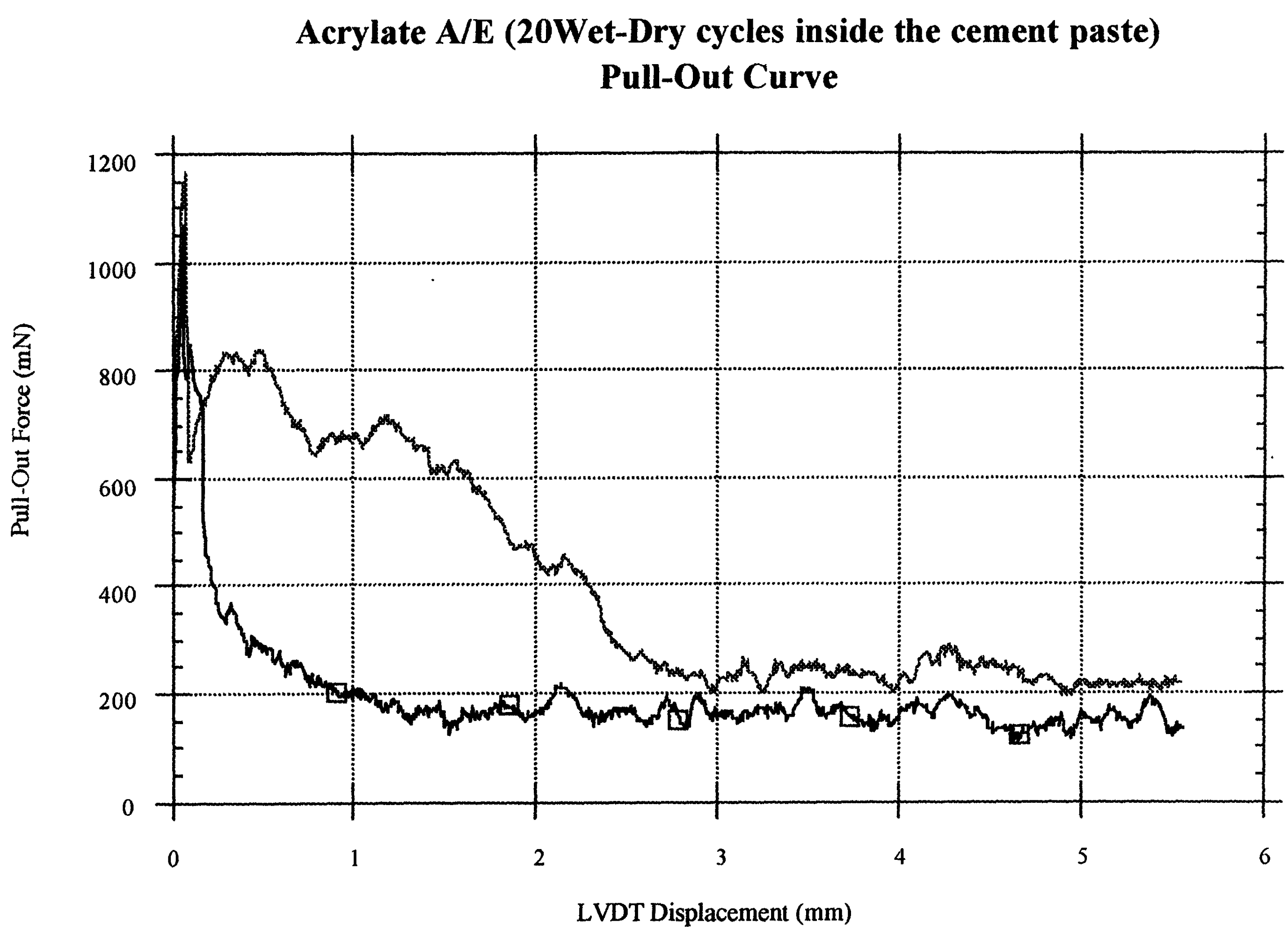


Figure 6-5: The pull-out curve of acrylate-coated optical fibers A/E-types (20 Wet-Dry cycles inside the cement paste).

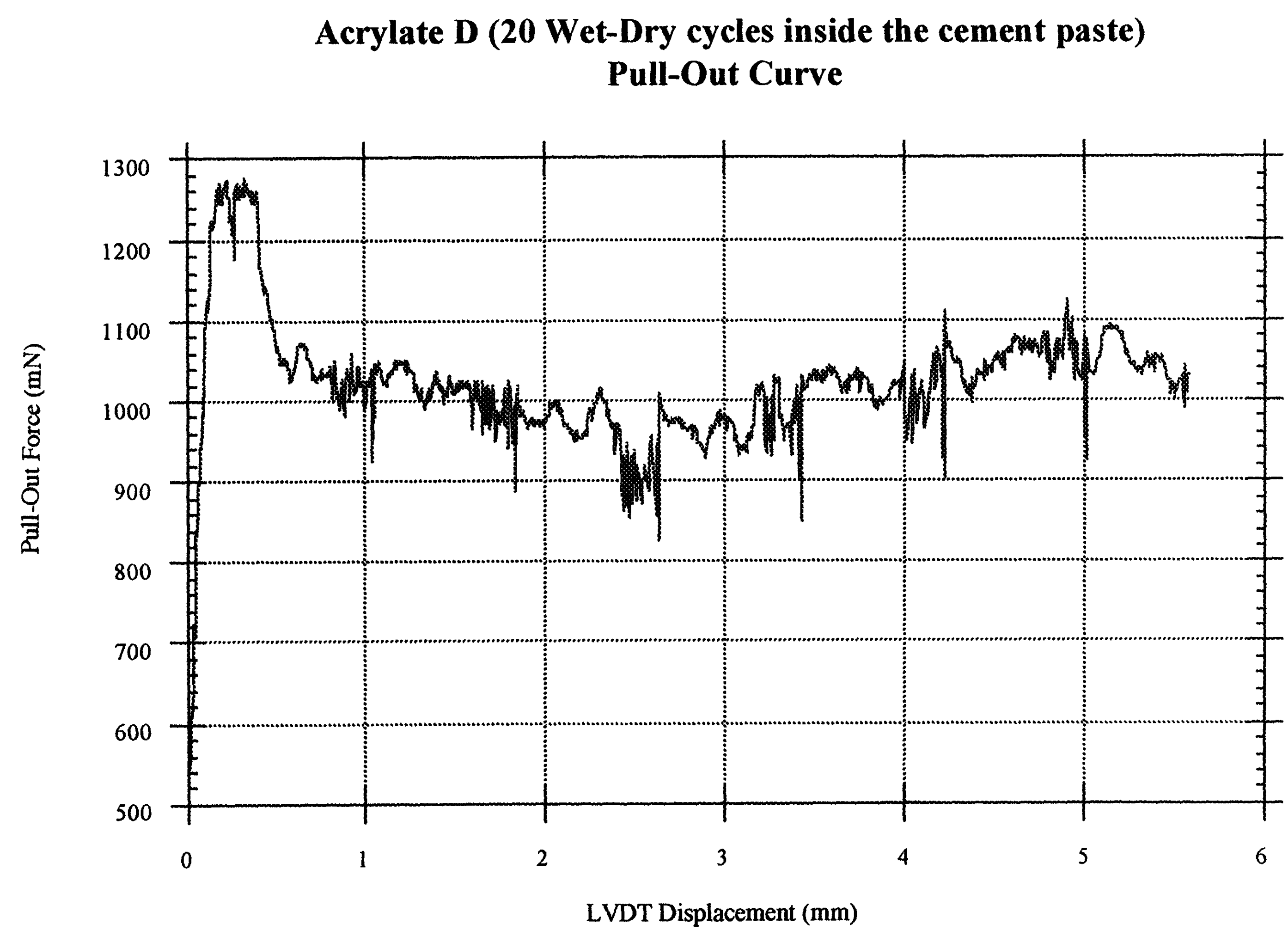


Figure 6-6: The pull-out curve of acrylate-coated optical fiber D-type (20 Wet-Dry cycles inside the cement paste).

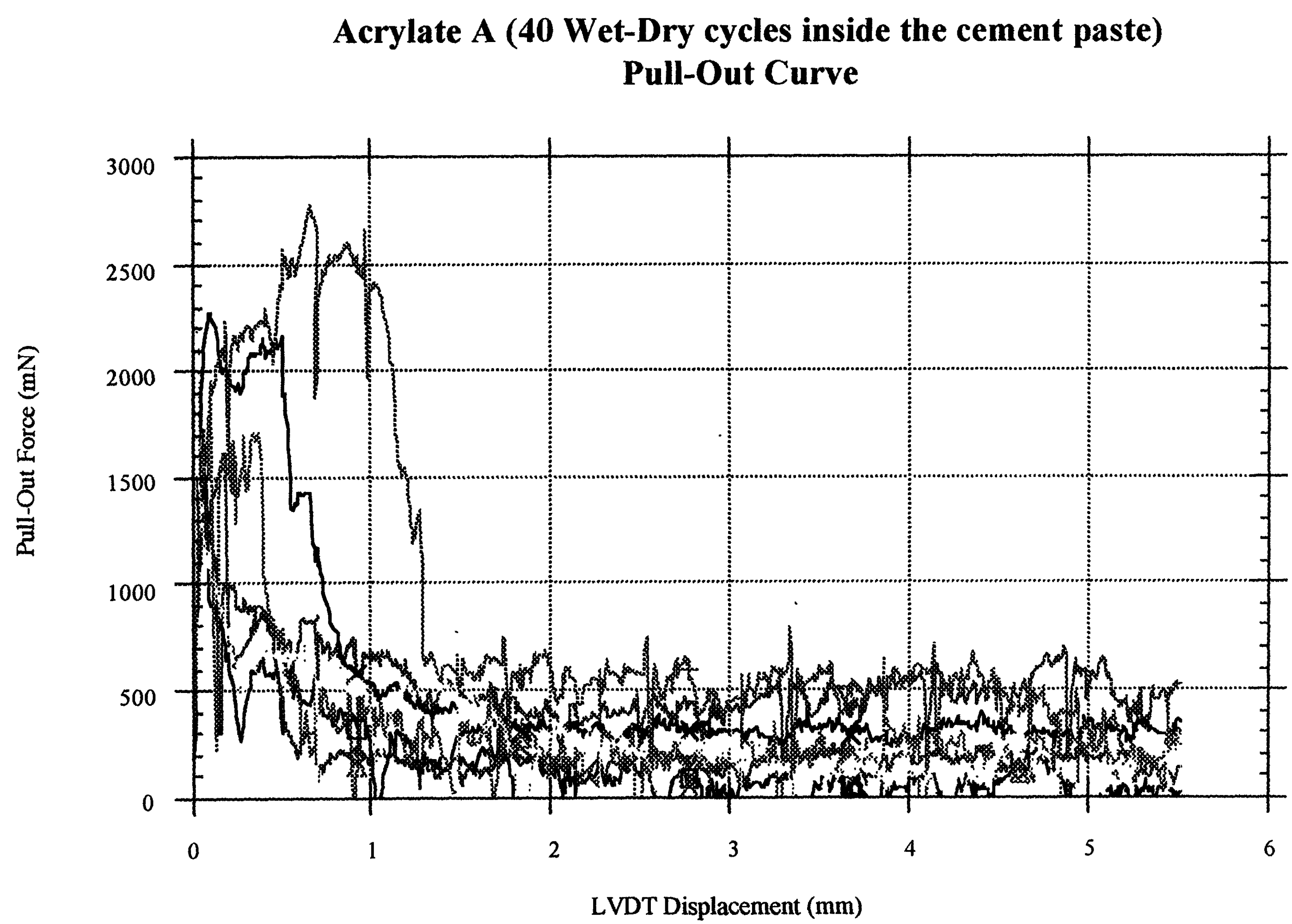


Figure 6-7: The pull-out curve of acrylate-coated optical fiber A-type (40 Wet-Dry cycles inside the cement paste).

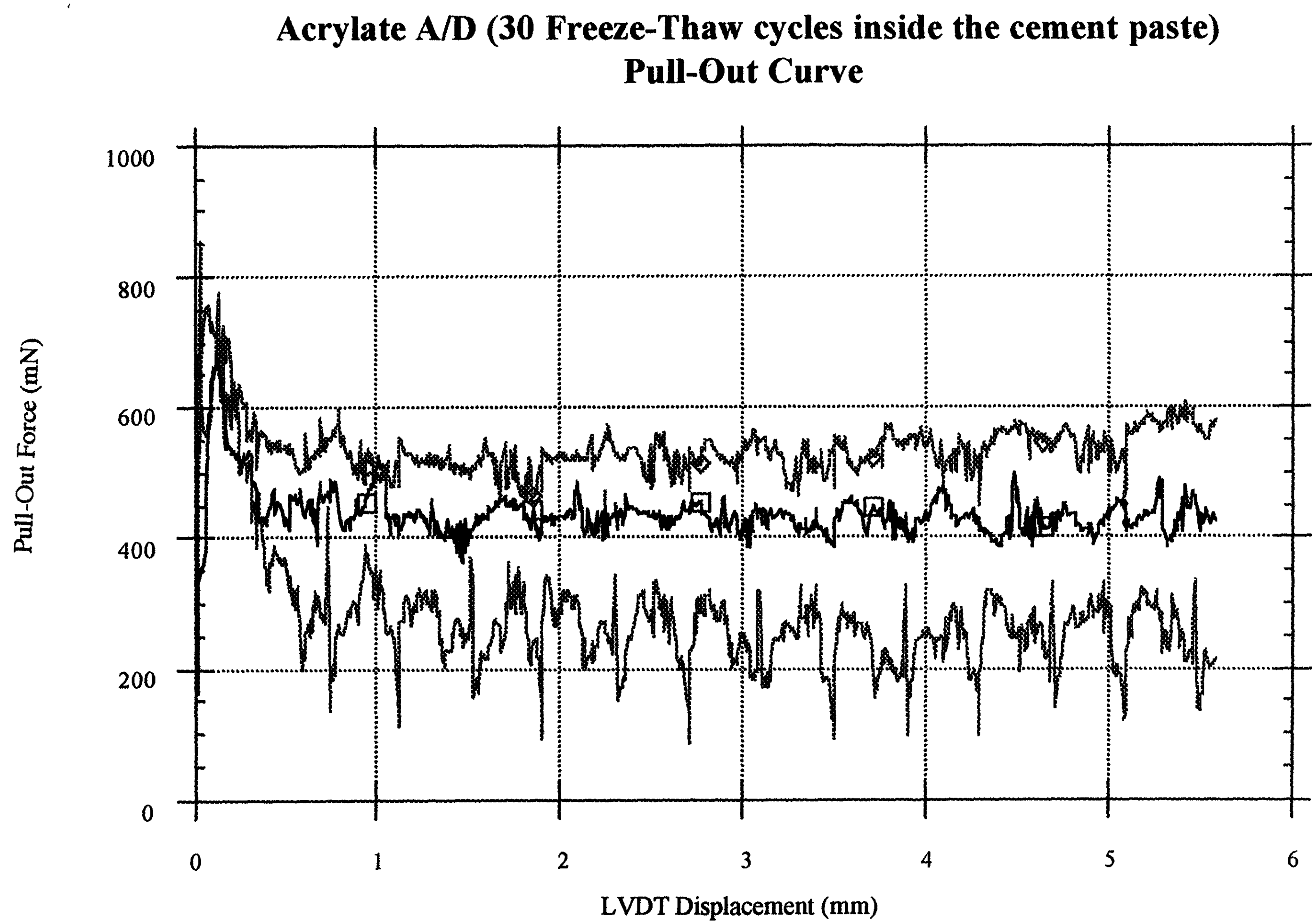


Figure 6-8: The pull-out curve of acrylate-coated optical fibers A/D-types (30 Freeze-Thaw cycles inside the cement paste).

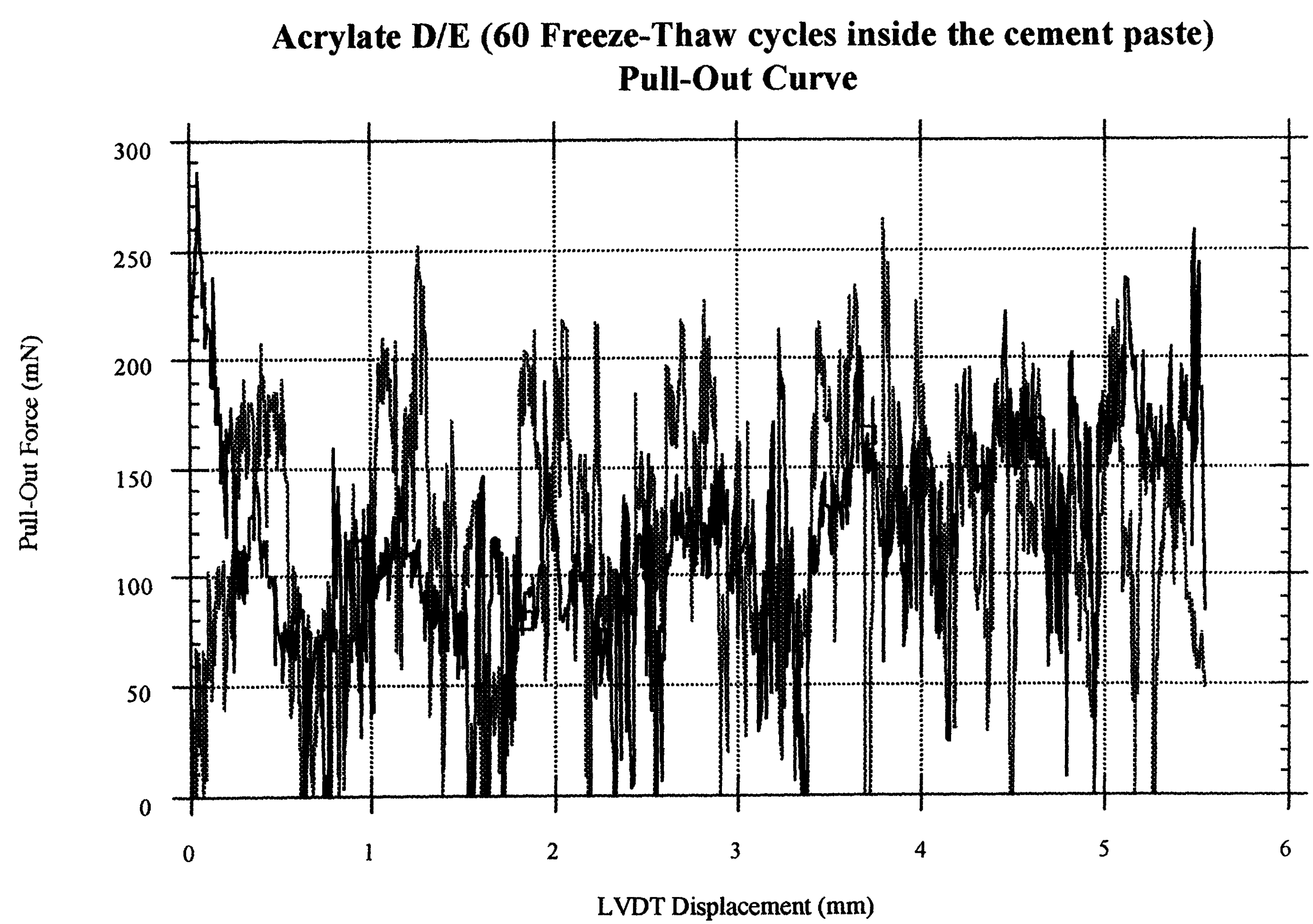


Figure 6-9: The pull-out curve of acrylate-coated optical fibers D/E-types (60 Freeze-Thaw cycles inside the cement paste).

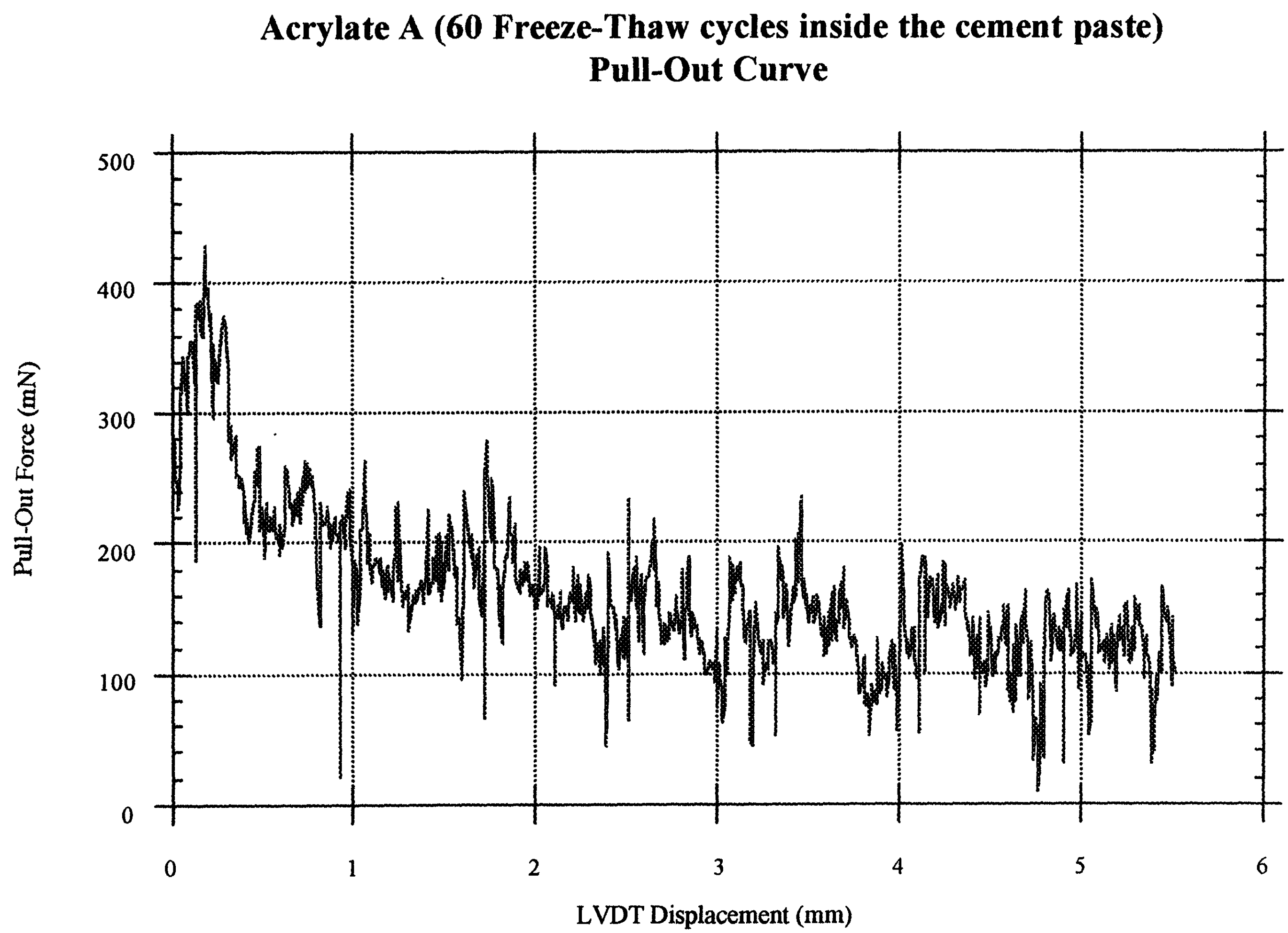


Figure 6-10: The pull-out curve of acrylate-coated optical fiber A-type (60 Freeze-Thaw cycles inside the cement paste).

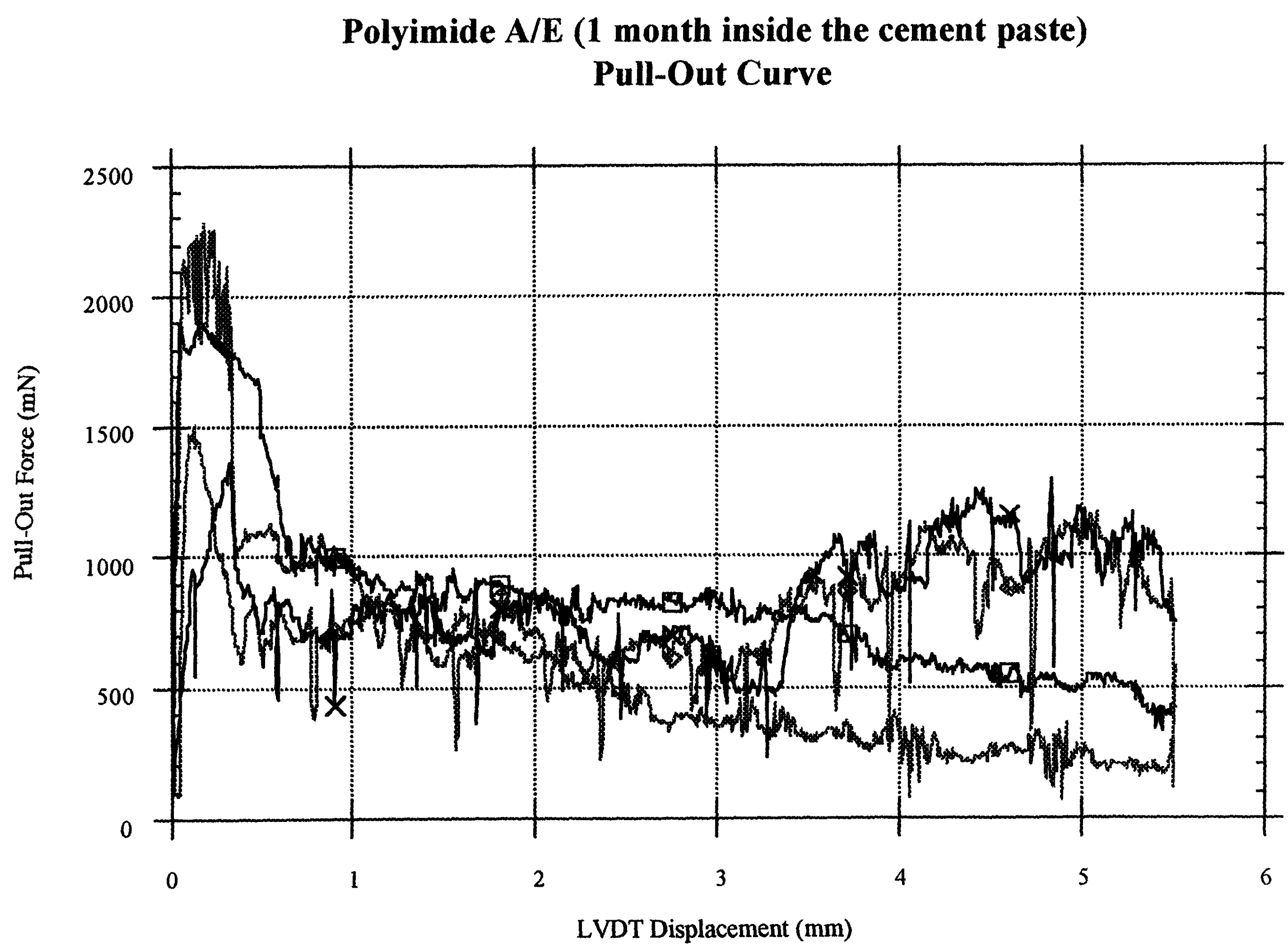
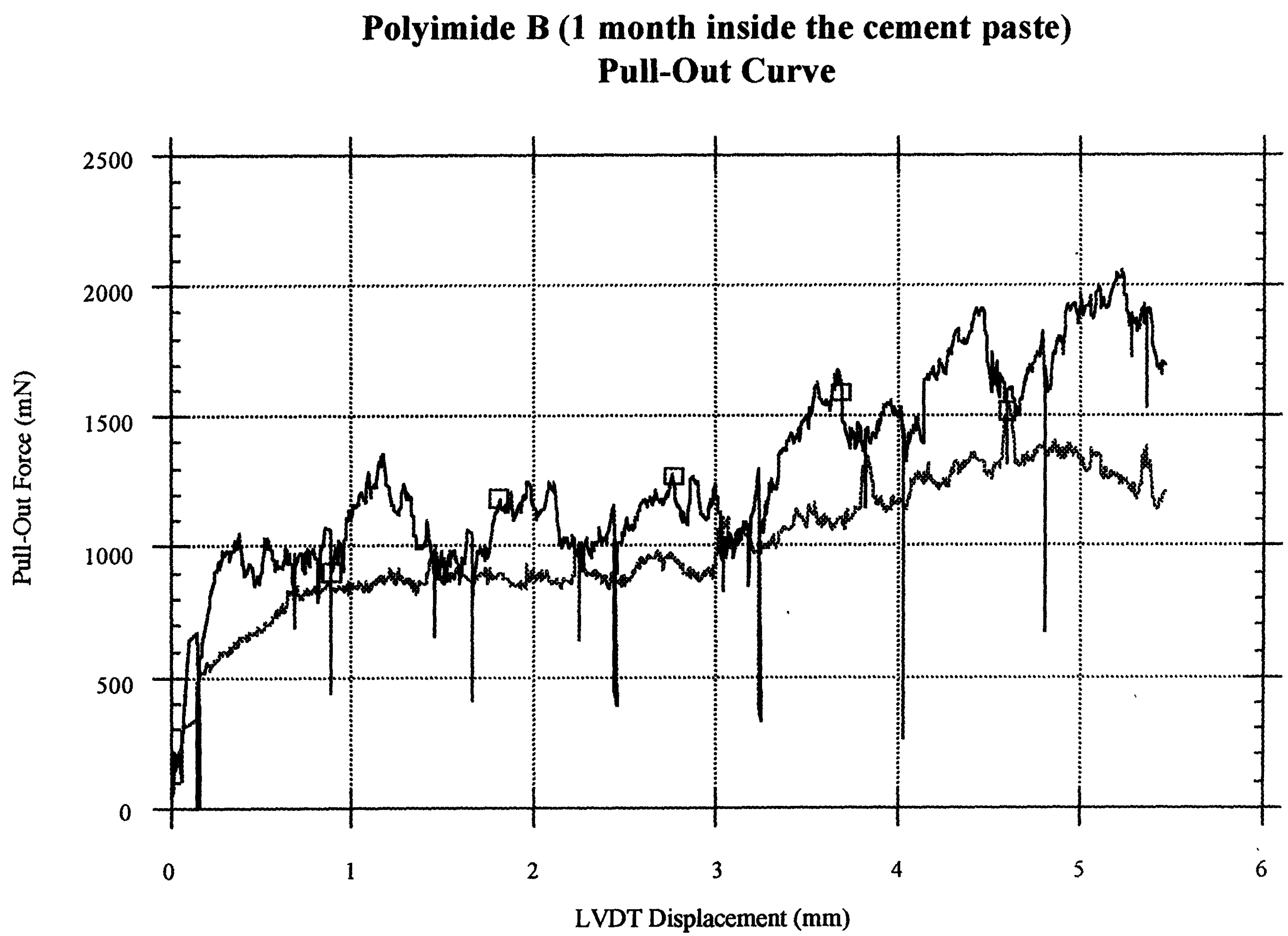


Figure 6-11: The pull-out curve of polyimide-coated optical fibers A/E-types (1 month inside the cement paste).



6-12 : The pull-out curve of polyimide-coated optical fibers B-type (1 month inside the cement paste).

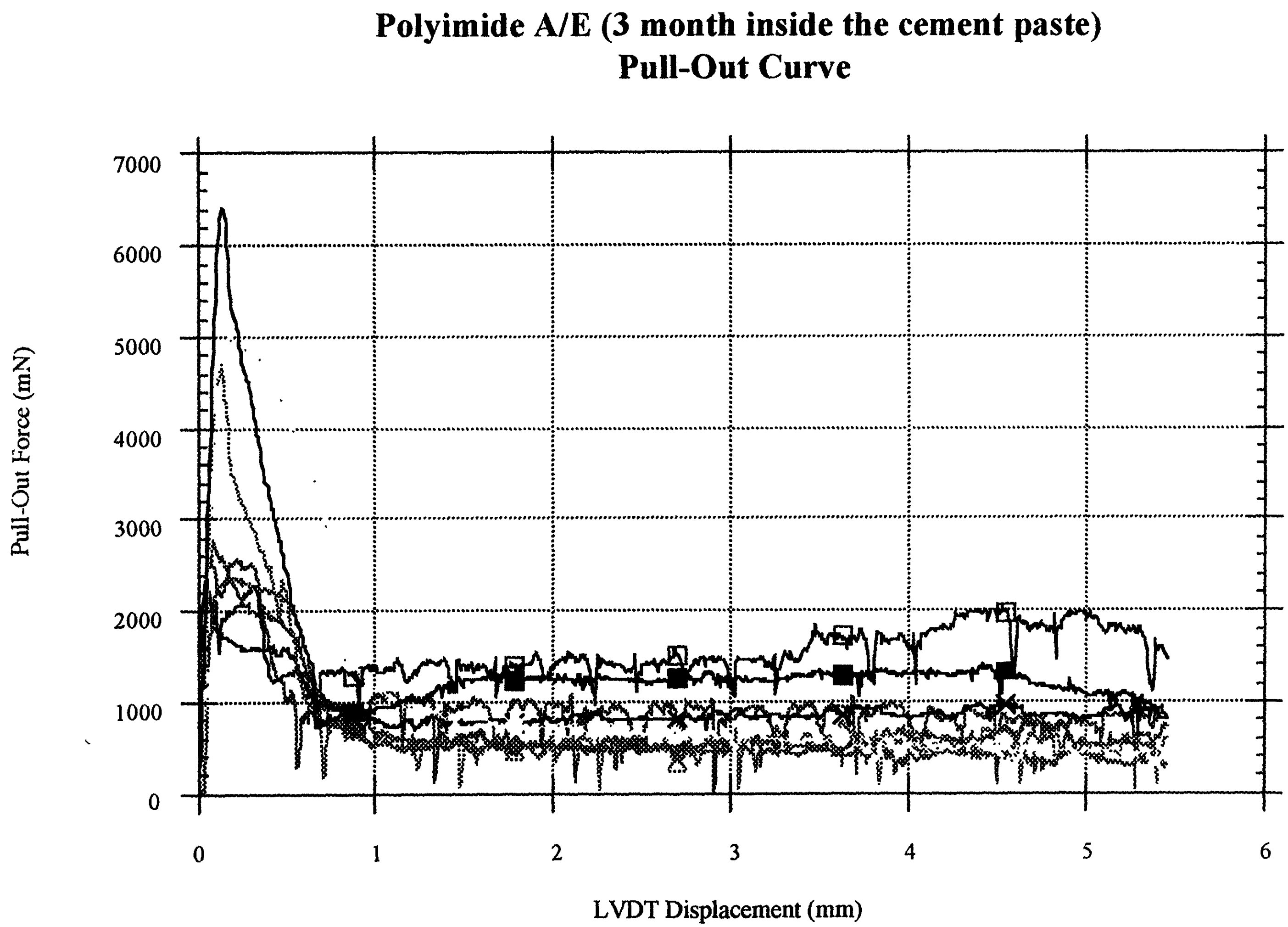


Figure 6-13: The pull-out curve of polyimide-coated optical fibers A/E-types (3 month inside the cement paste).

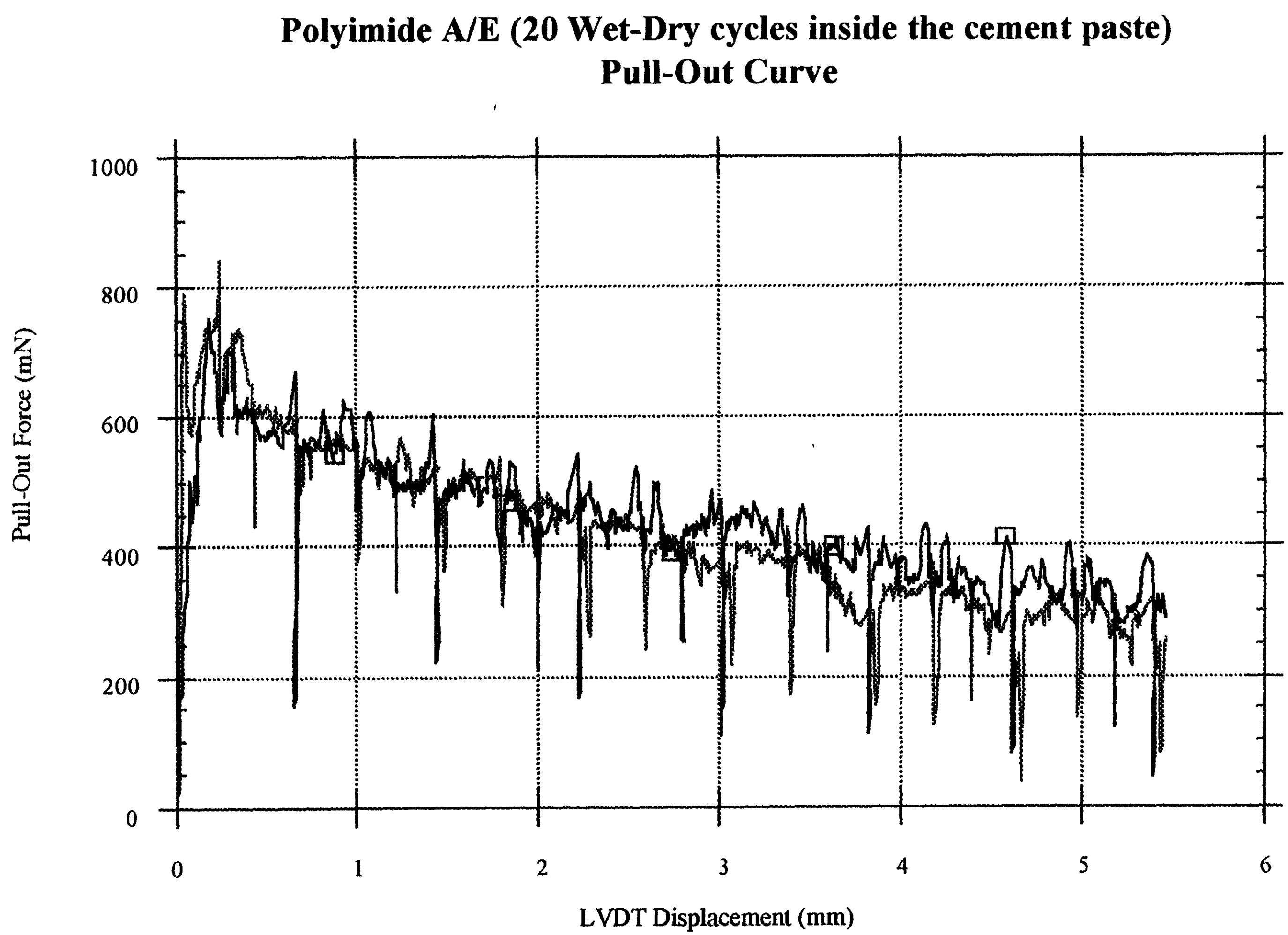


Figure 6-14: The pull-out curve of polyimide-coated optical fibers A/E-types (20 Wet-Dry cycles inside the cement paste)

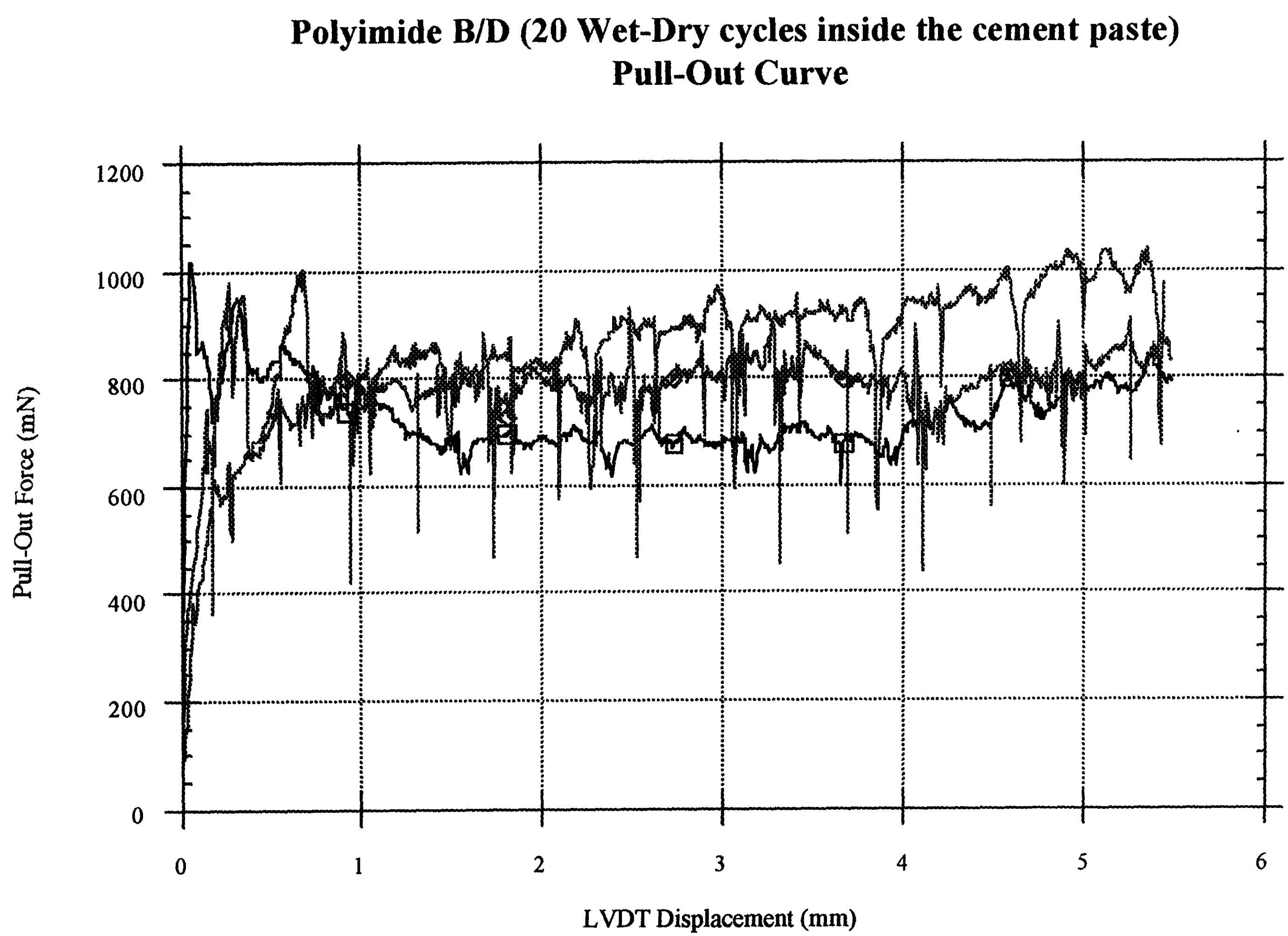


Figure 6-15: The pull-out curve of polyimide-coated optical fibers B/D-types (20 Wet-Dry cycles inside the cement paste).

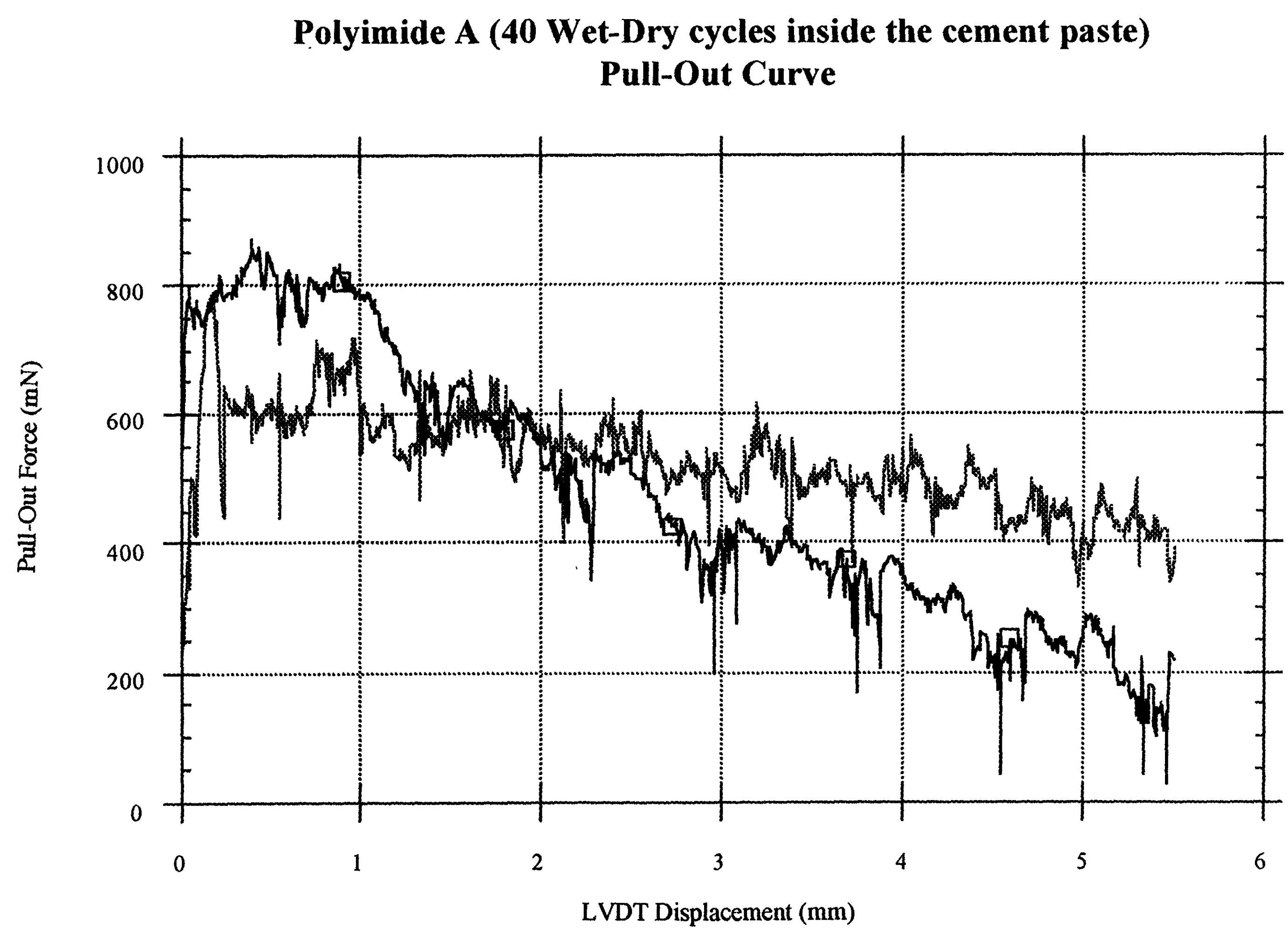


Figure 6-16: The pull-out curve of polyimide-coated optical fibers A-type (40 Wet-Dry cycles inside the cement paste).

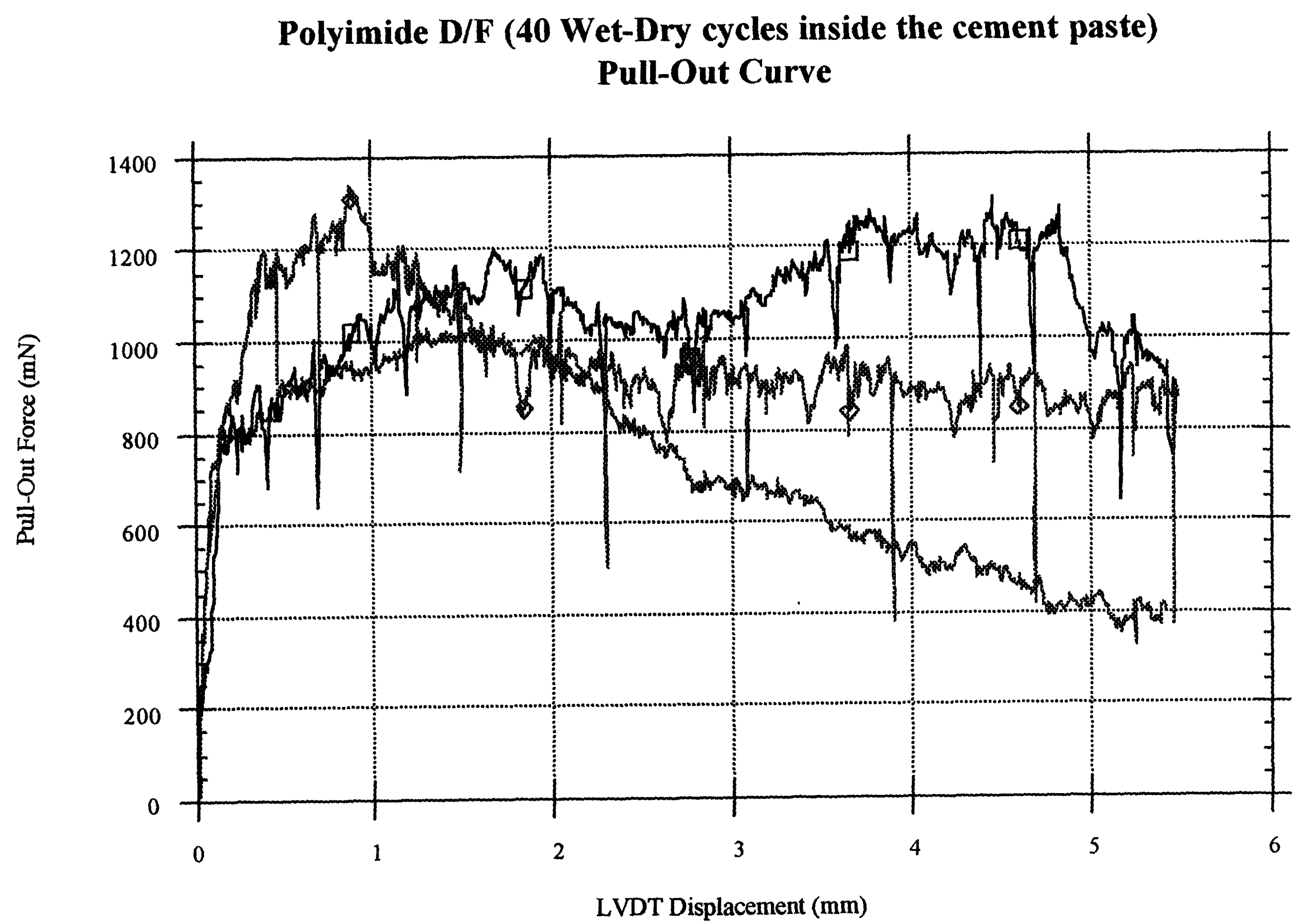


Figure 6-17: The pull-out curve of polyimide-coated optical fibers D/F-types (40 Wet-Dry cycles inside the cement paste).

Polyimide A (30 Freeze-Thaw cycles inside the cement paste) Pull-Out Curve

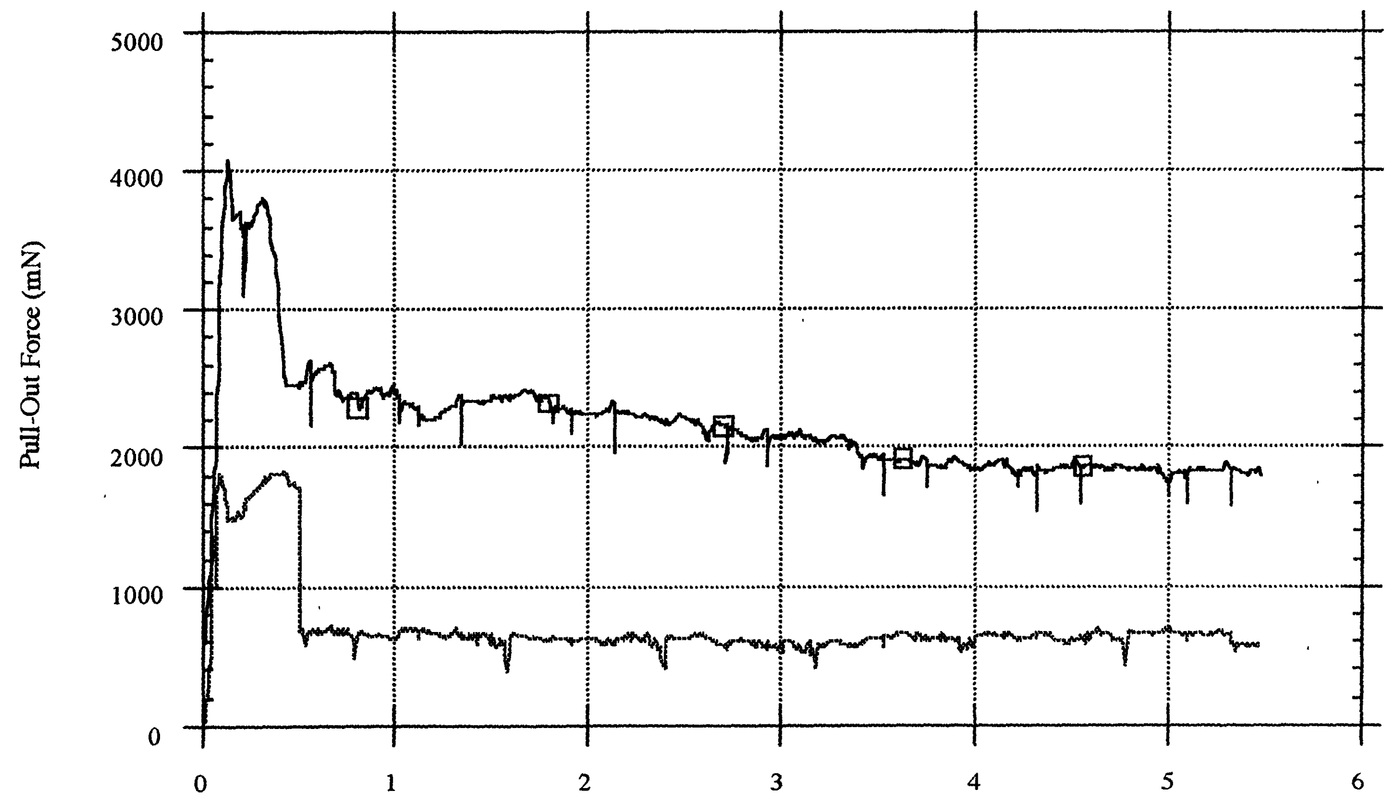


Figure 6-18: The pull-out curve of polyimide-coated optical fibers A-type (30 Freeze-Thaw cycles inside the cement paste).

Polyimide D (30 Freeze-Thaw cycles inside the cement paste) Pull-Out Curve

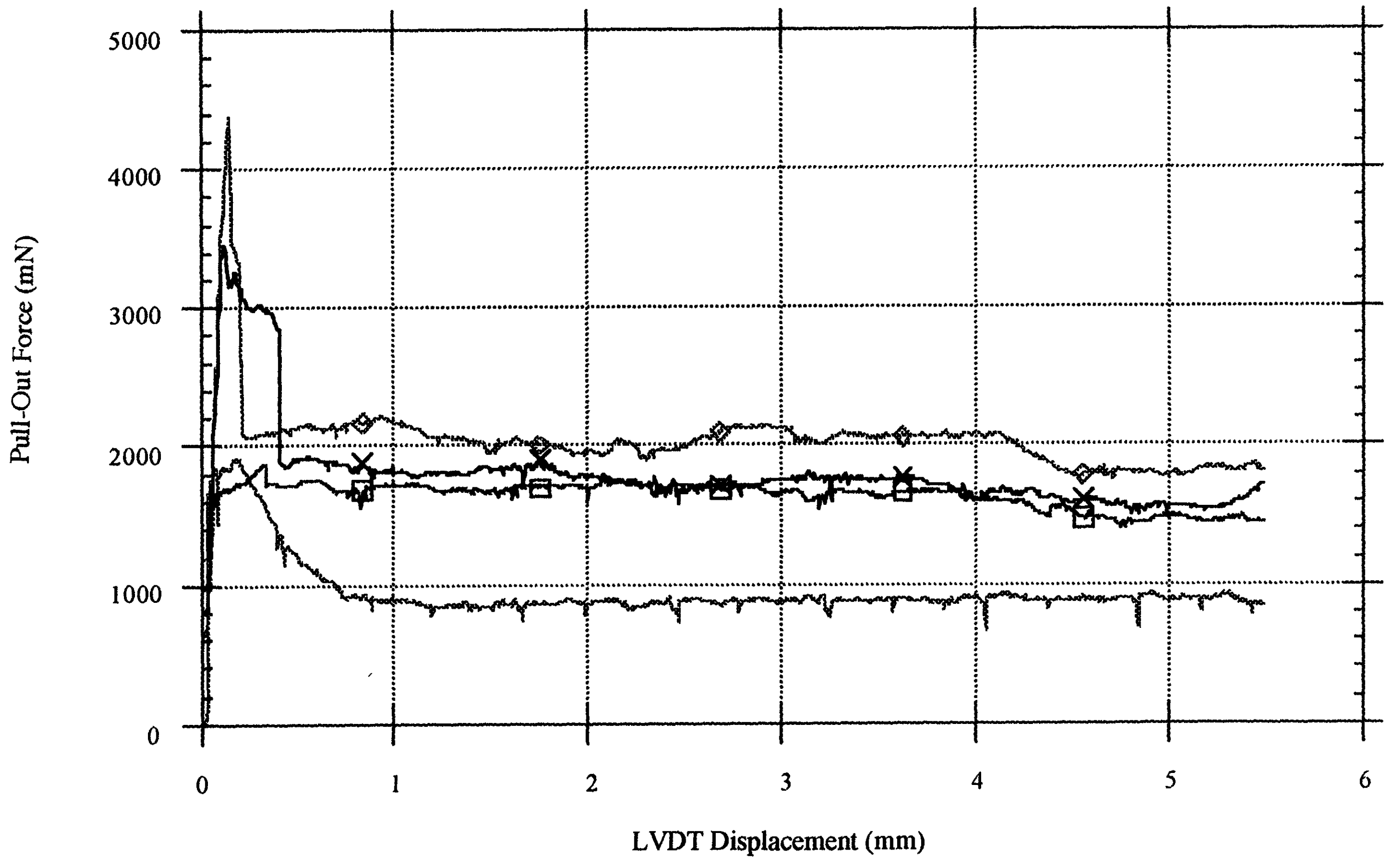


Figure 6-19: The pull-out curve of polyimide-coated optical fibers D-type (30 Freeze-Thaw cycles inside the cement paste).

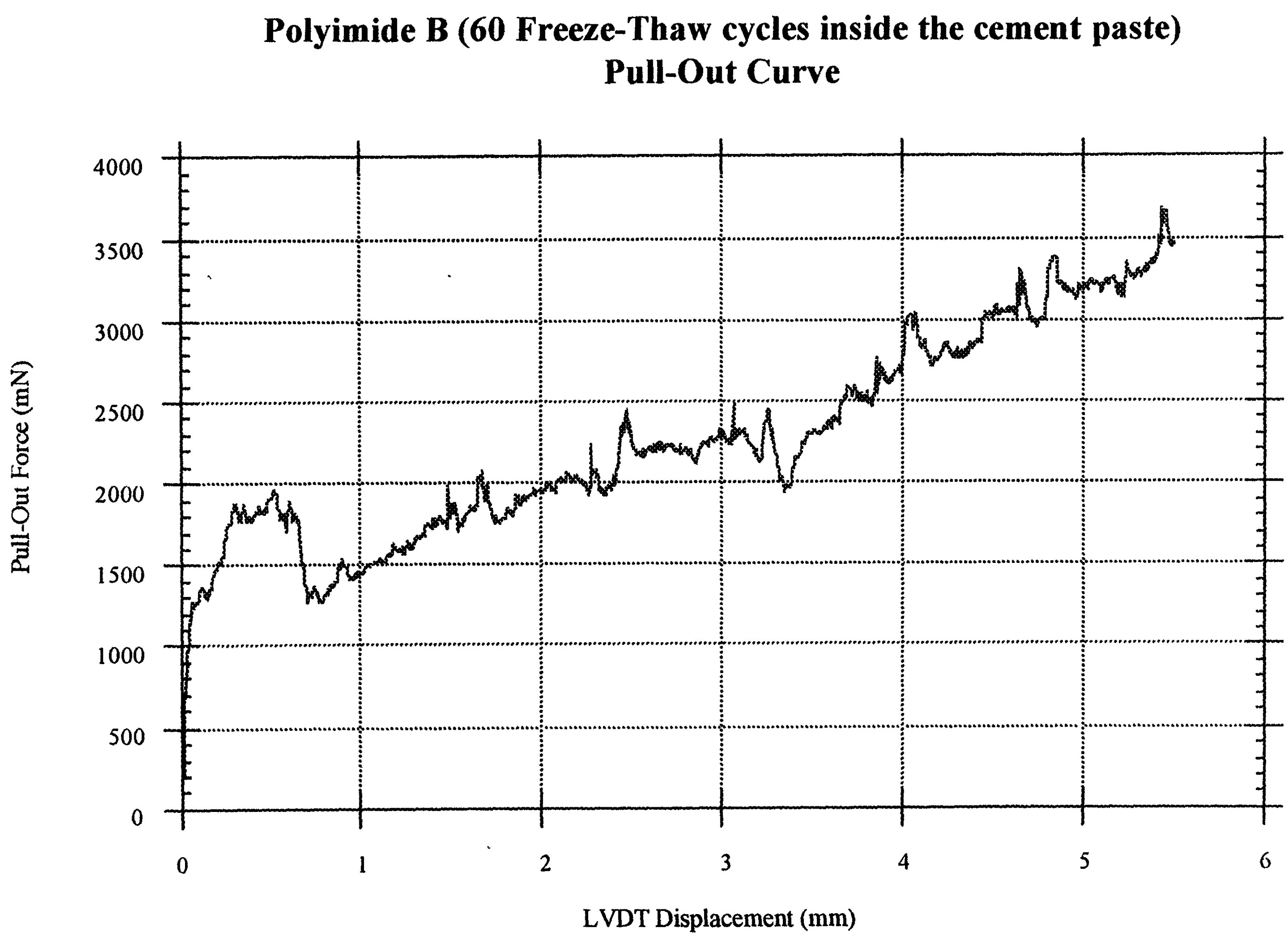


Figure 6-20: The pull-out curve of polyimide-coated optical fibers B-type (60 Freeze-Thaw cycles inside the cement paste).

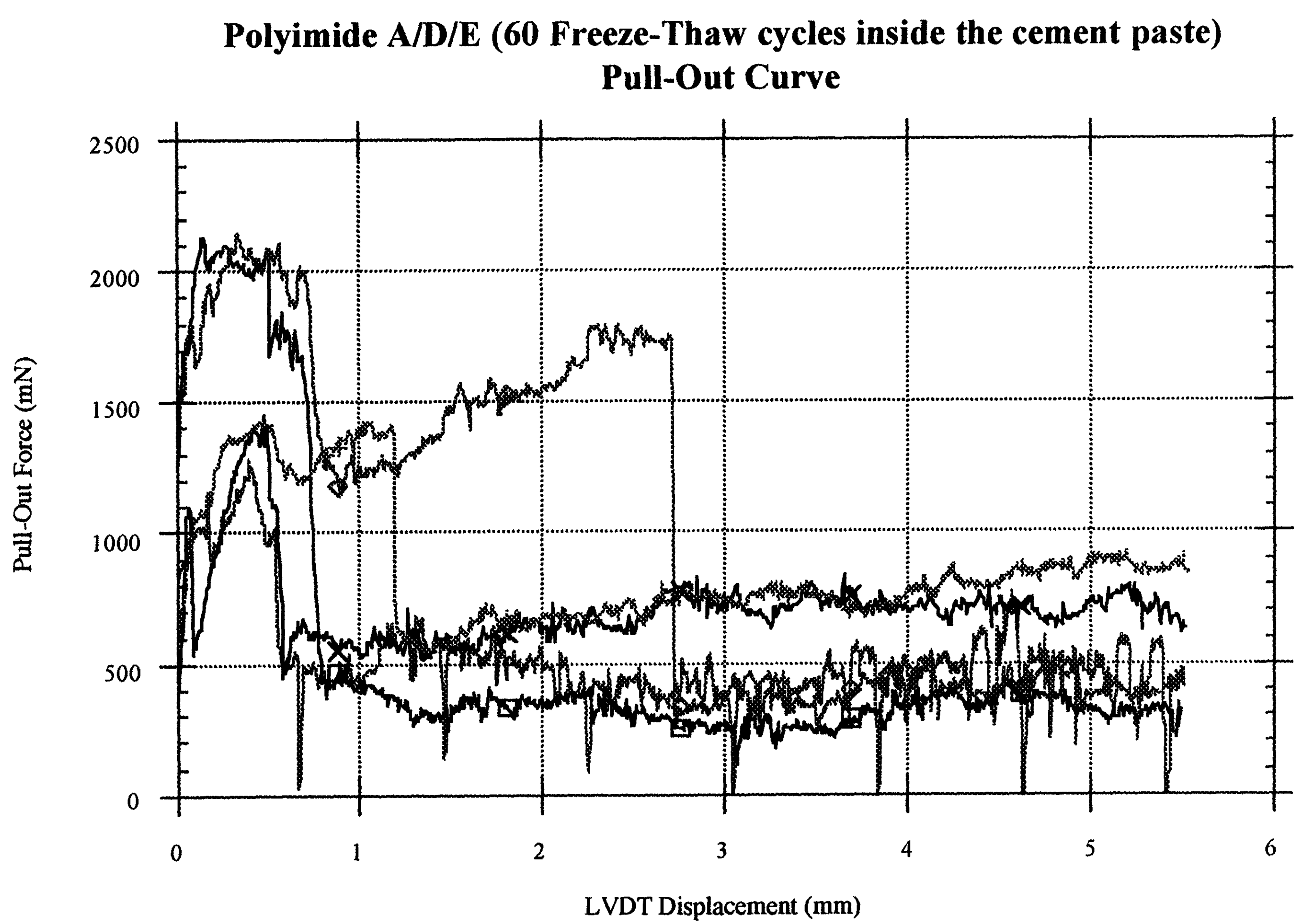


Figure 6-21: The pull-out curve of polyimide-coated optical fibers A/D/E-types (60 Freeze-Thaw cycles inside the cement paste)

Teftzel-Silicone B (1 month inside the cement paste)
Pull-Out Curve

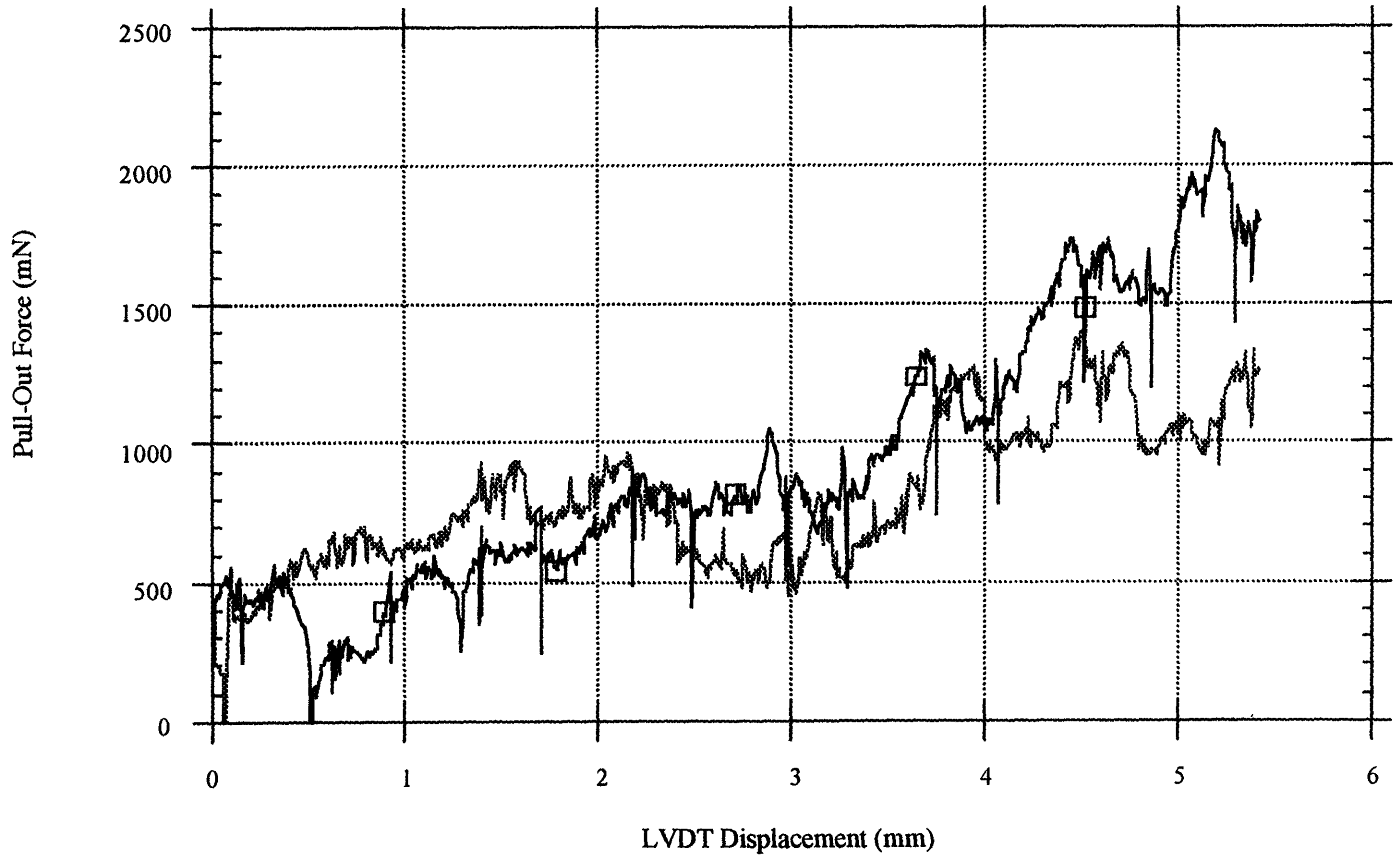


Figure 6-22: The pull-out curve of teftzel-silicone-coated optical fibers B-type (1 month inside the cement paste).

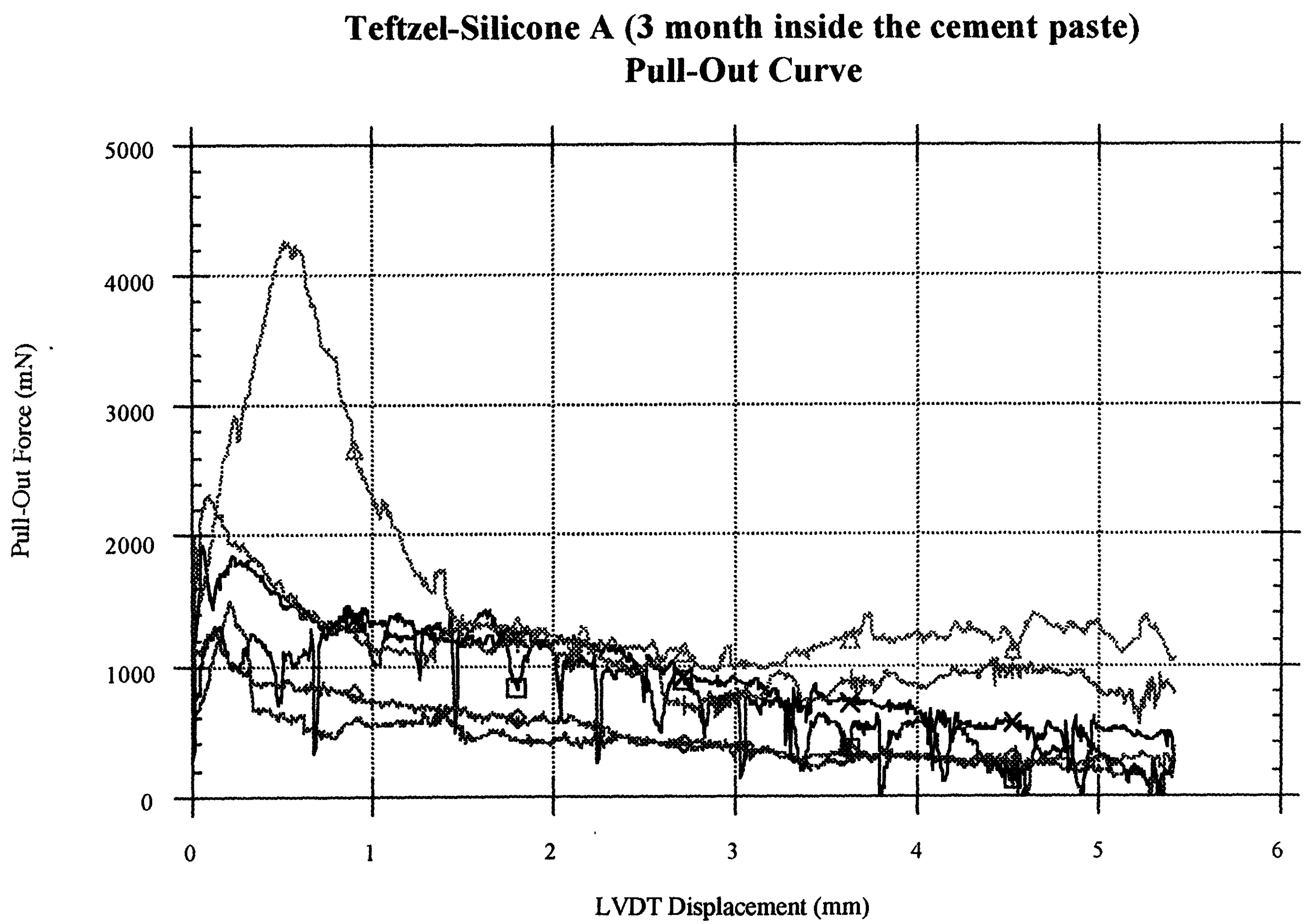


Figure 6-23: The pull-out curve of teftzel-silicone-coated optical fibers A-type (3 month inside the cement paste).

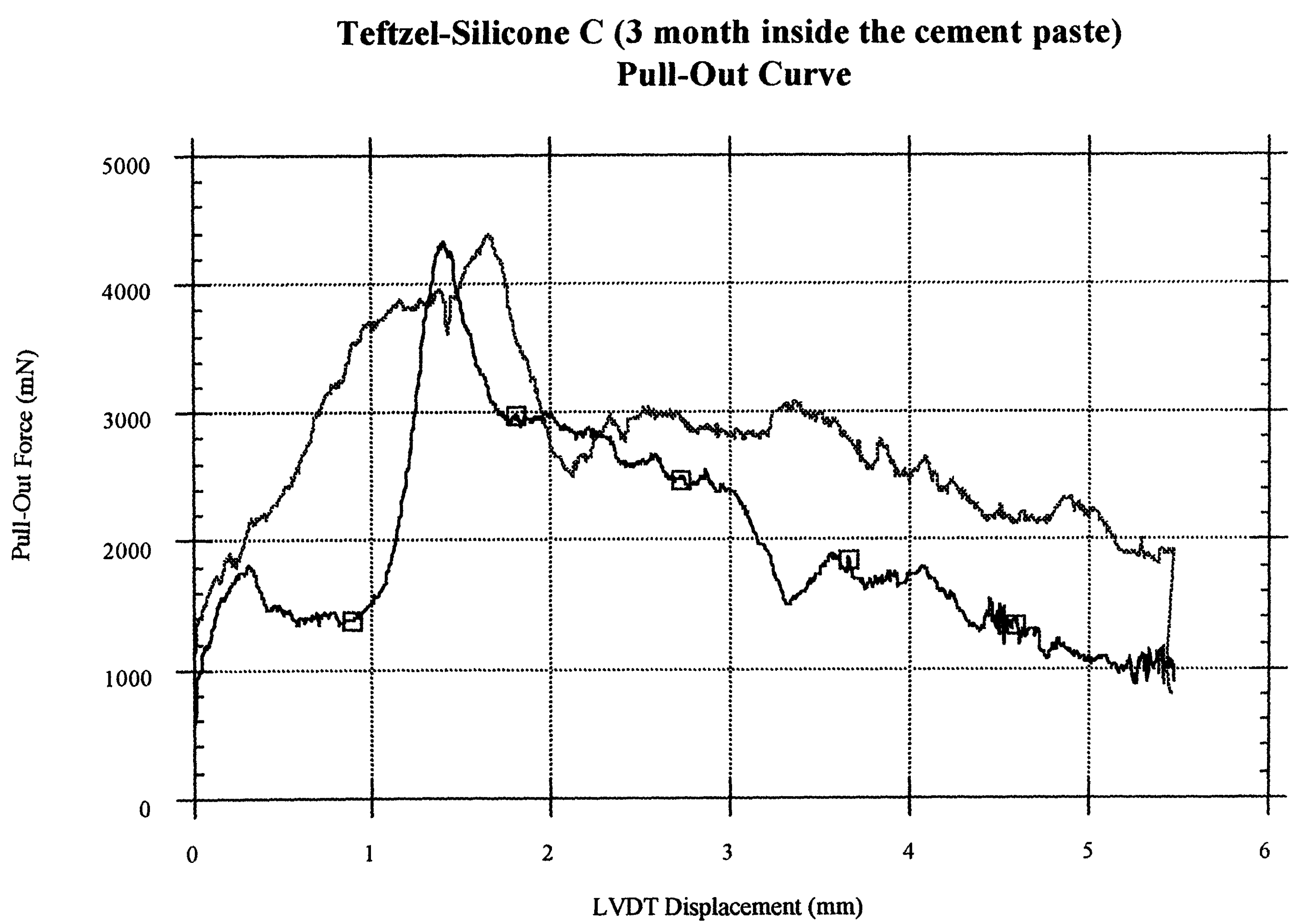


Figure 6-24: The pull-out curve of teftzel-silicone-coated optical fibers C-type (3 month inside the cement paste).

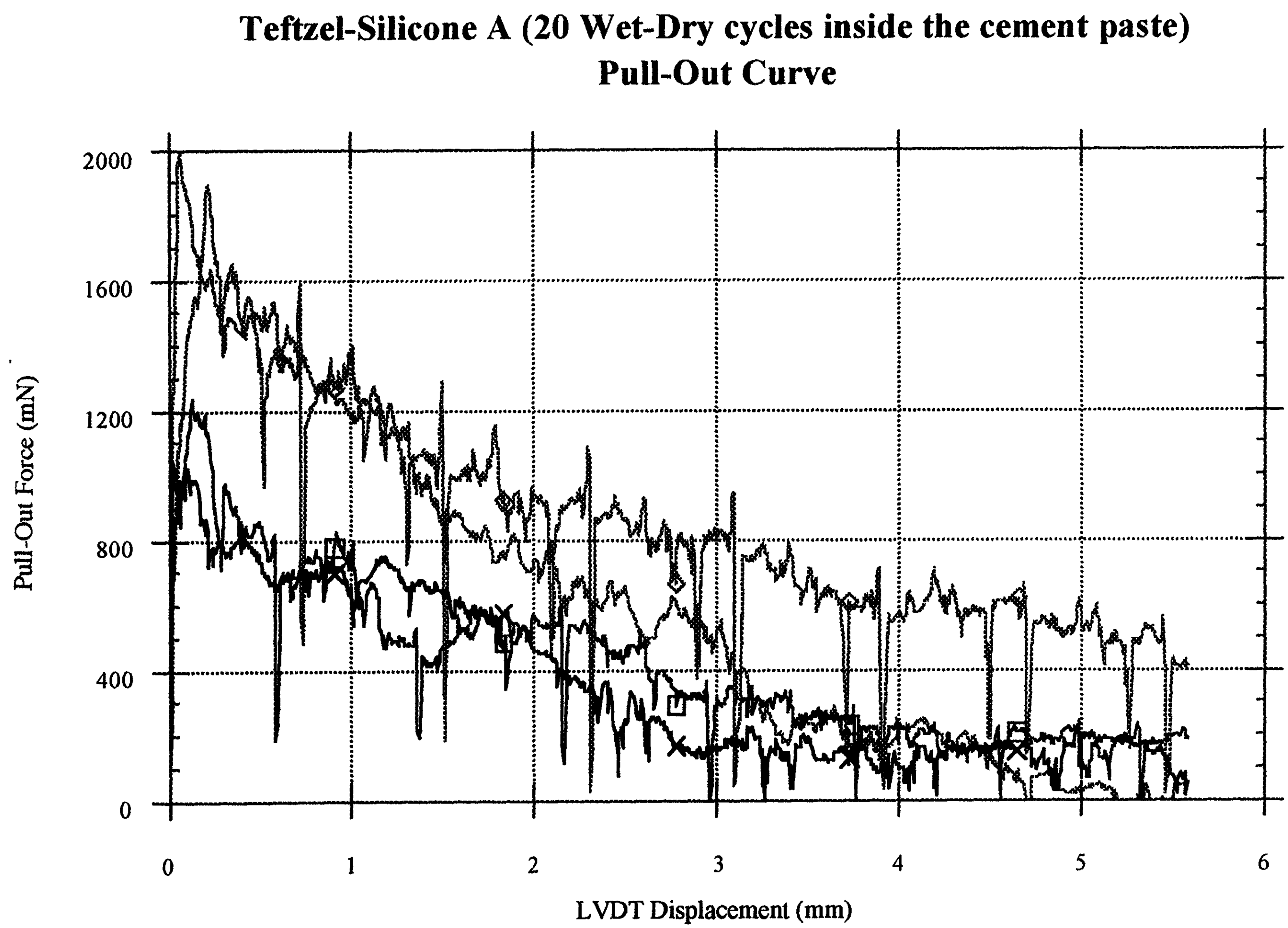


Figure 6-25: The pull-out curve of teftzel-silicone-coated optical fibers A-type (20 Wet-Dry cycles inside the cement paste).

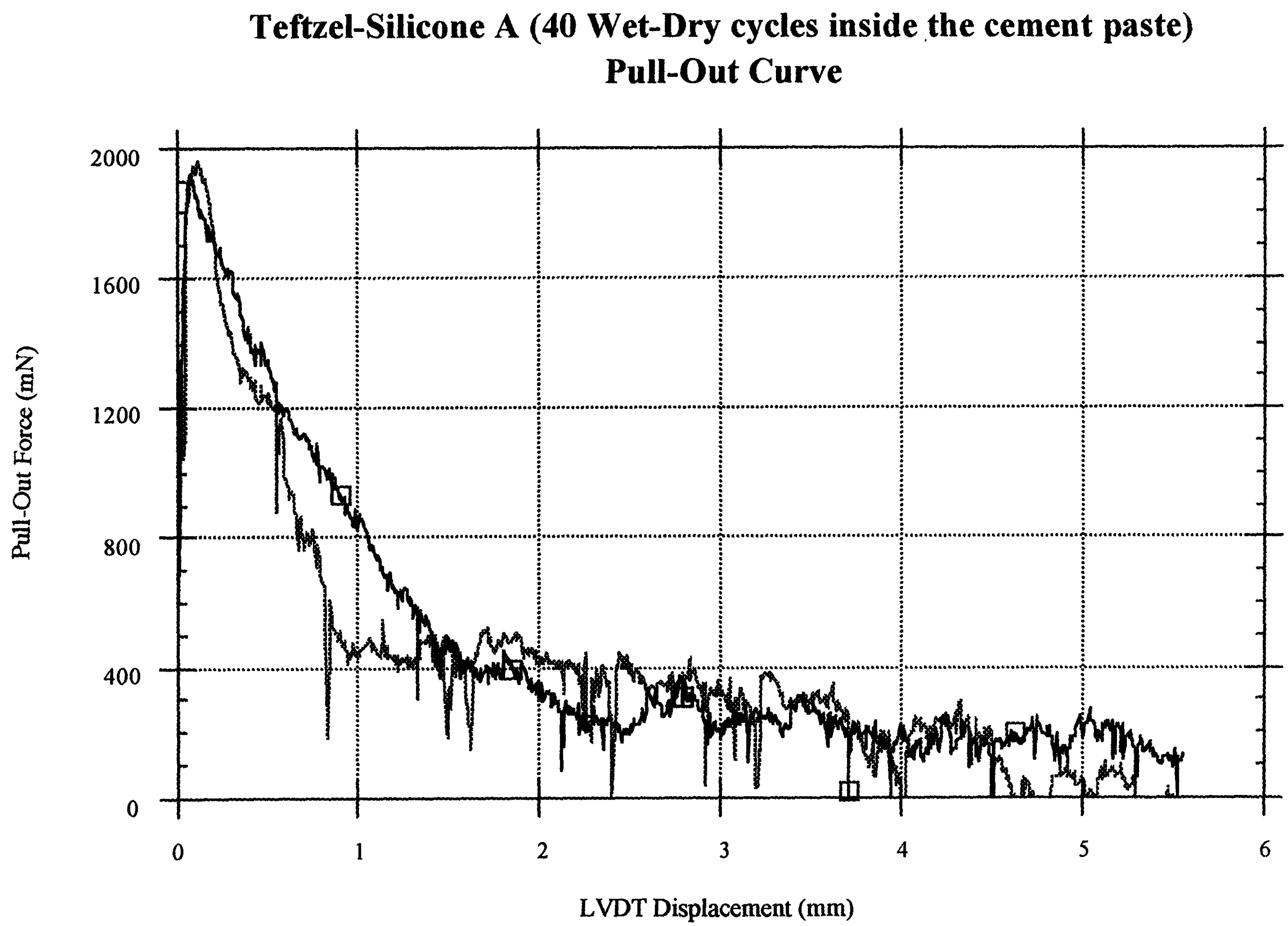


Figure 6-26: The pull-out curve of teftzel-silicone-coated optical fibers A-type (40 Wet-Dry cycles inside the cement paste).

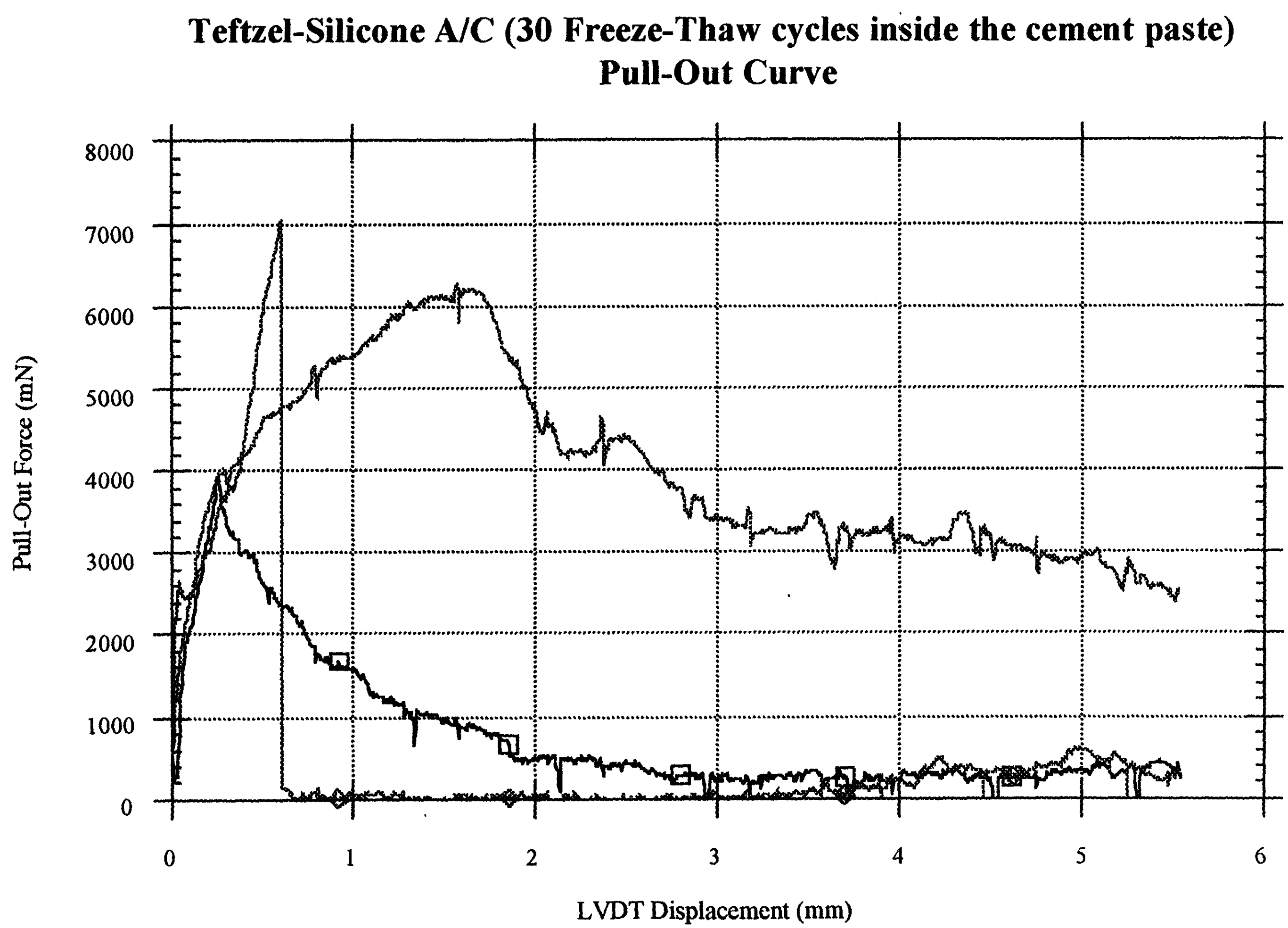


Figure 6-27: The pull-out curve of teftzel-silicone-coated optical fibers A/C-types (30 Freeze-Thaw cycles inside the cement paste).

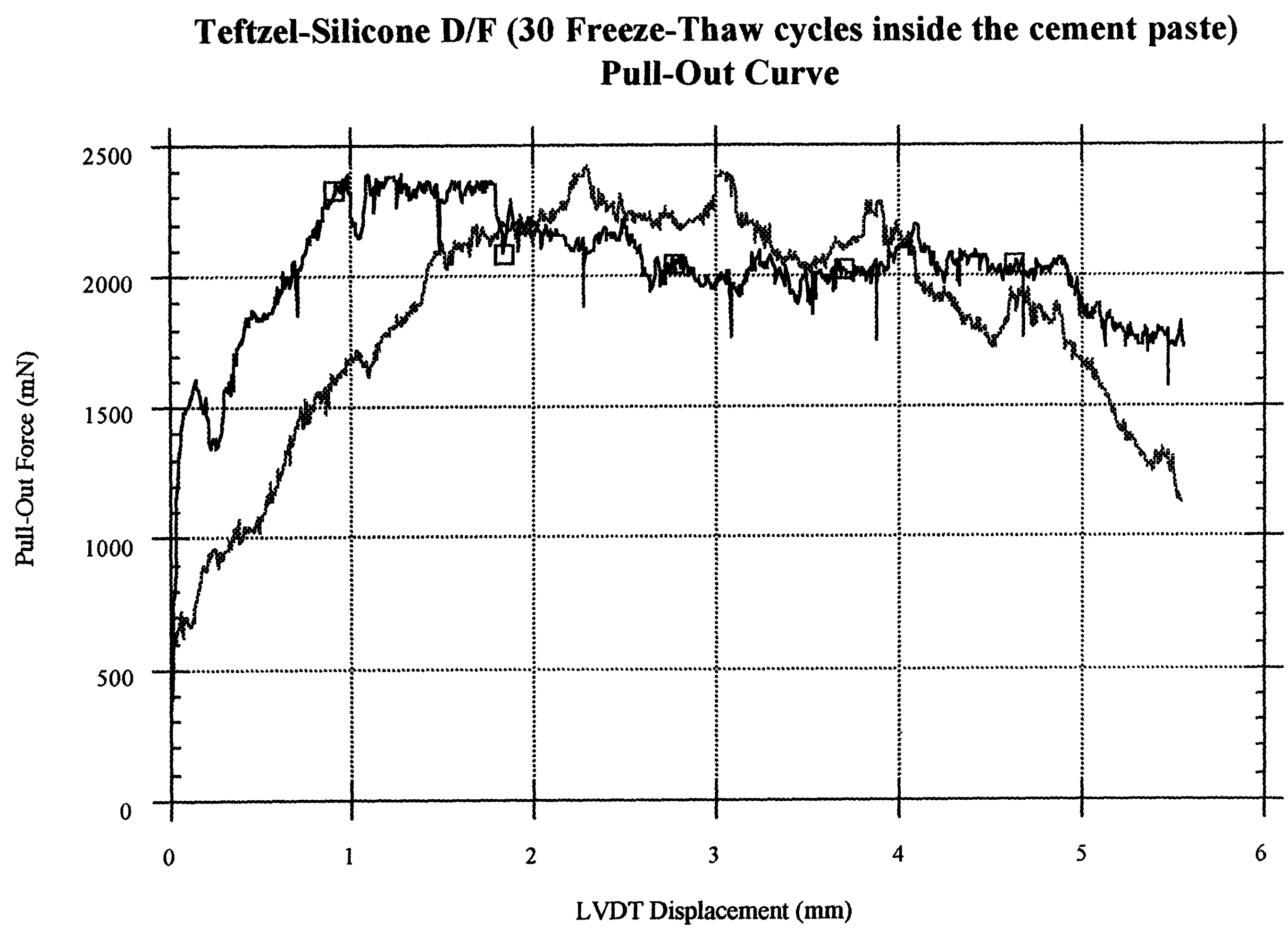


Figure 6-28: The pull-out curve of teftzel-silicone-coated optical fibers D/F-types (30 Freeze-Thaw cycles inside the cement paste).

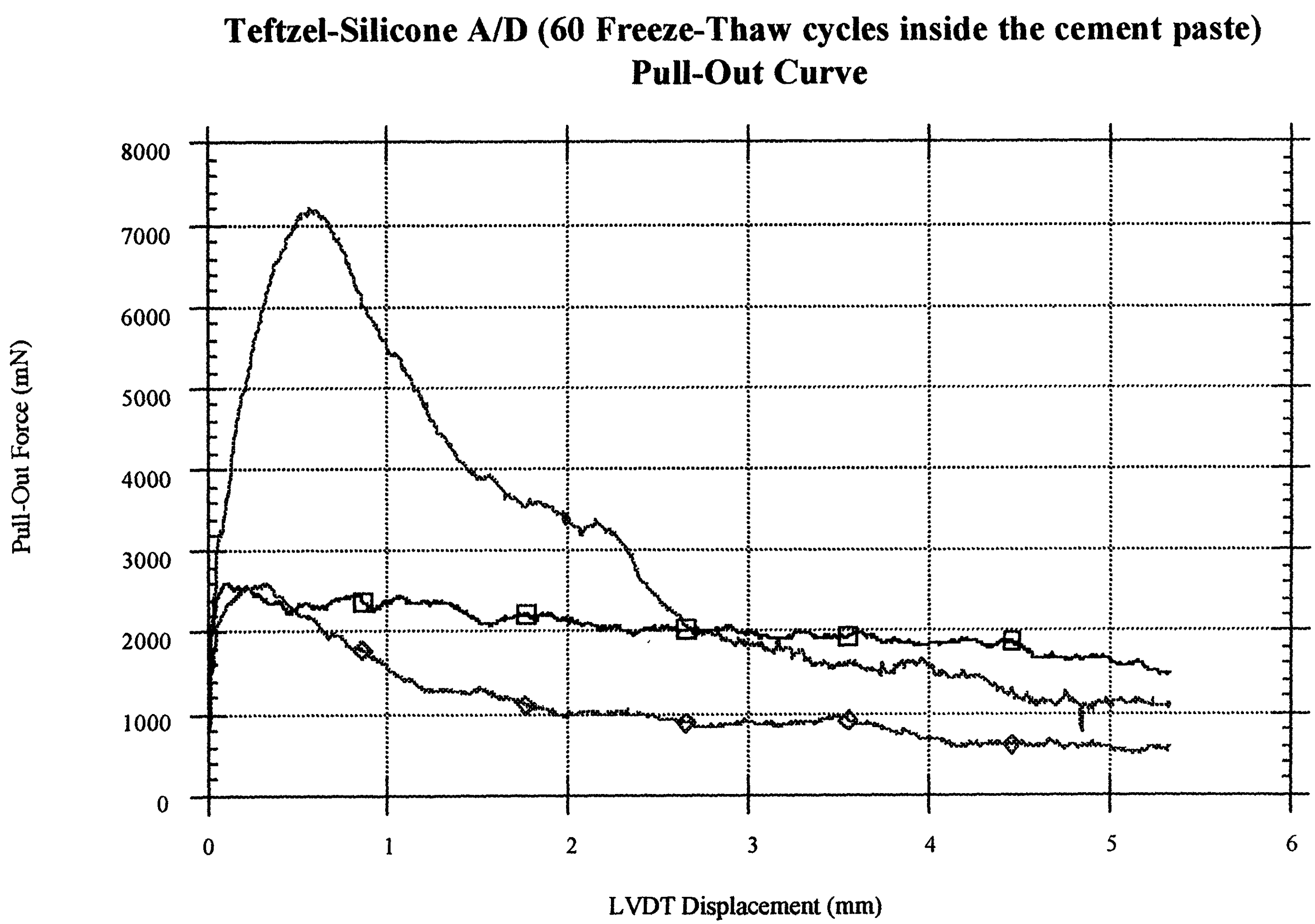


Figure 6-29: The pull-out curve of teftzel-silicone-coated optical fibers A/D-types (60 Freeze-Thaw cycles inside the cement paste).

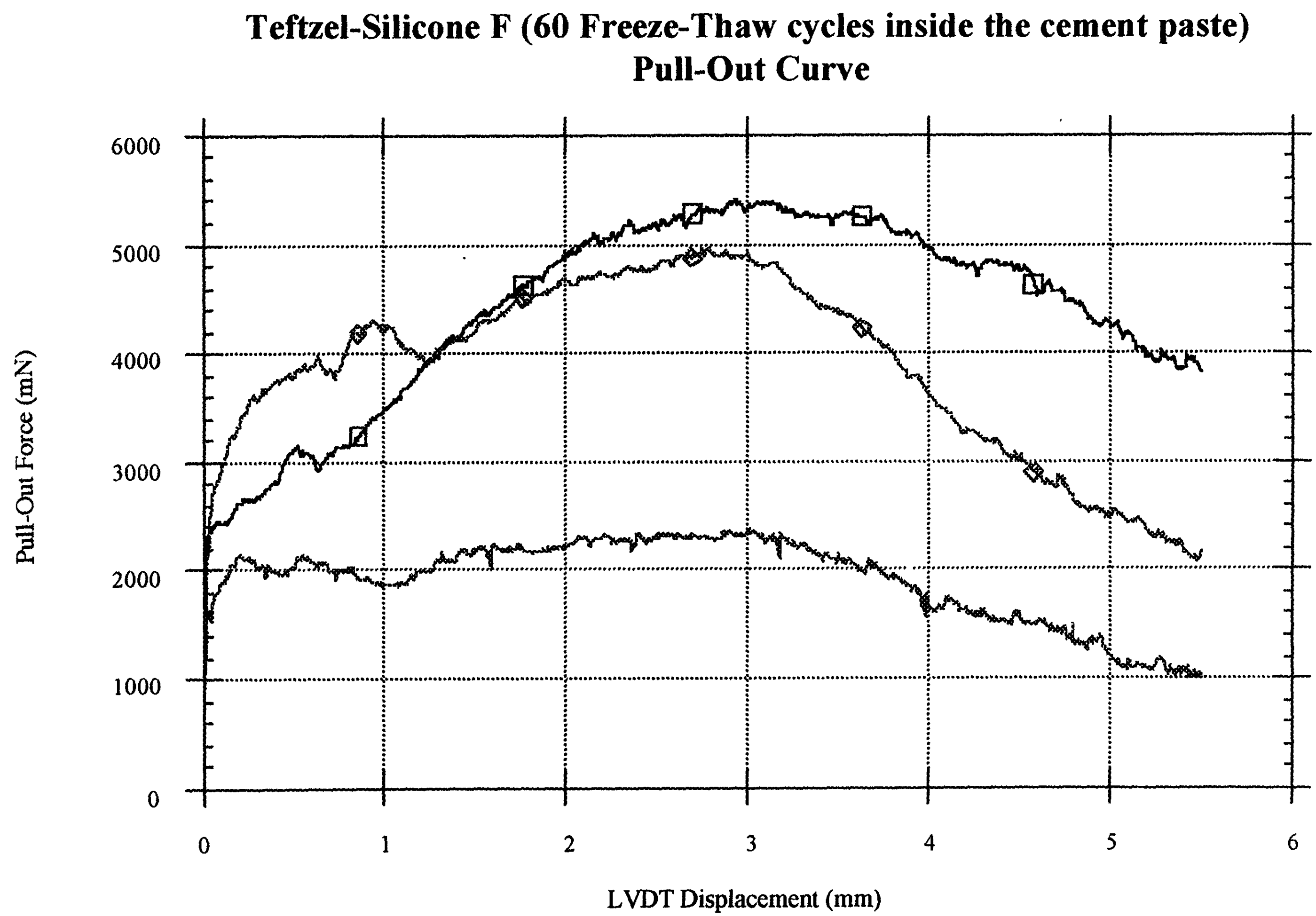


Figure 6-30: The pull-out curve of teftzel-silicone-coated optical fibers F-type (60 Freeze-Thaw cycles inside the cement paste).

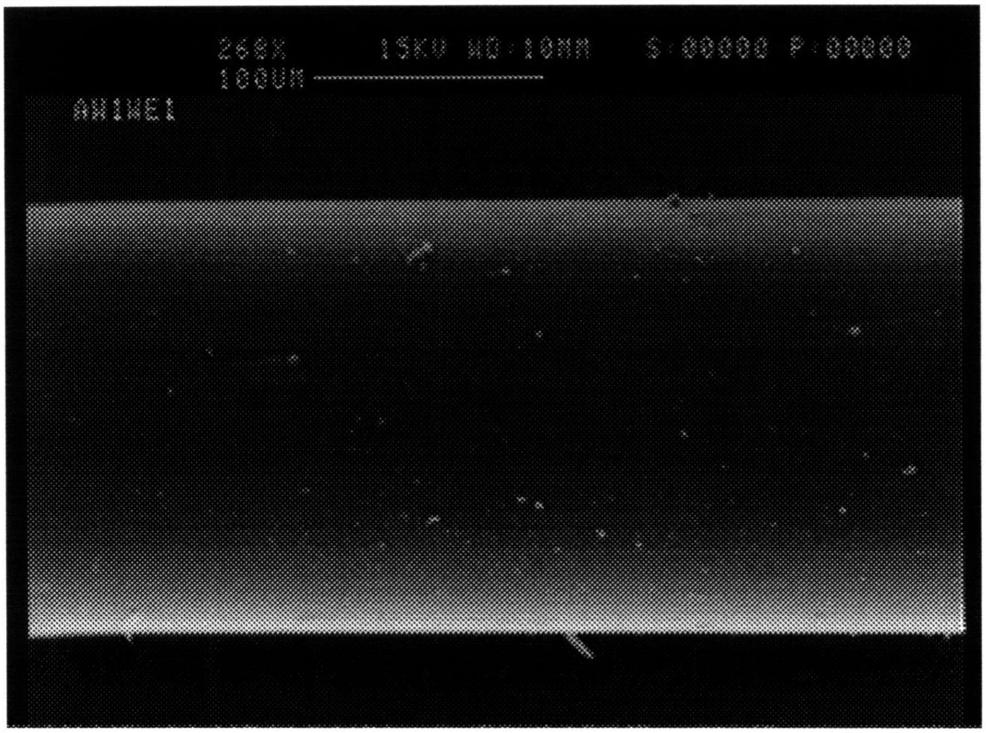


Figure 6-31: The Acrylate-coated optical-fiber inside the water tank for one week-period (268 X).

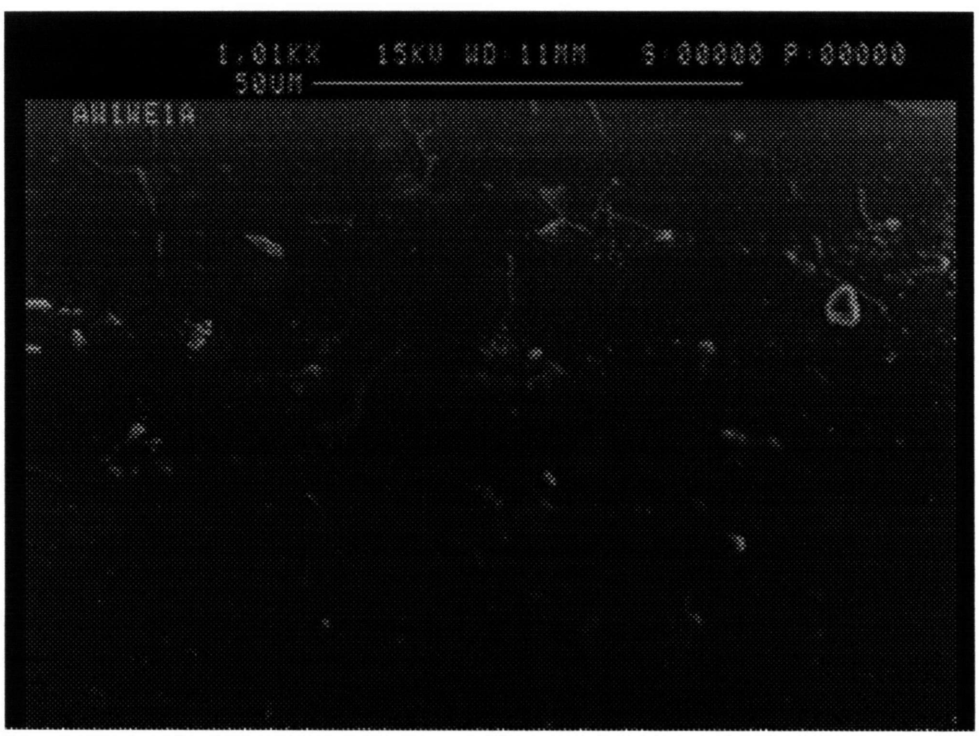


Figure 6-32: The Acrylate-coated optical-fiber inside the water tank for one week-period (1010 X).

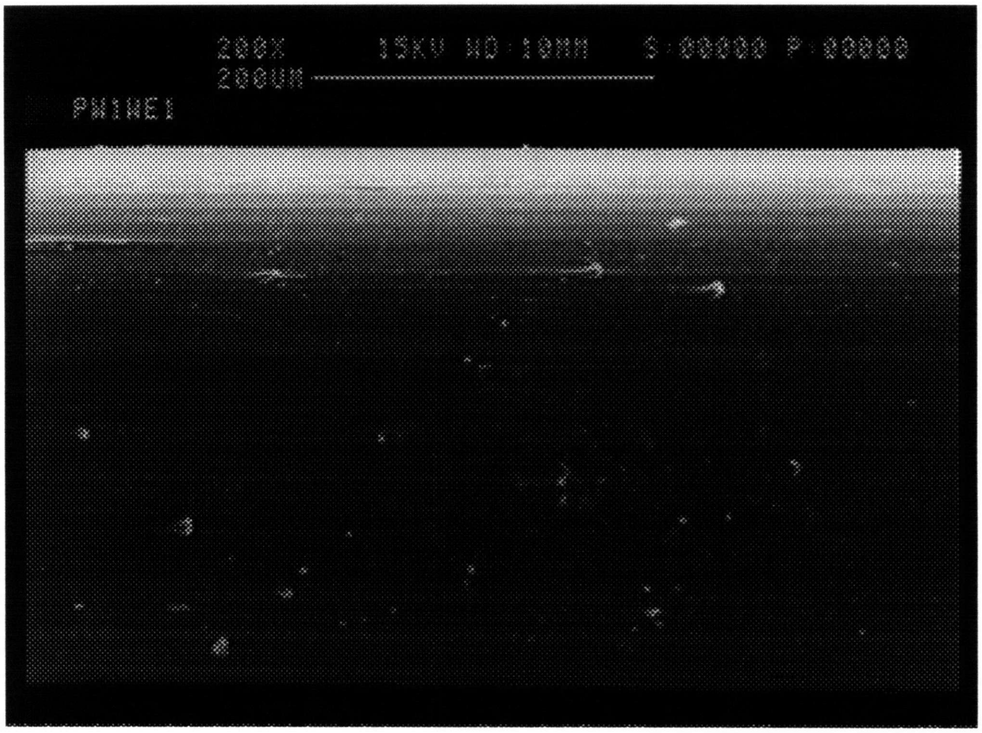


Figure 6-33: The Polyimide-coated optical-fiber inside the water tank for one week-period (200 X).

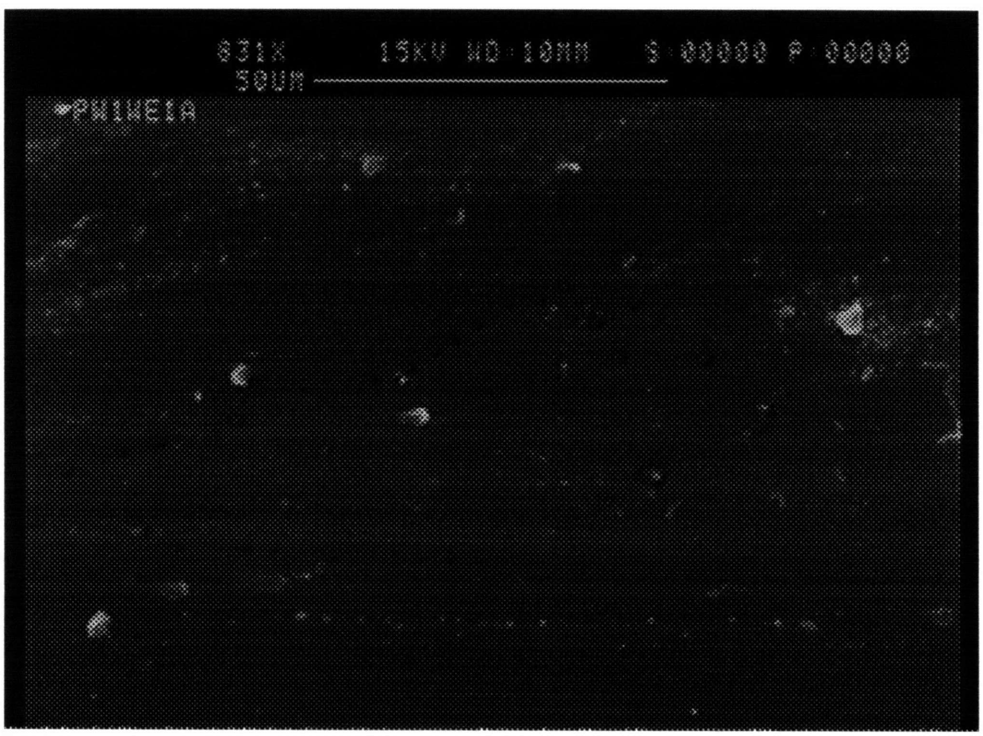


Figure 6-34: The Polyimide-coated optical-fiber inside the water tank for one week-period (831 X).

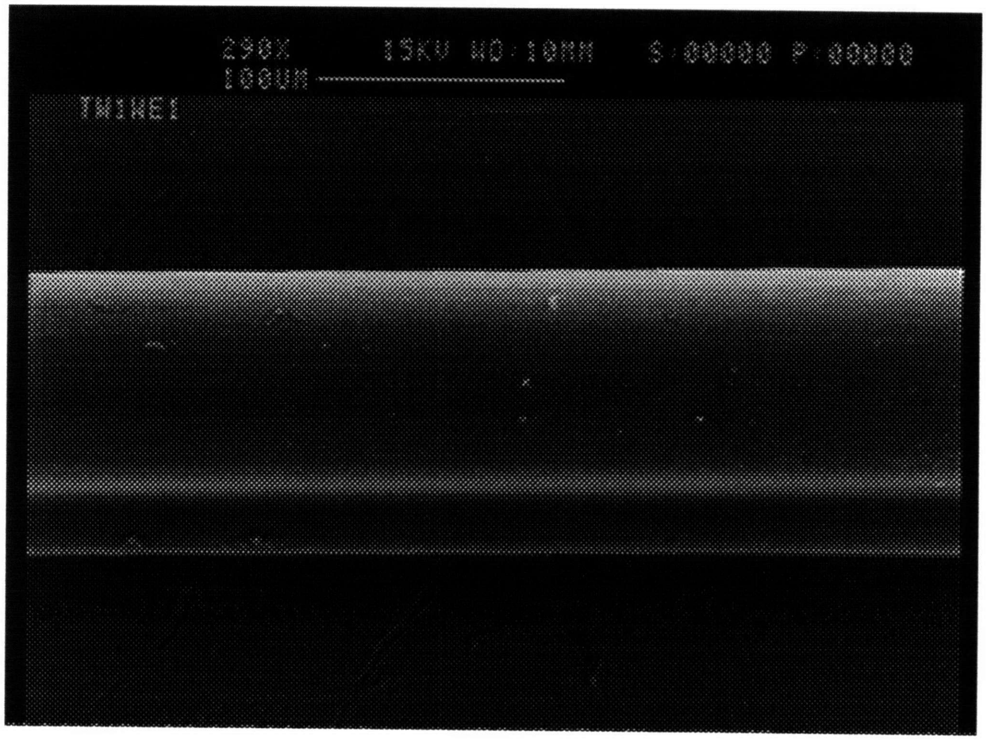


Figure 6-35: The Teftzel-Silicone-coated optical-fiber inside the water tank for one week-period (290 X).

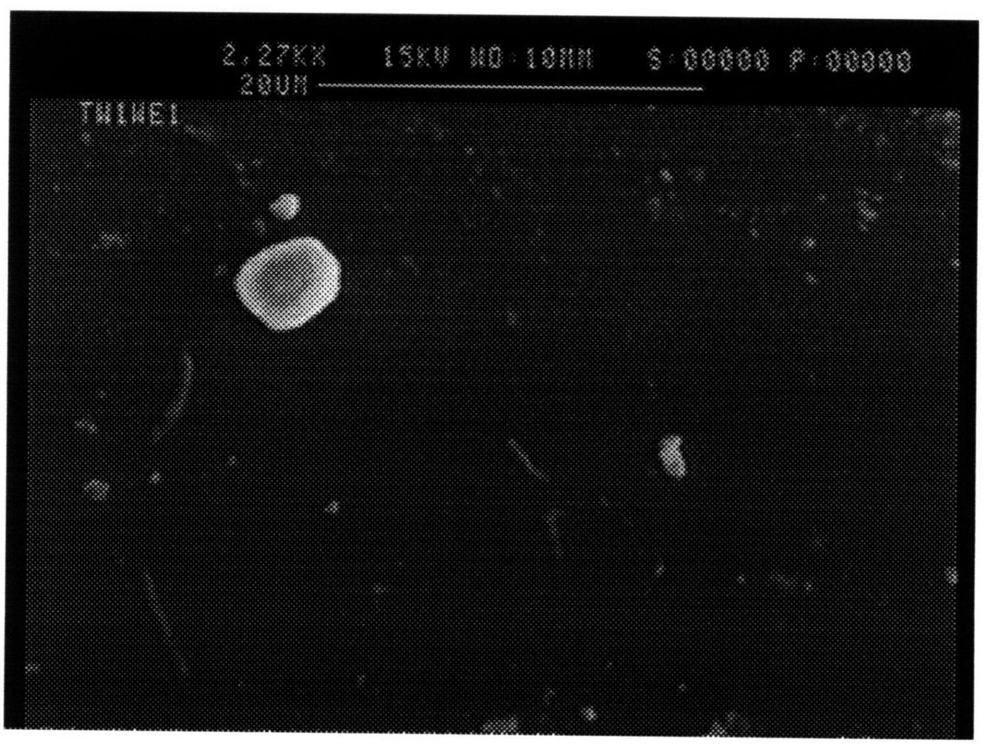


Figure 6-36: The Teftzel-Silicone-coated optical-fiber inside the water tank for one week-period (2,270 X).

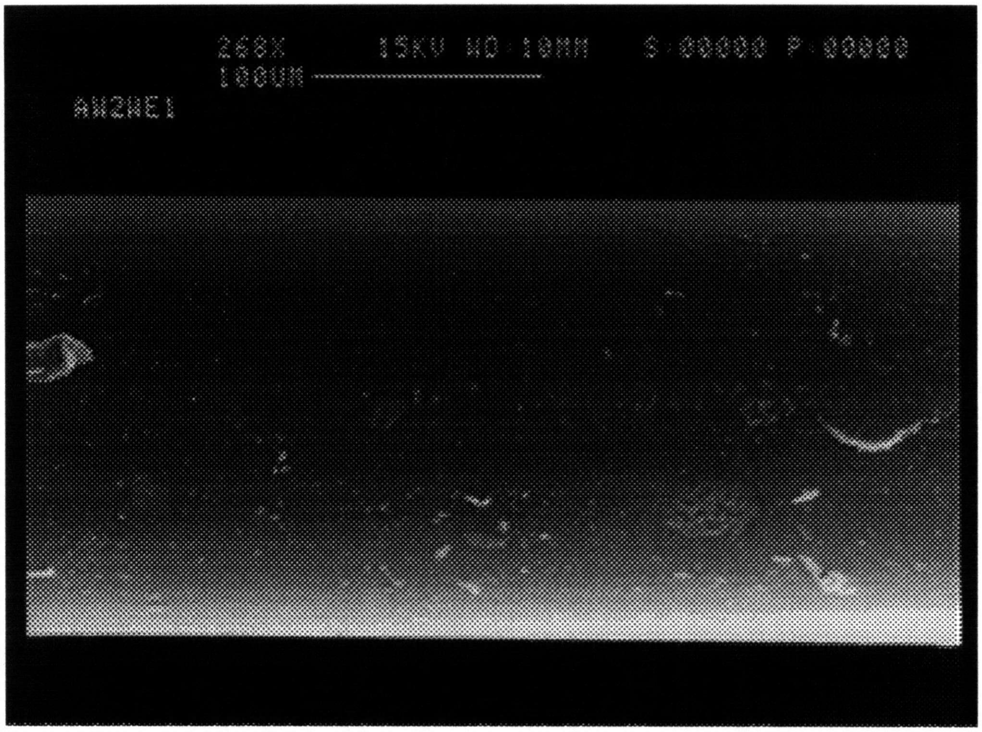


Figure 6-37: The Acrylate-coated optical-fiber inside the water tank for two week-period (268 X).

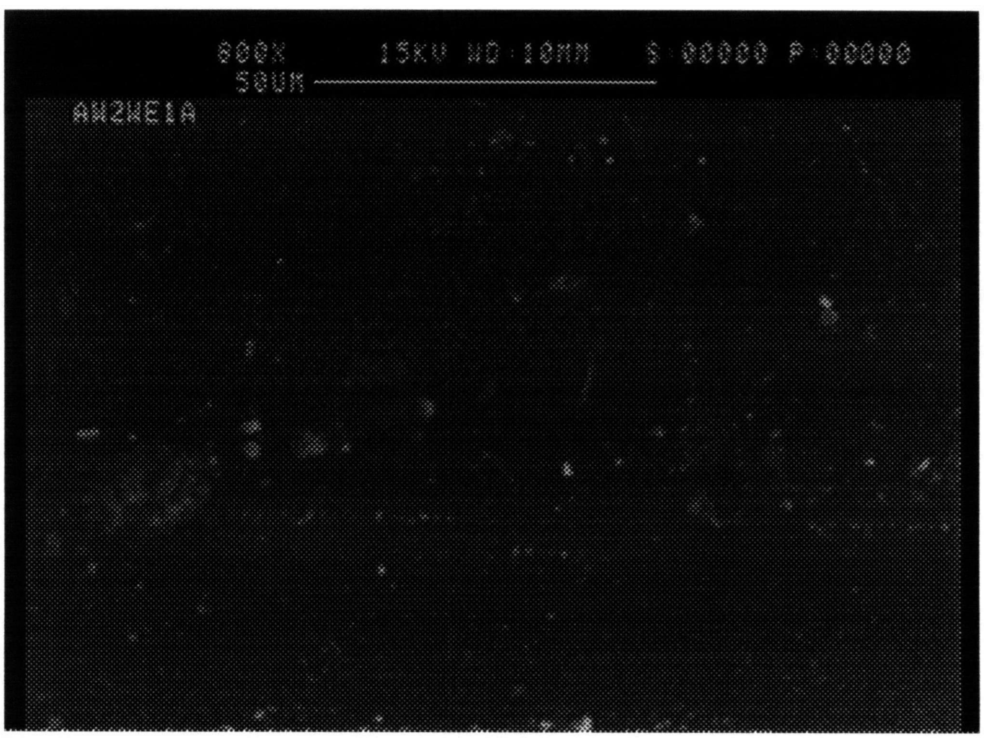


Figure 6-38: The Acrylate-coated optical-fiber inside the water tank for two week-period (800 X).

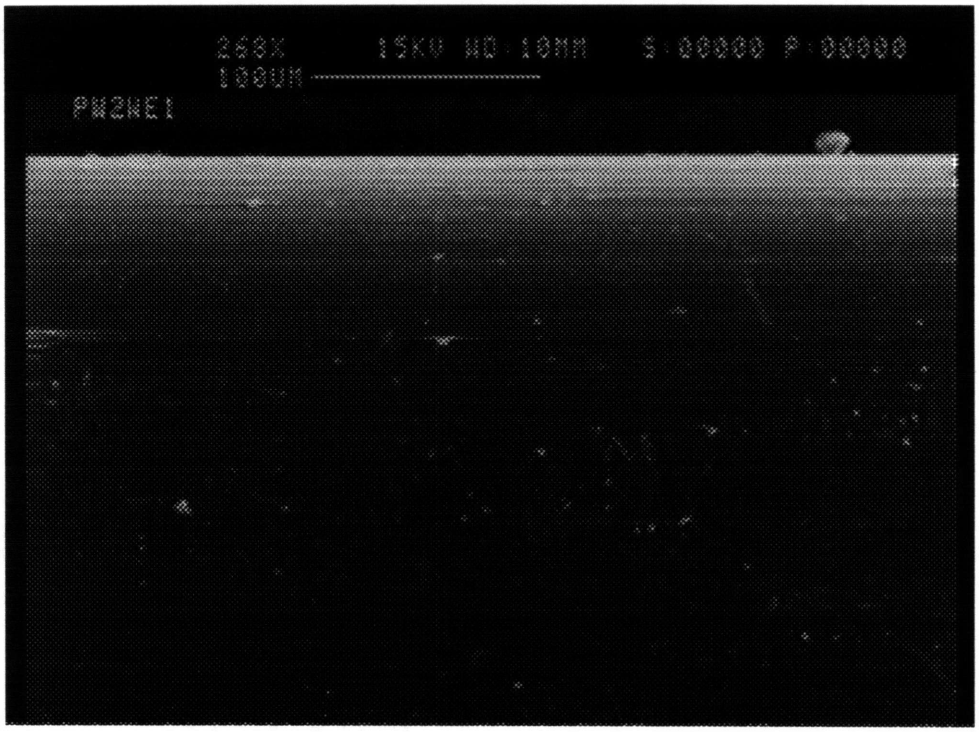


Figure 6-39: The Polyimide-coated optical-fiber inside the water tank for two week-period (268 X).

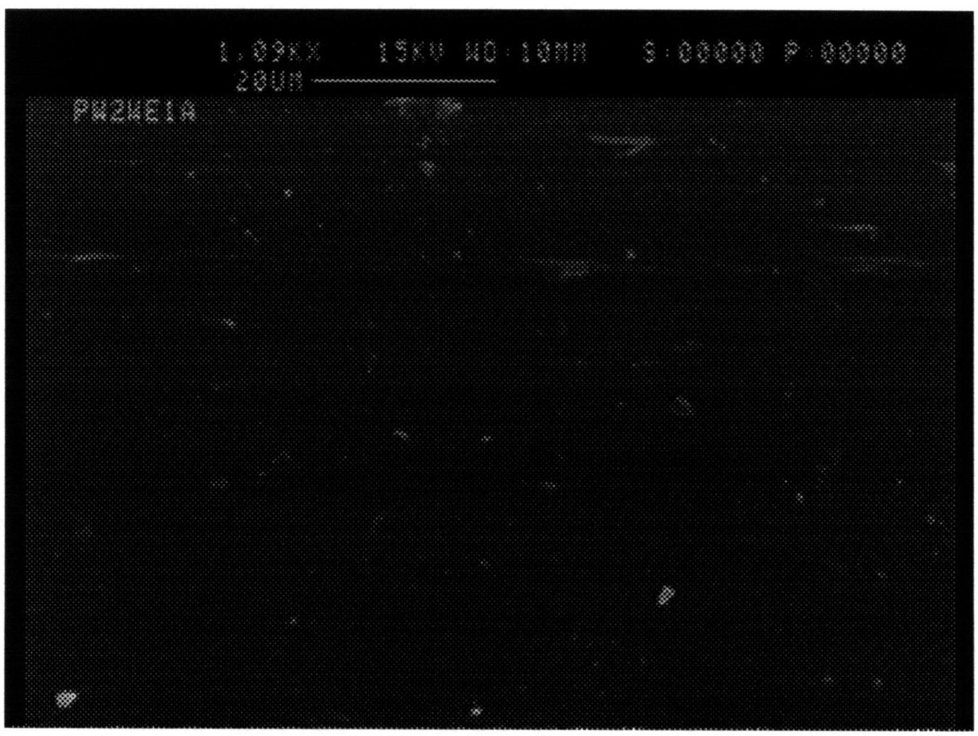


Figure 6-40: The Polyimide-coated optical-fiber inside the water tank for two week-period (1,090 X).

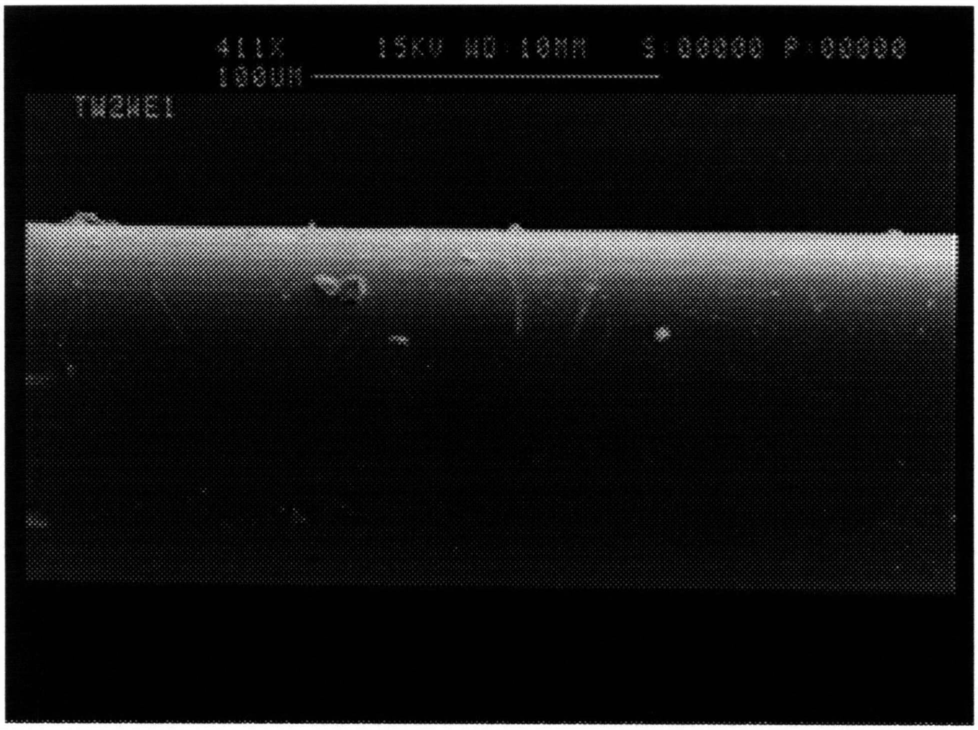


Figure 6-41: The Teftzel-Silicone-coated optical-fiber inside the water tank for two week-period (411 X).

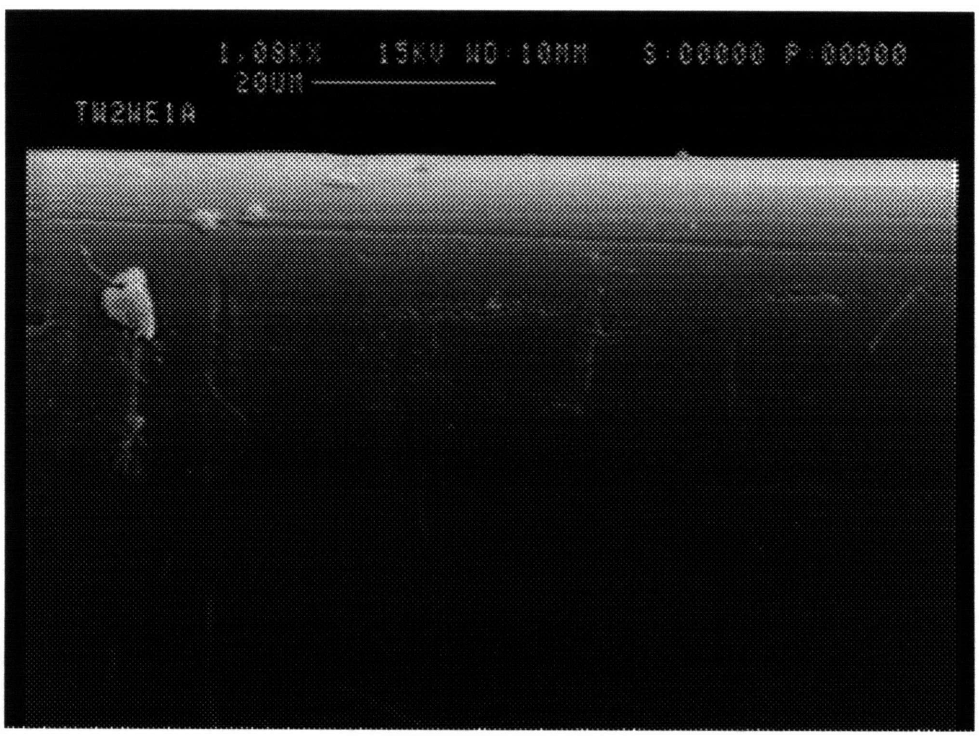


Figure 6-42: The Teftzel-Silicone-coated optical-fiber inside the water tank for two week-period (1,080 X).

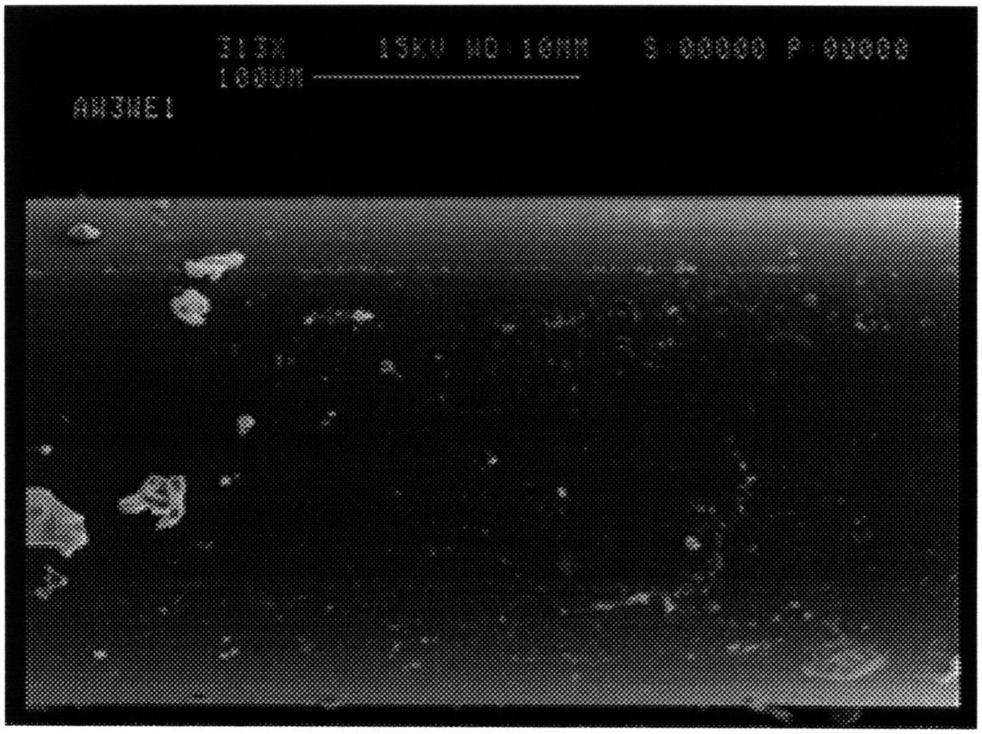


Figure 6-43: The Acrylate-coated optical-fiber inside the water tank for three week-period (313 X).

Figure 6-44: The Acrylate-coated optical-fiber inside the water tank for three week-period (1,310 X).

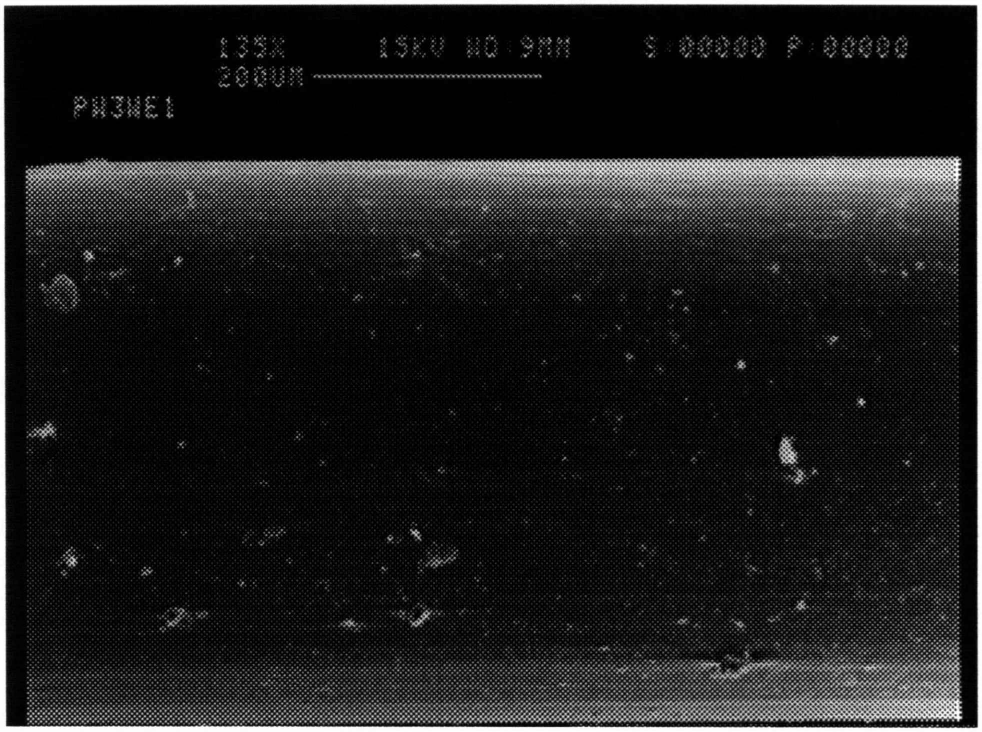


Figure 6-45: The Polyimide-coated optical-fiber inside the water tank for three week-period (135 X).

Figure 6-46: The Polyimide-coated optical-fiber inside the water tank for three week-period (1,160 X).

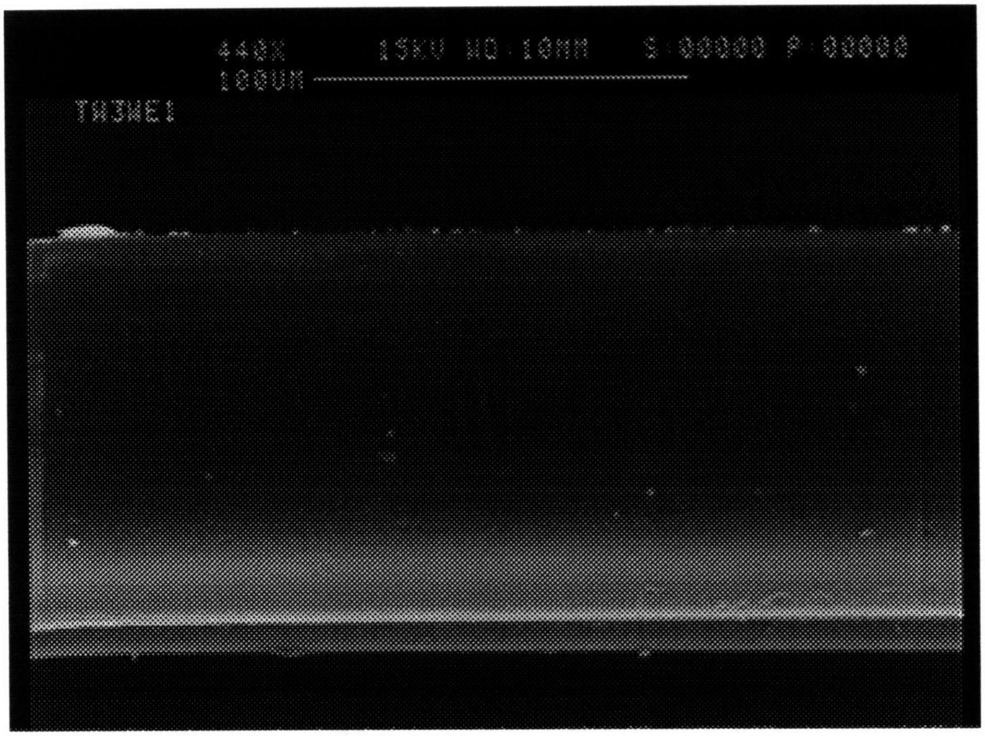


Figure 6-47: The Teftzel-Silicone-coated optical-fiber inside the water tank for three week-period (440 X).

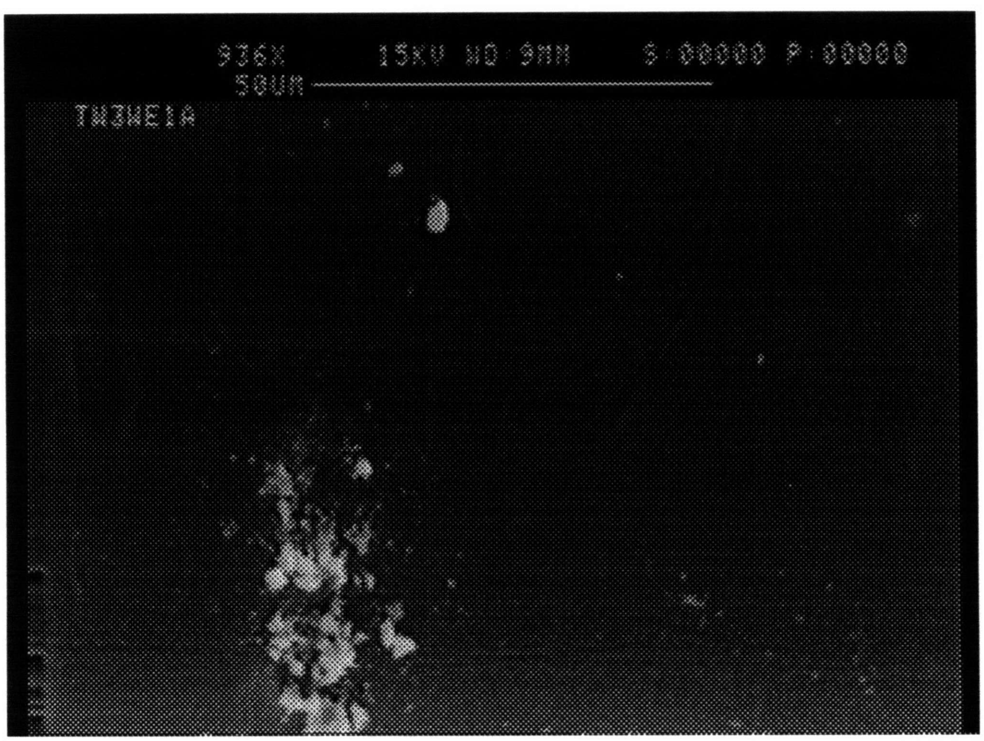


Figure 6-48: The Teftzel-Silicone-coated optical-fiber inside the water tank for three week-period (936 X).

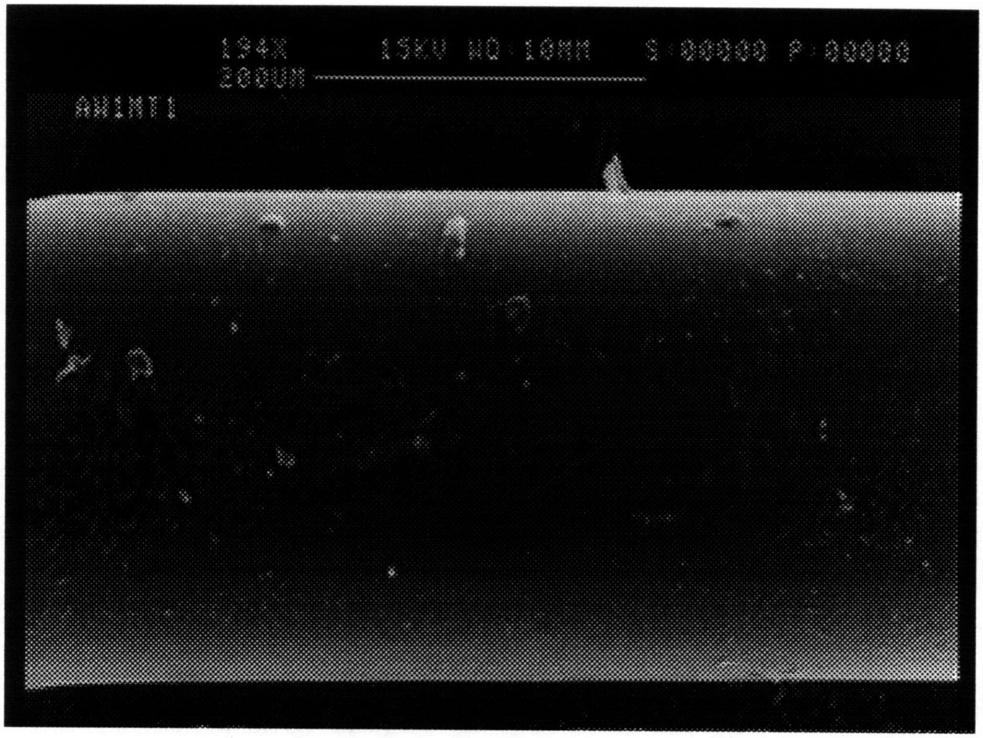


Figure 6-49: The Acrylate-coated optical-fiber inside the water tank for one month-period (194 X).

Figure 6-50: The Acrylate-coated optical-fiber inside the water tank for one month-period (1,110 X).

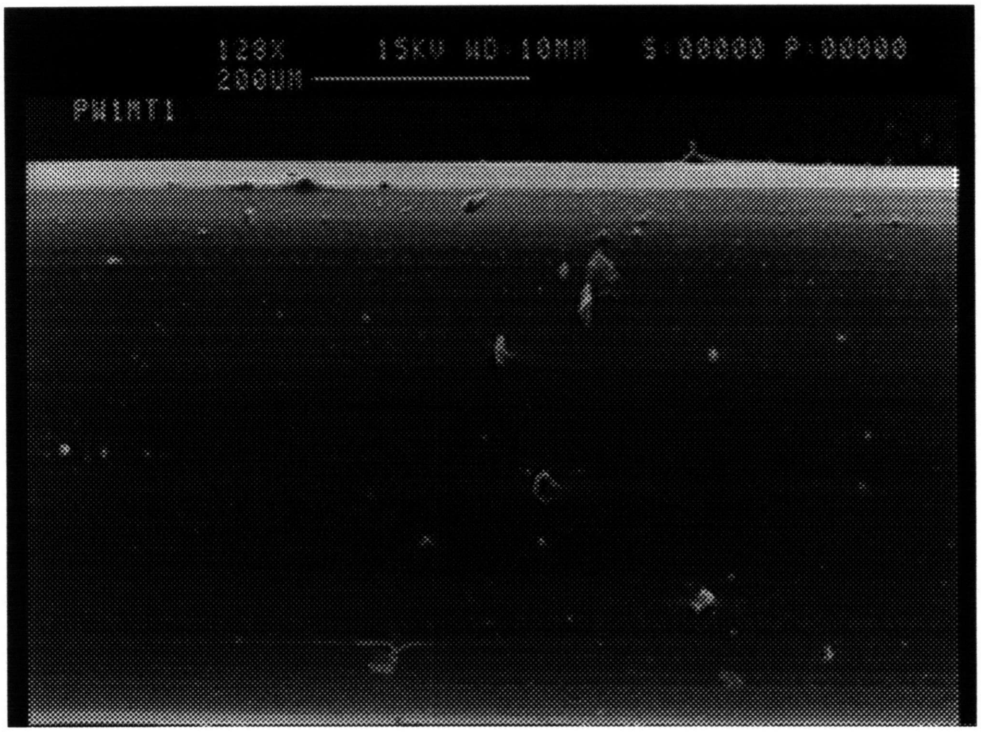


Figure 6-51: The Polyimide-coated optical-fiber inside the water tank for one month-period (128 X).

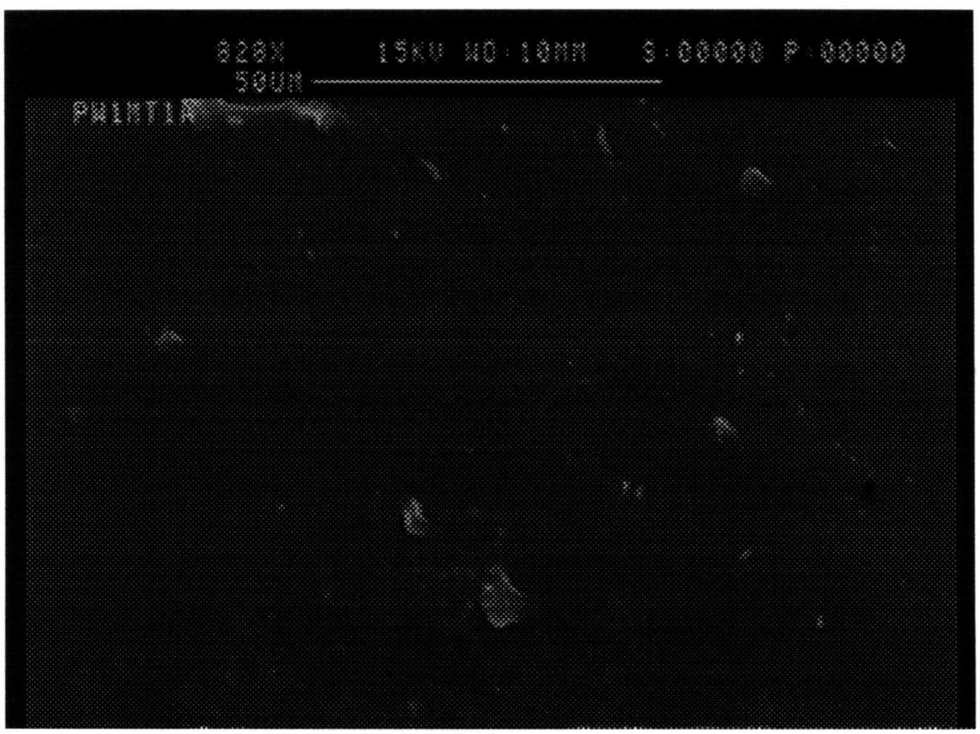


Figure 6-52: The Polyimide-coated optical-fiber inside the water tank for one month-period (828 X).

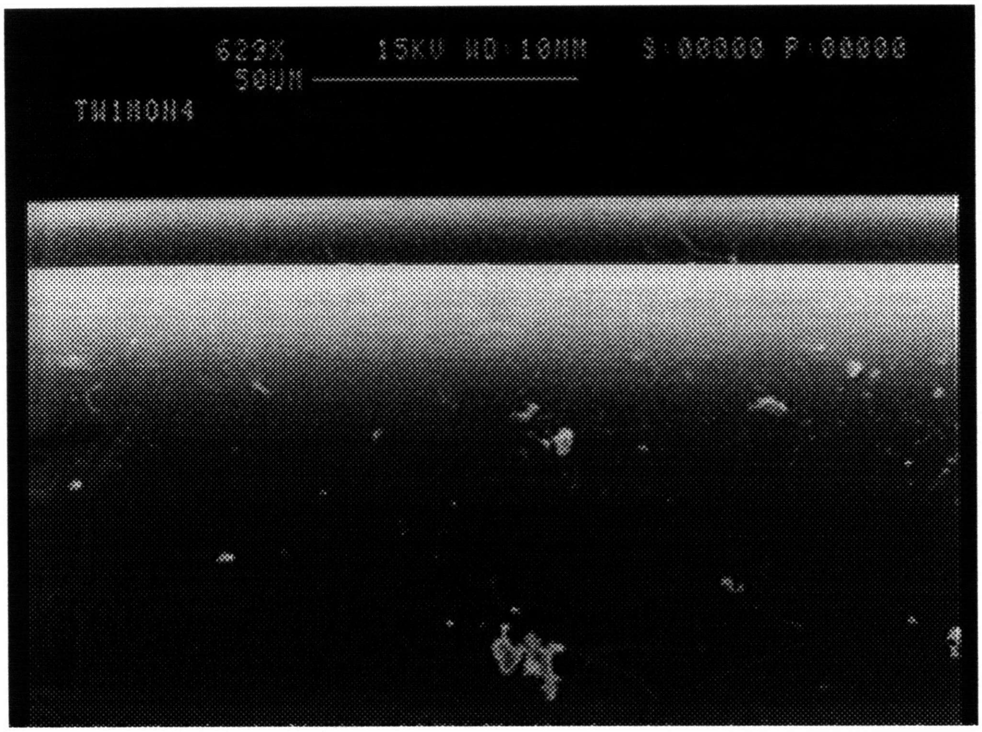


Figure 6-53: The Teftzel-Silicone-coated optical-fiber inside the water tank for one month-period (629 X).

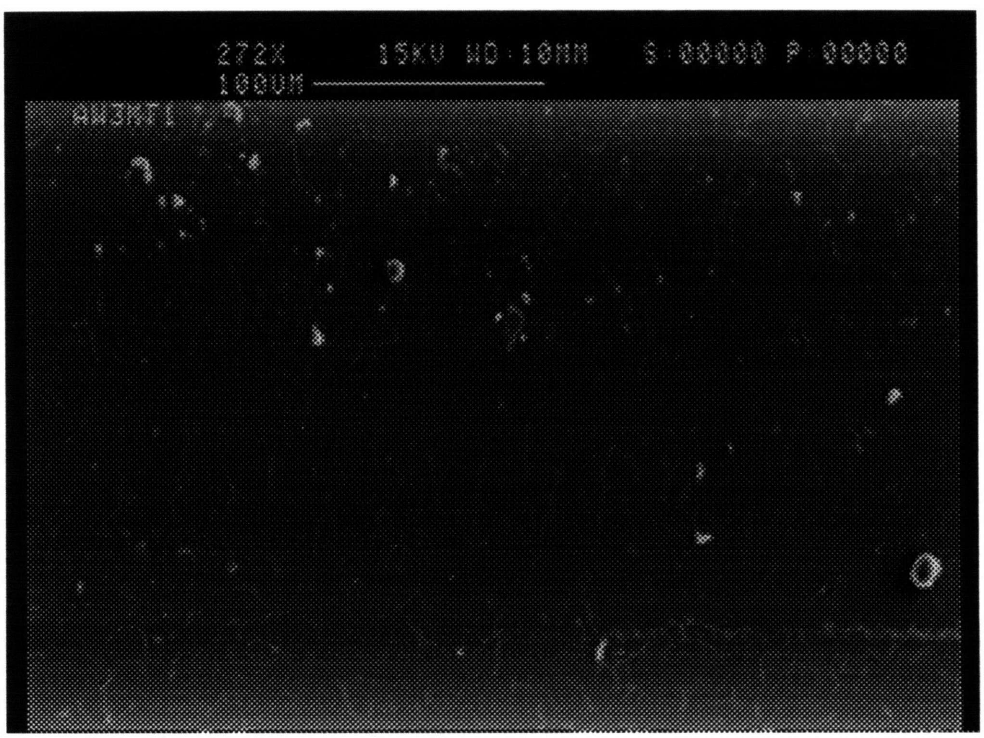


Figure 6-54: The Acrylate-coated optical-fiber inside the water tank for three month-period (272 X).

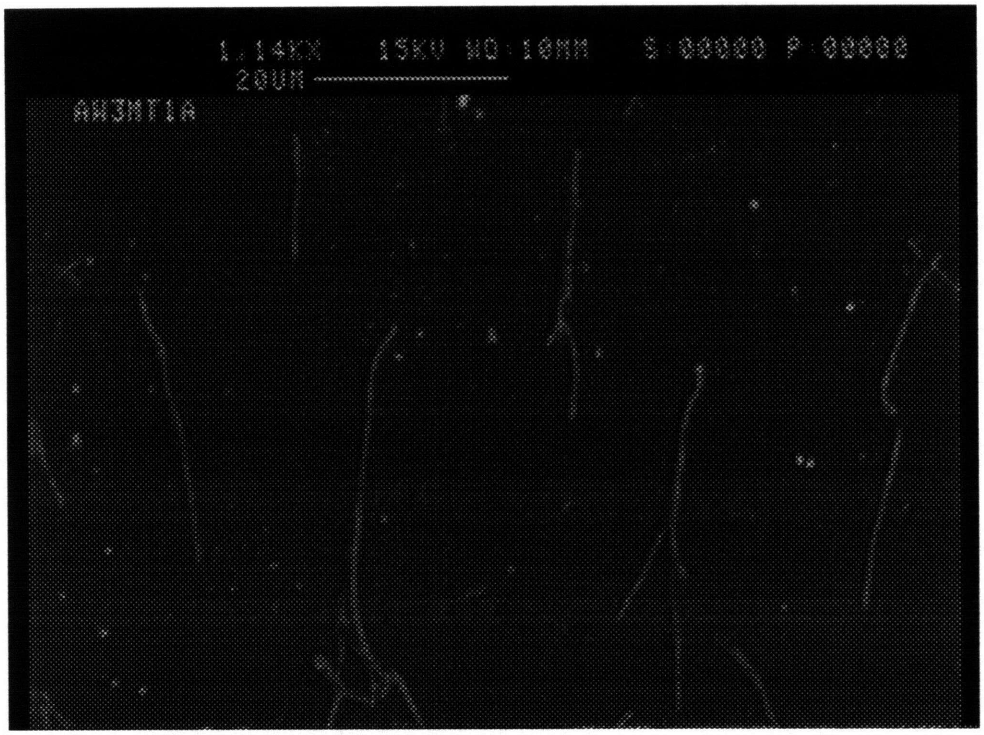


Figure 6-55: The Acrylate-coated optical-fiber inside the water tank for three month-period (1,140 X).

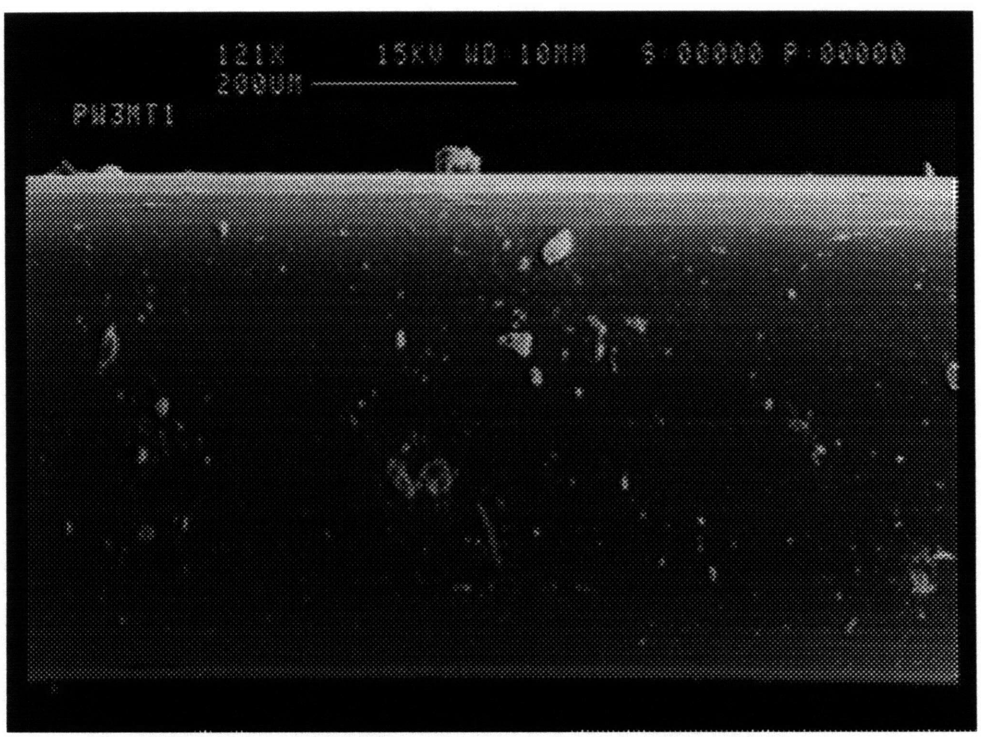


Figure 6-56: The Polyimide-coated optical-fiber inside the water tank for three month-period (121 X).

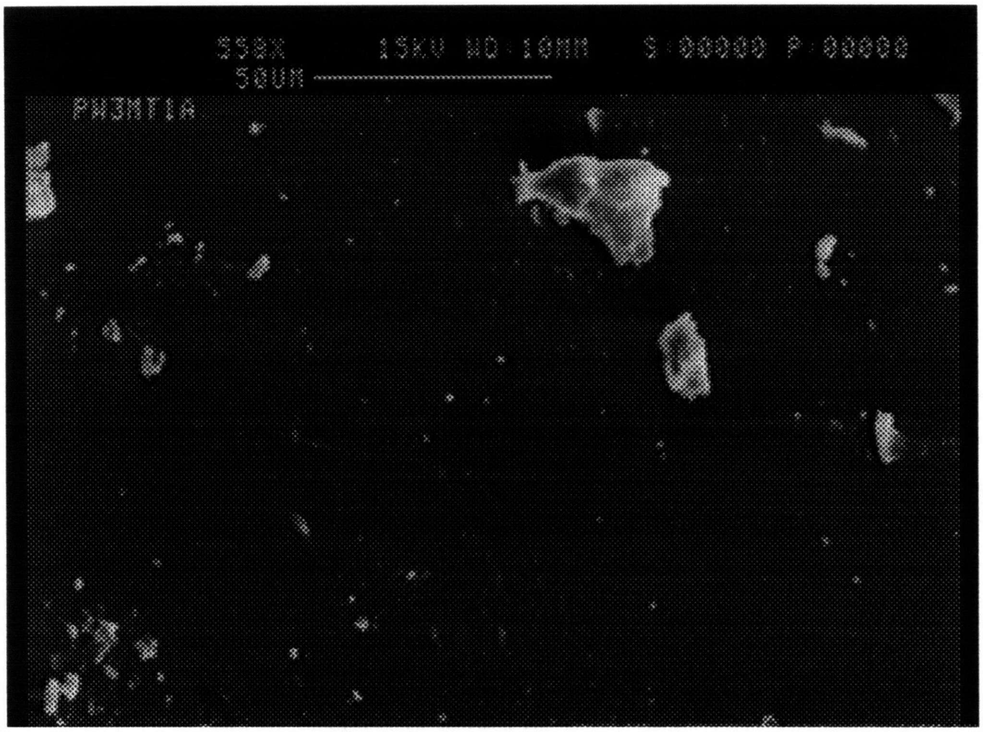


Figure 6-57: The Polyimide-coated optical-fiber inside the water tank for three month-period (558 X).

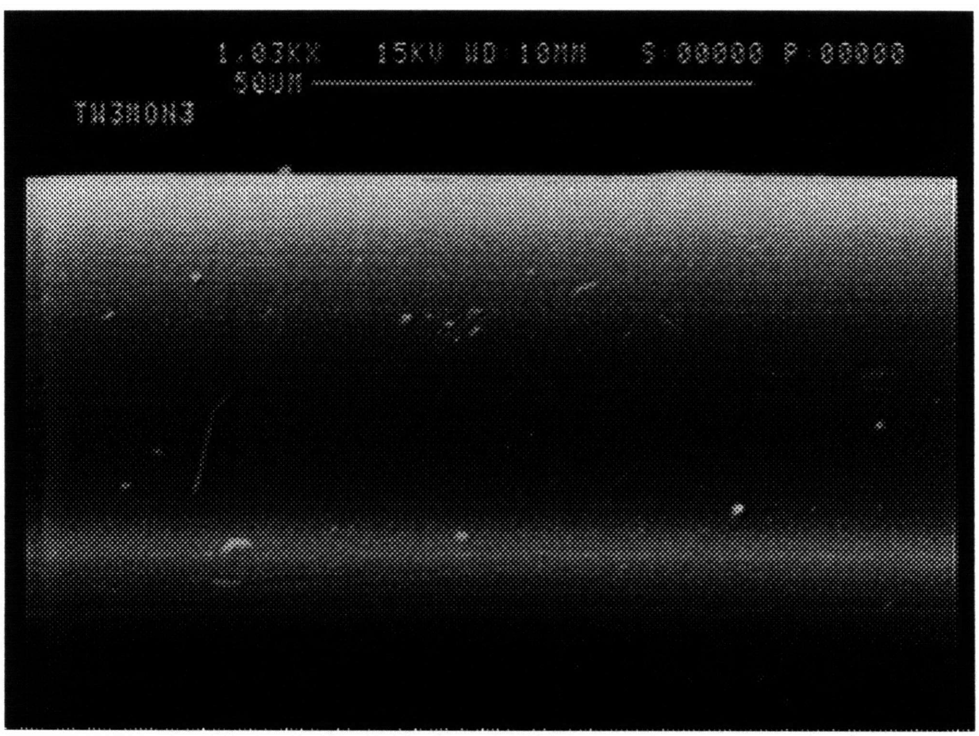


Figure 6-58:The Teftzel-Silicone-coated optical-fiber inside the water tank for three month-period (1030 X).

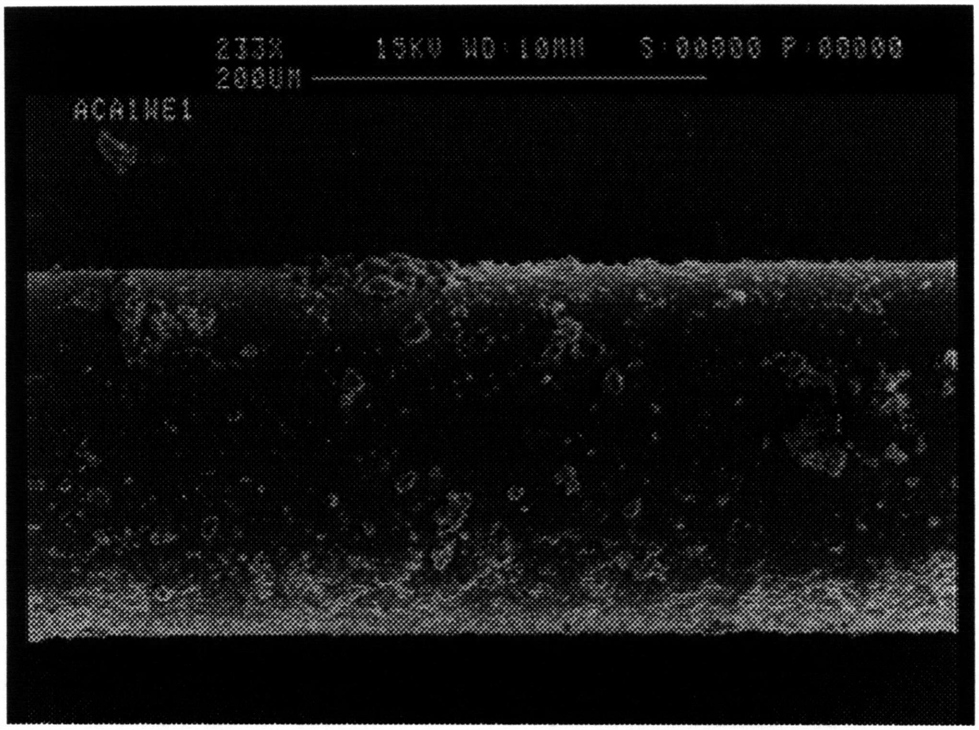


Figure 6-59: The Acrylate-coated optical-fiber in the $Ca(OH)_2$ solution for one-week-period (233 X).

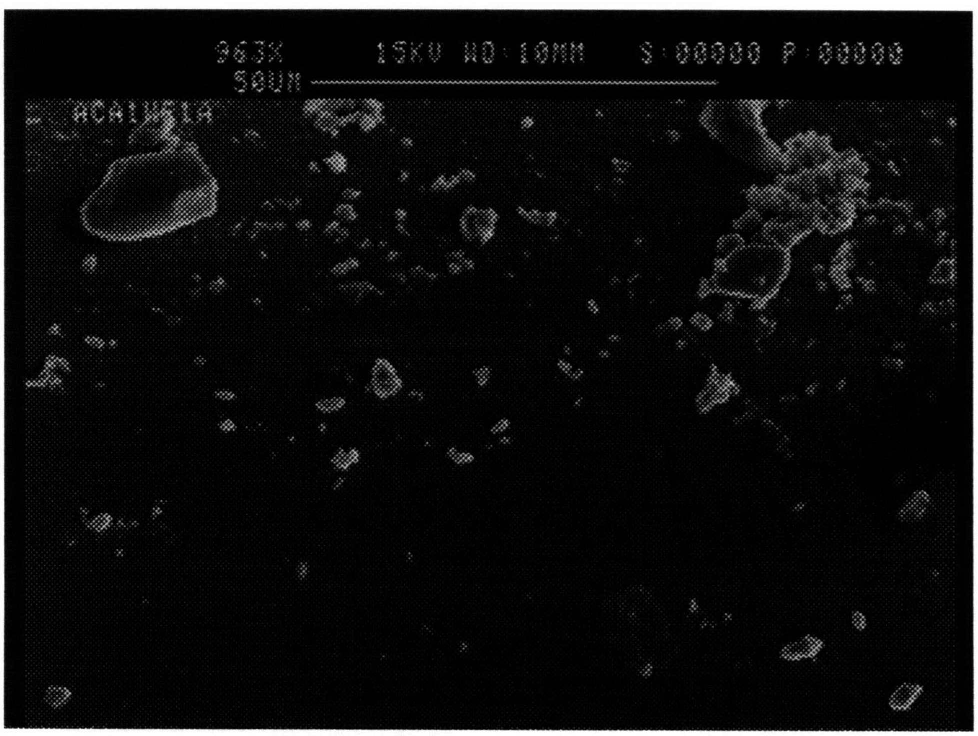


Figure 6-60: The Acrylate-coated optical-fiber in the $Ca(OH)_2$ solution for one-week-period (963 X).

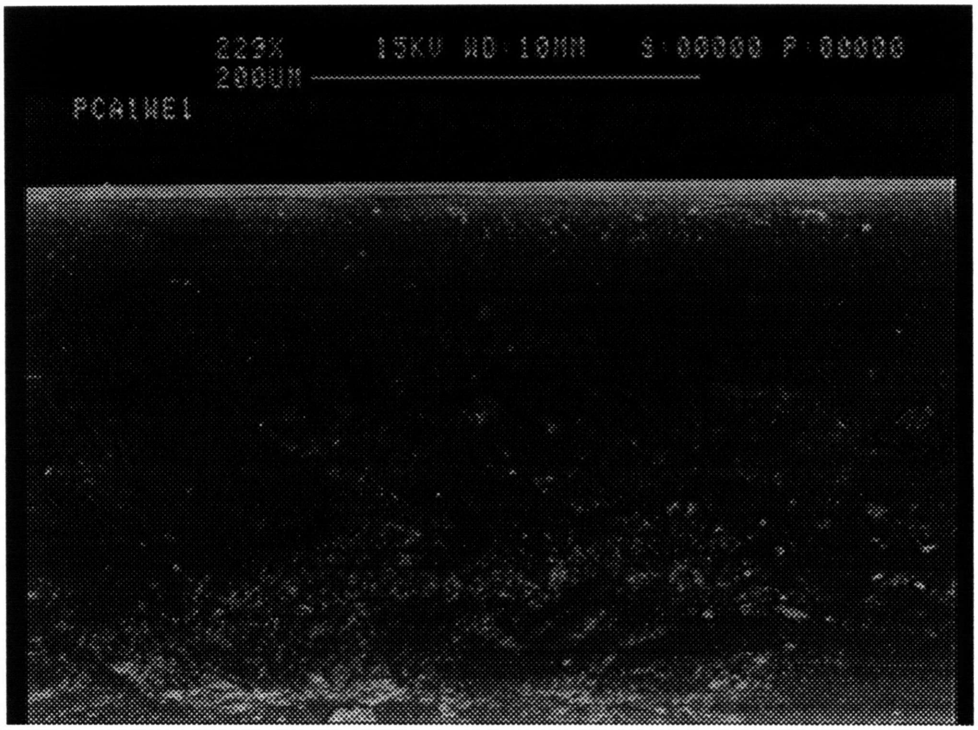


Figure 6-61: The Polyimide-coated optical-fiber in theCa(OH)$_2$ solution for one-week-period (229 X).

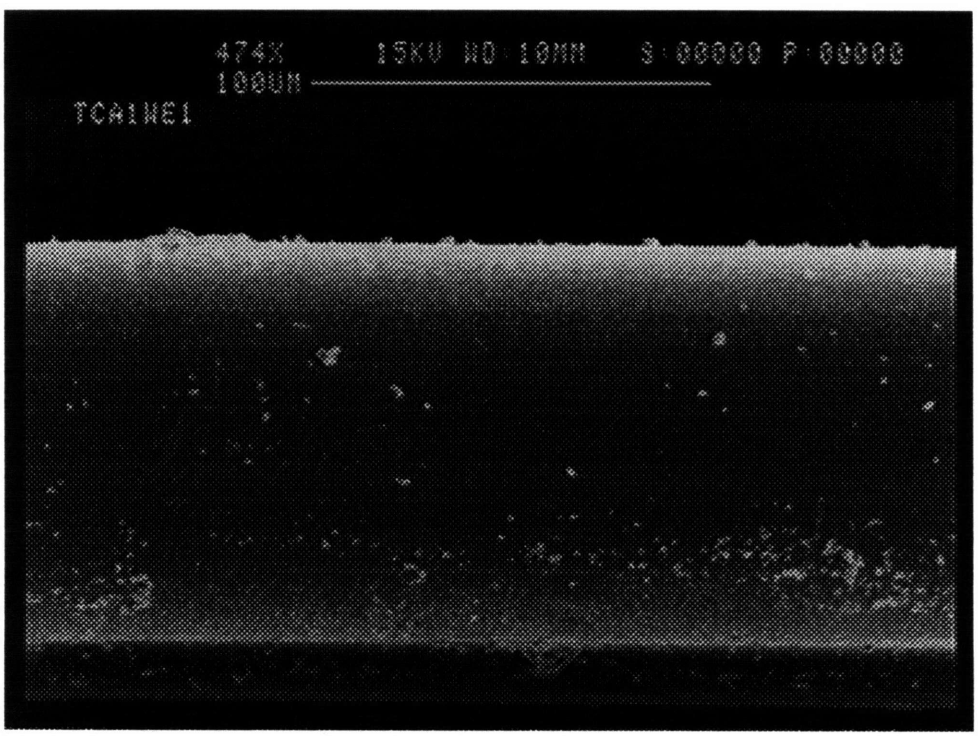


Figure 6-62:The Teftzel-Silicone-coated optical-fiber in the Ca(OH)$_2$ solution for one-week-period (474 X).

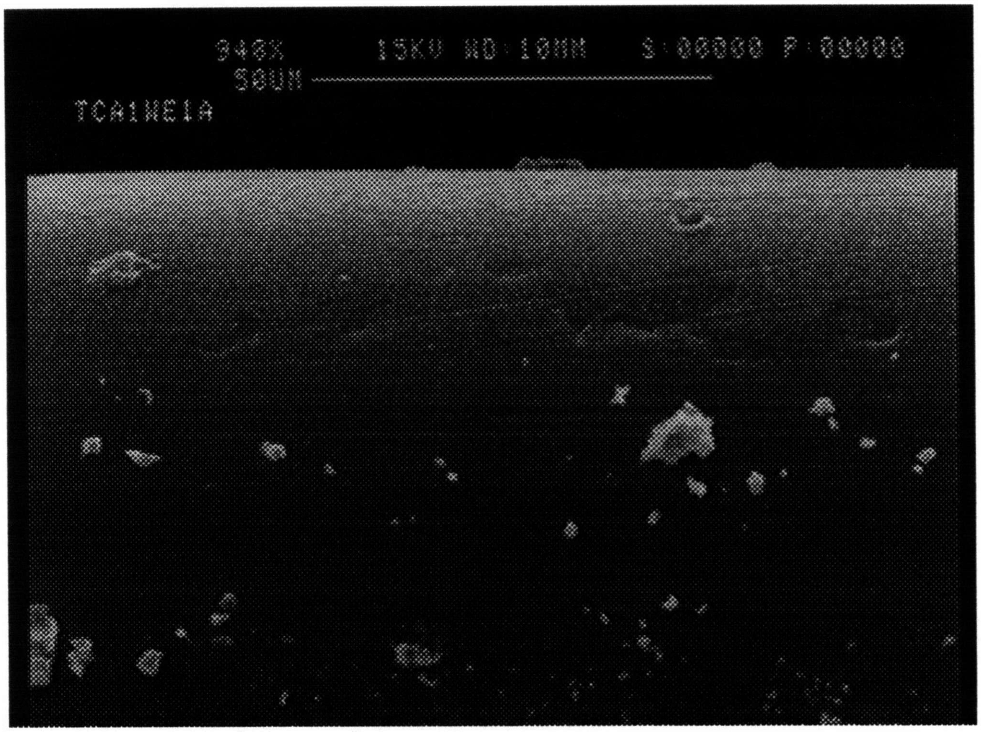


Figure 6-63:The Teftzel-Silicone-coated optical-fiber in the $Ca(OH)_2$ solution for one-week-period (948 X).

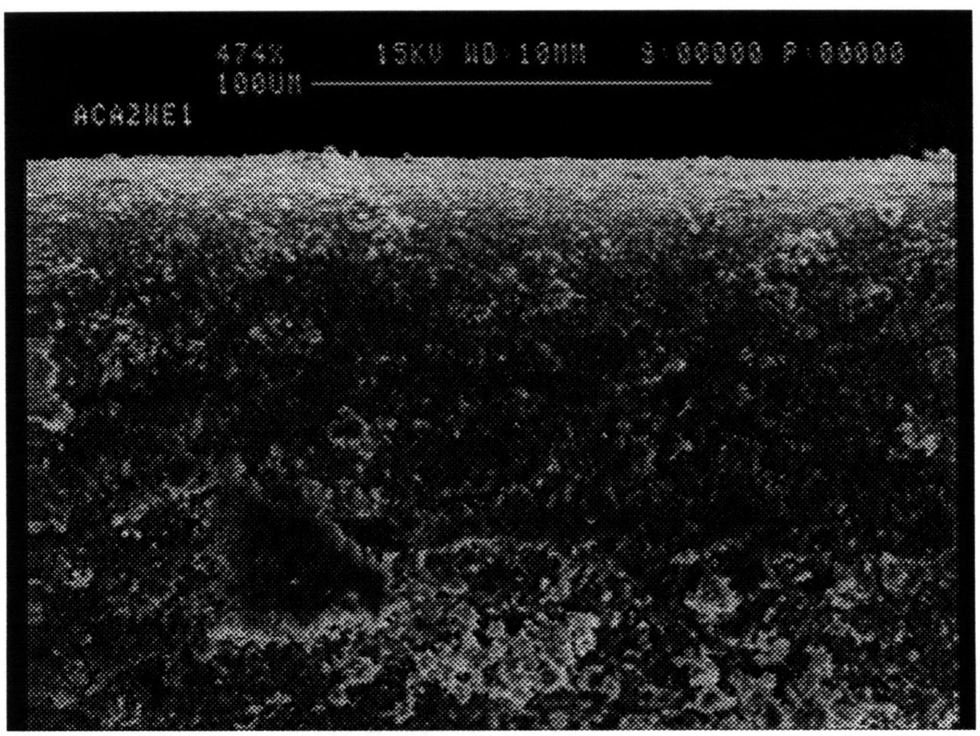


Figure 6-64: The Acrylate-coated optical-fiber in the $Ca(OH)_2$ solution for two-week-period (474 X).

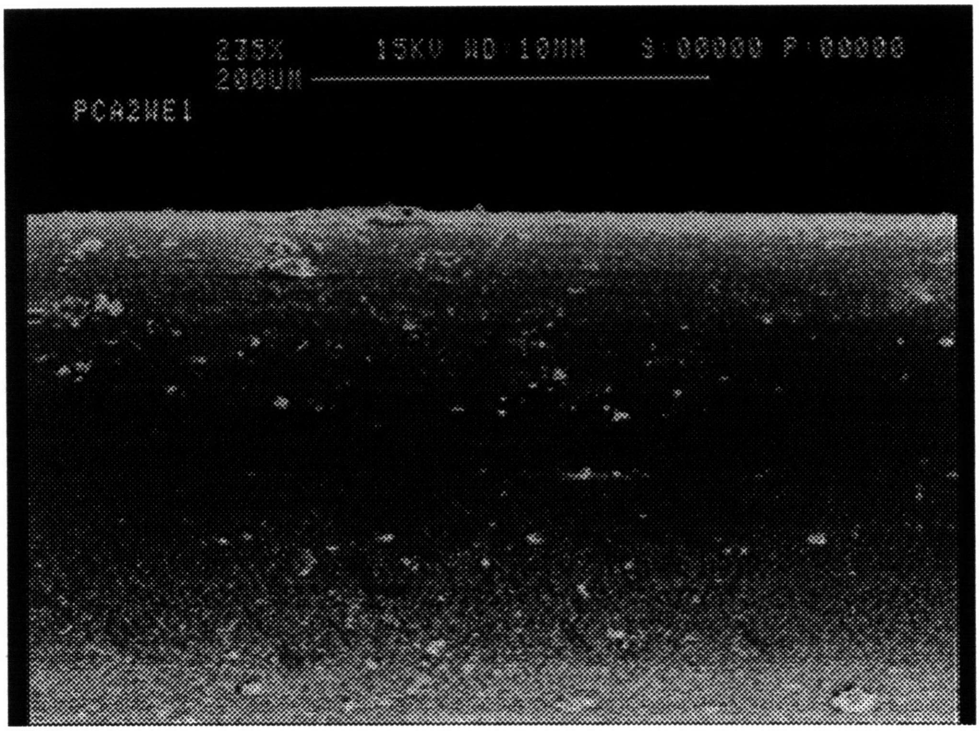


Figure 6-65: The Polyimide-coated optical-fiber in the $Ca(OH)_2$ solution for two-week-period (235 X).

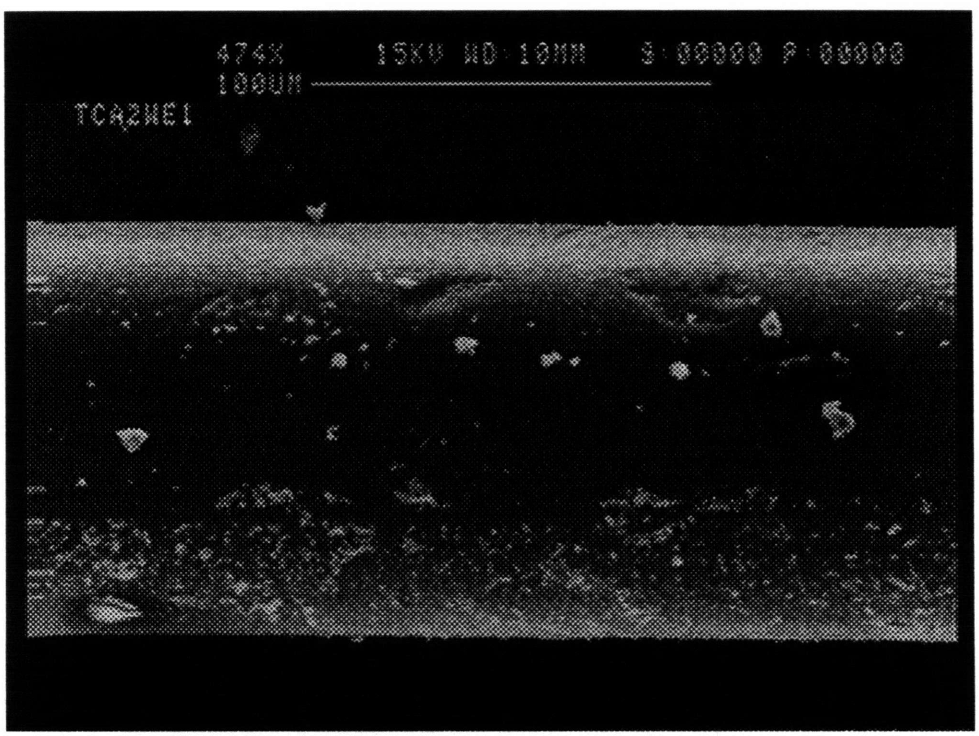


Figure 6-66:The Teftzel-Silicone-coated optical-fiber in the $Ca(OH)_2$ solution for two-week-period (474 X).

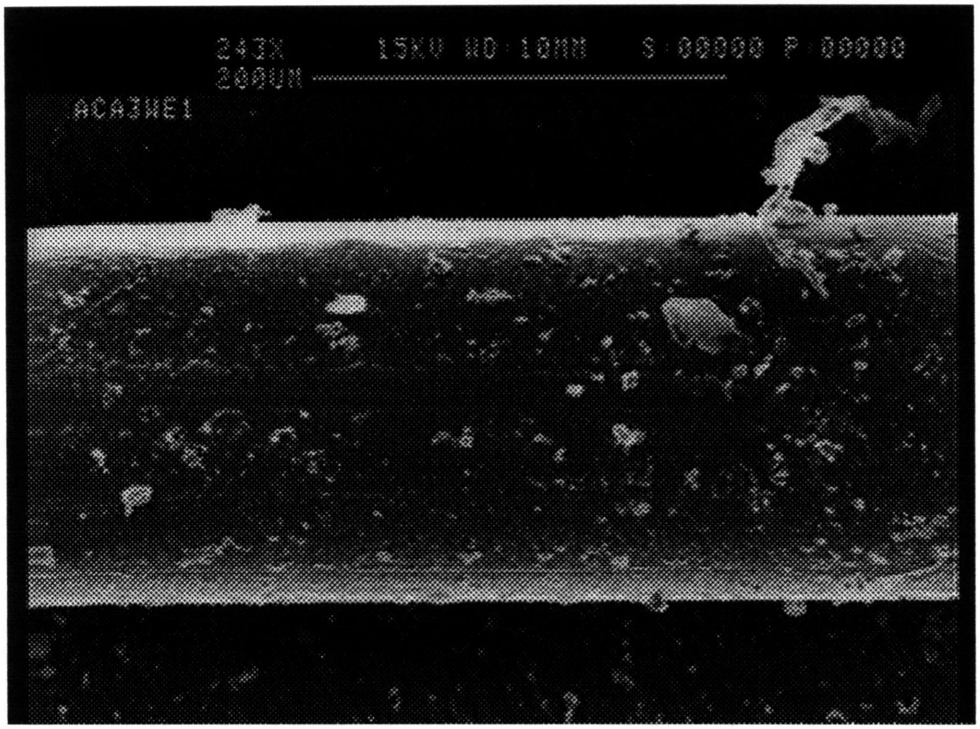


Figure 6-67: The Acrylate-coated optical-fiber in the $Ca(OH)_2$ solution for three-week-period (243 X).

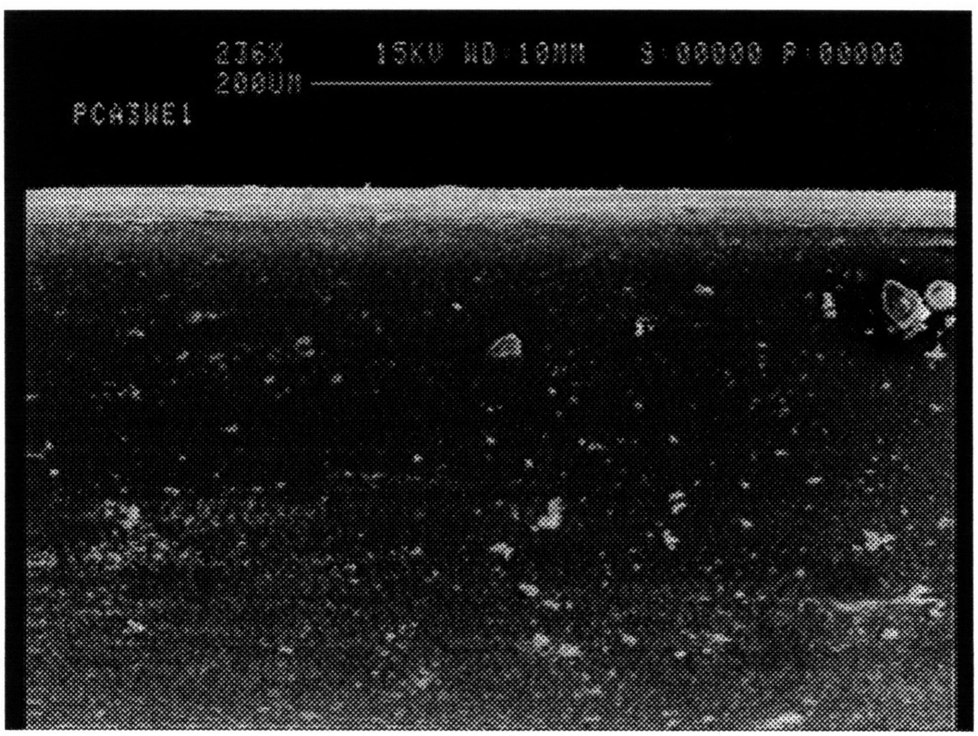


Figure 6-68: The Polyimide-coated optical-fiber in the $Ca(OH)_2$ solution for three-week-period (236 X).

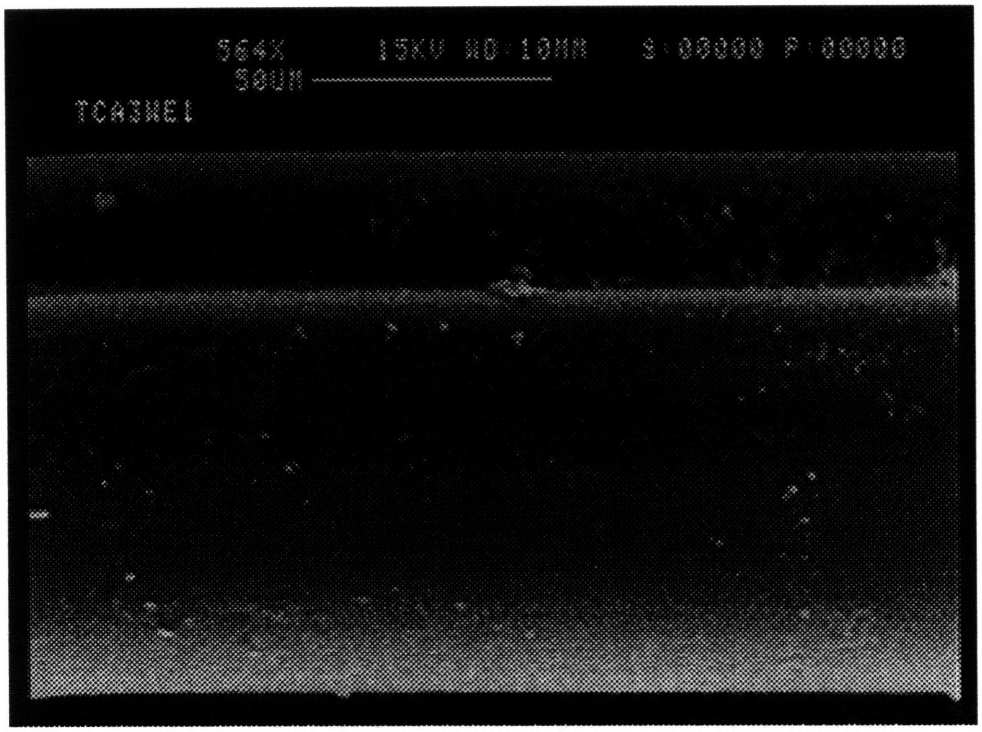


Figure 6-69:The Teftzel-Silicone-coated optical-fiber in the $Ca(OH)_2$ solution for three-week-period (564 X).

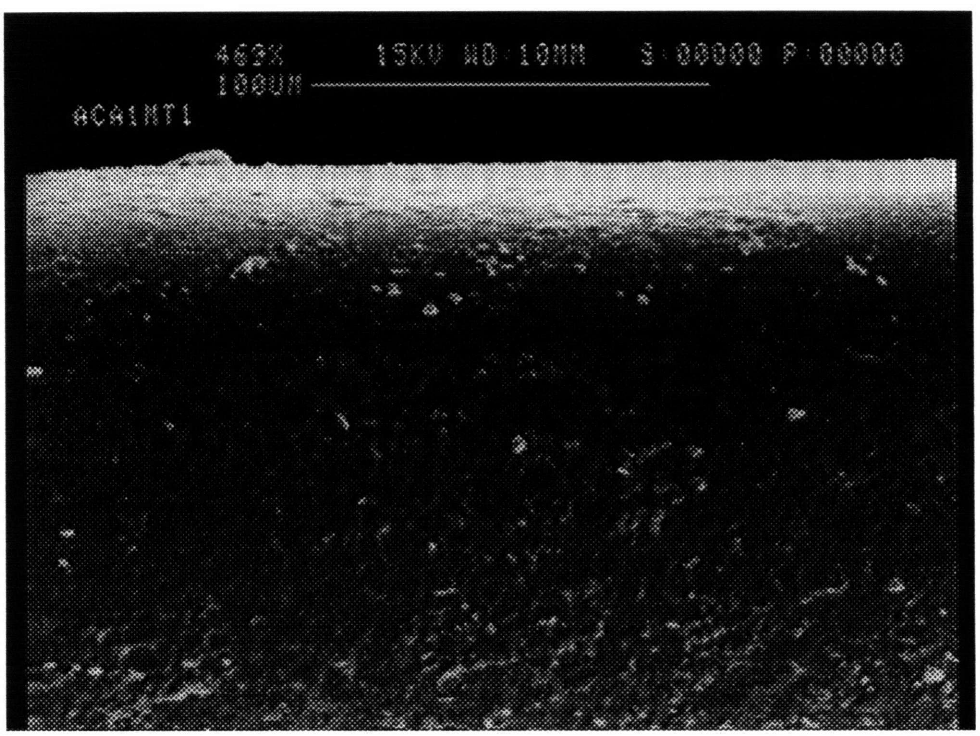


Figure 6-70: The Acrylate-coated optical-fiber in the $Ca(OH)_2$ solution for one-month-period (469 X).

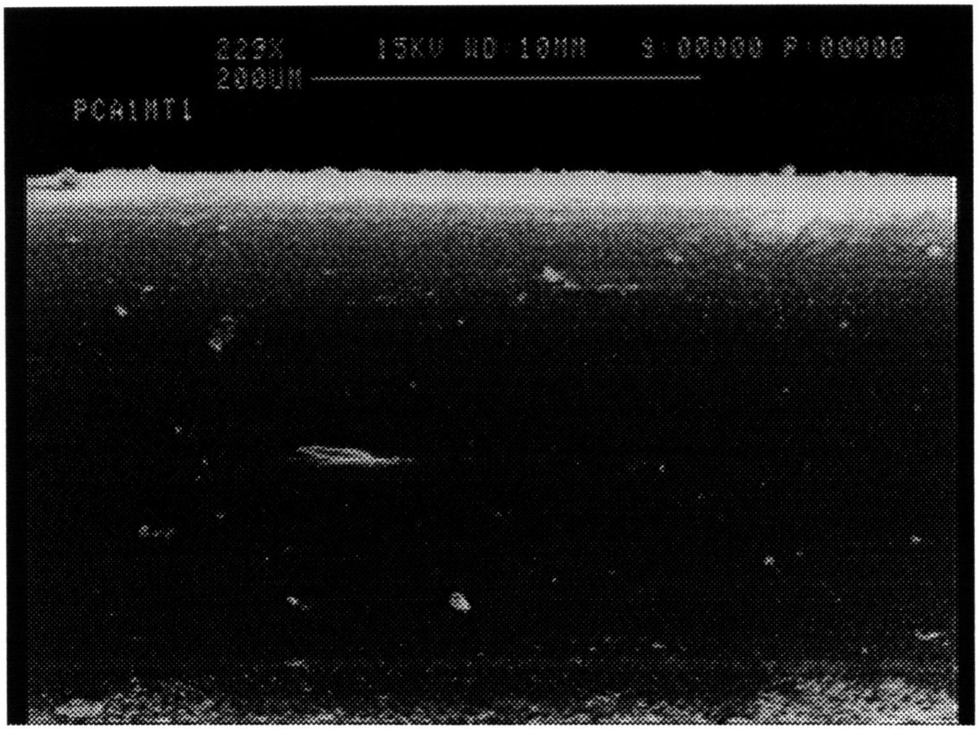


Figure 6-71: The Polyimide-coated optical-fiber in the $Ca(OH)_2$ solution for one-month-period (229 X).

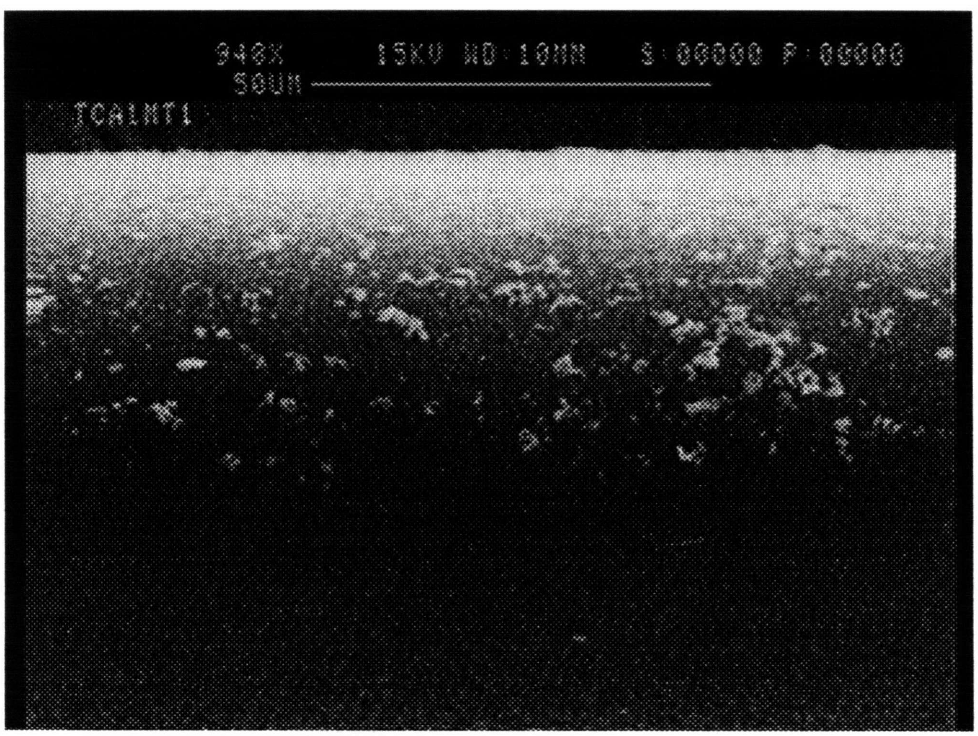


Figure 6-72:The Teftzel-Silicone-coated optical-fiber in the $Ca(OH)_2$ solution for one-month-period (948 X).

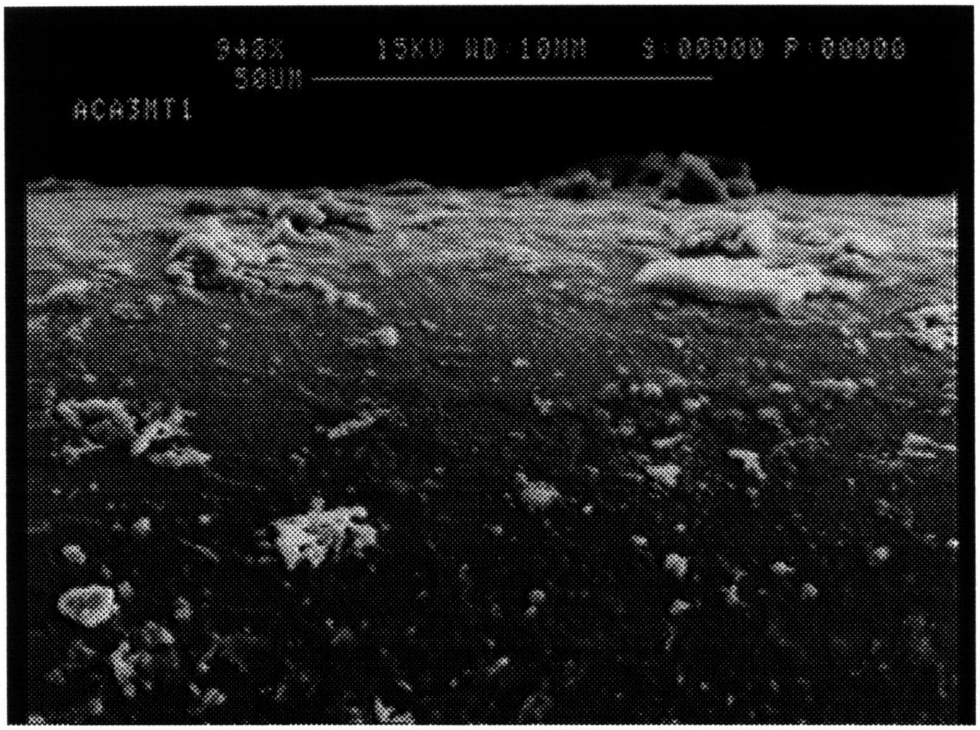


Figure 6-73: The Acrylate-coated optical-fiber in the $Ca(OH)_2$ solution for three-month-period (948 X).

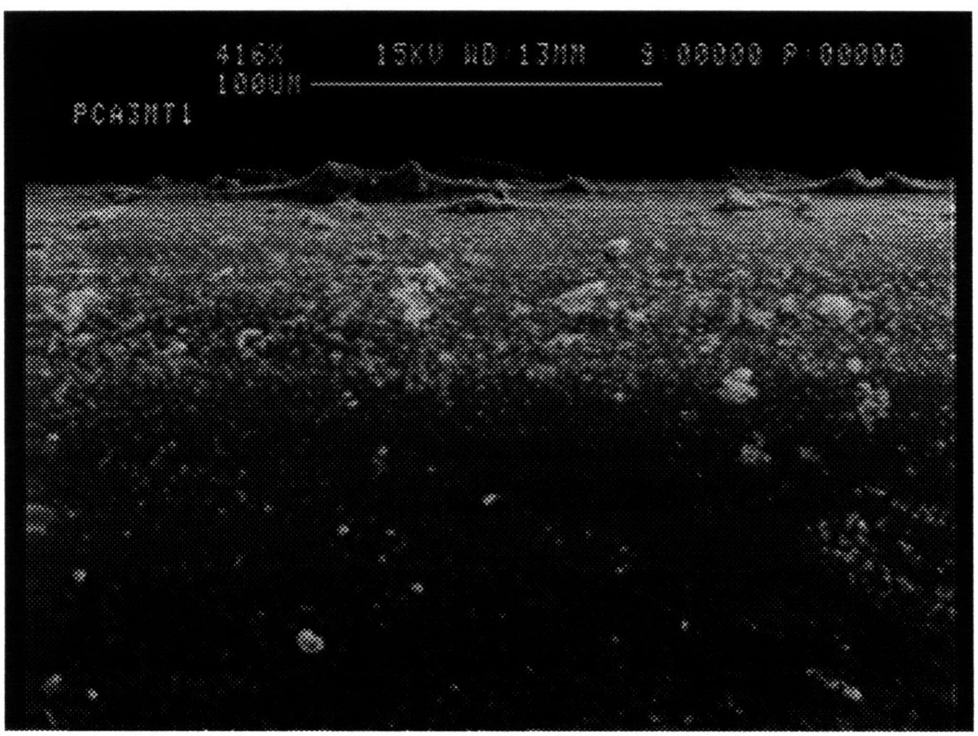


Figure 6-74: The Polyimide-coated optical-fiber in the $Ca(OH)_2$ solution for three-month-period (416 X).

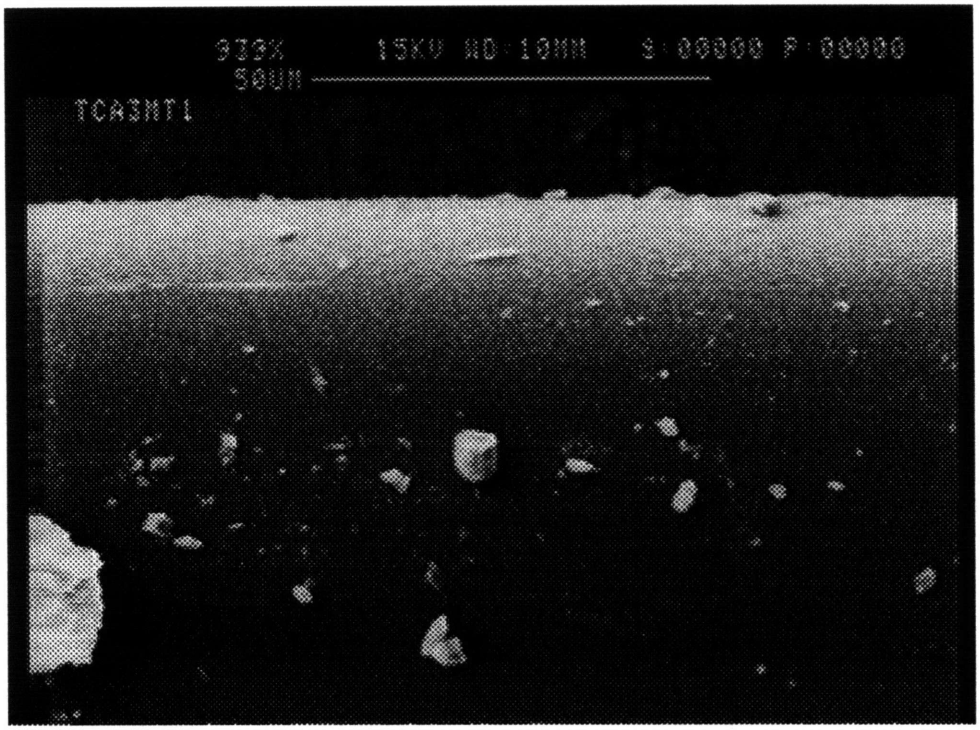


Figure 6-75:The Teftzel-Silicone-coated optical-fiber in the $Ca(OH)_2$ solution for three-month-period (939 X).

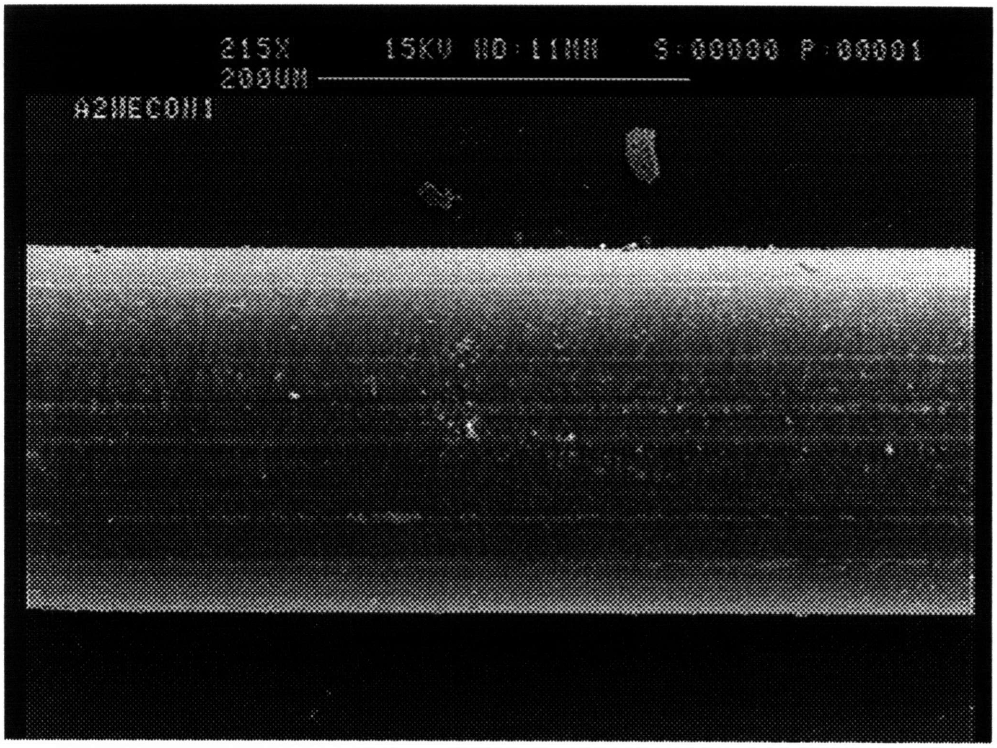


Figure 6-76: The Acrylate-coated optical fiber inside the cement paste for two weeks (215 X).

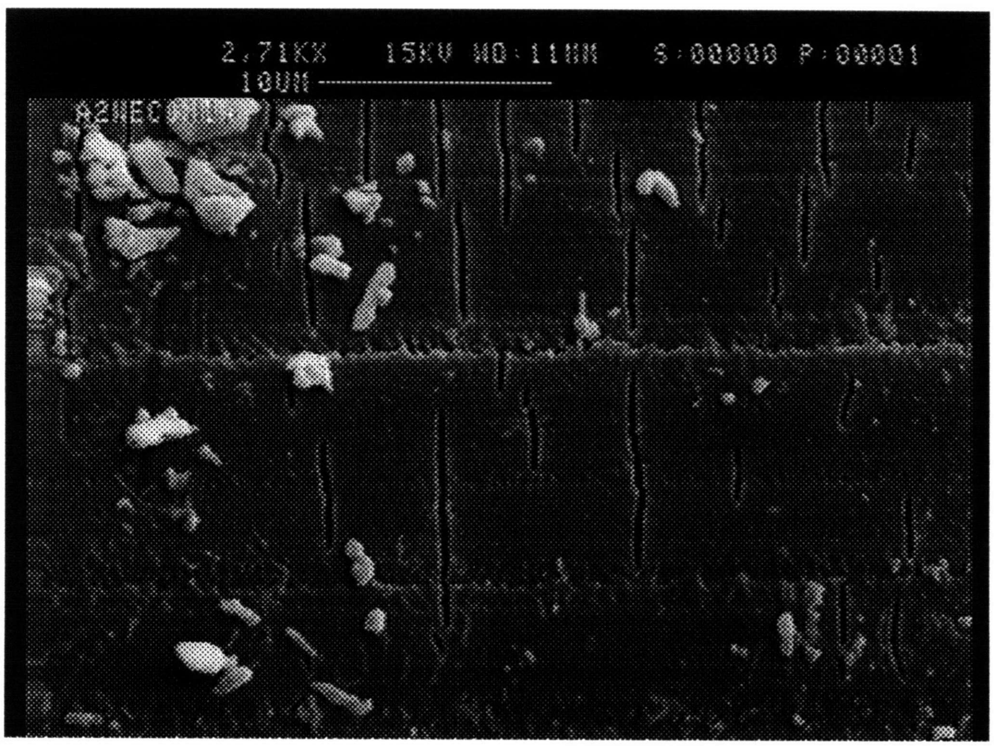


Figure 6-77: The Acrylate-coated optical fiber inside the cement paste for two weeks (2710 X).

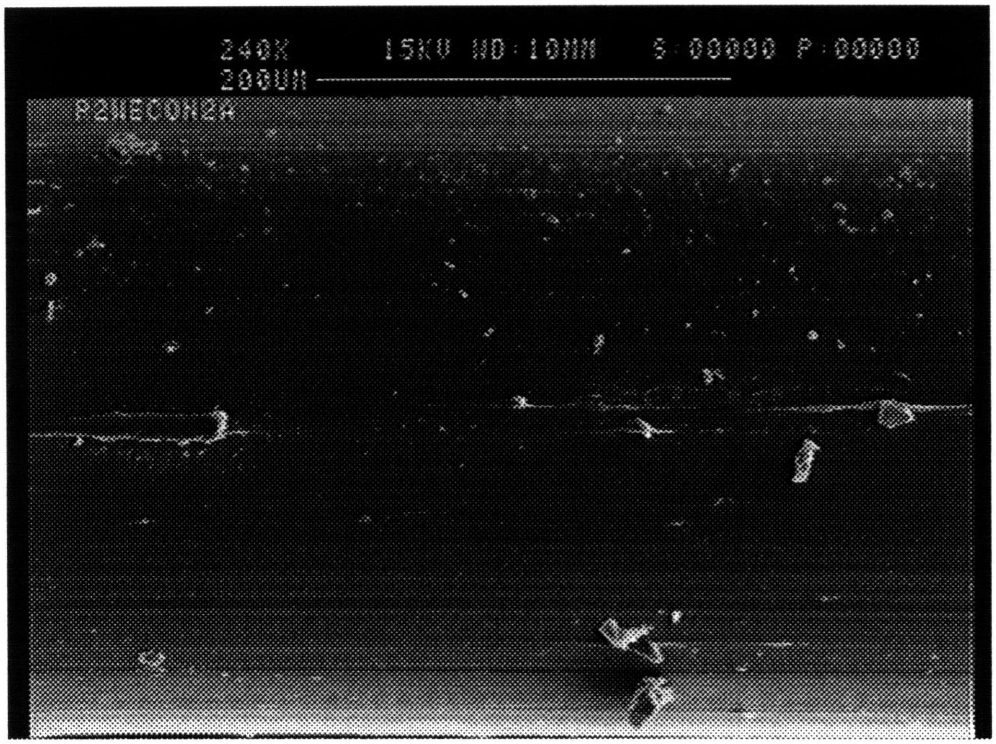


Figure 6-78: The Polyimide-coated optical-fiber inside the cement paste for two weeks (240 X).

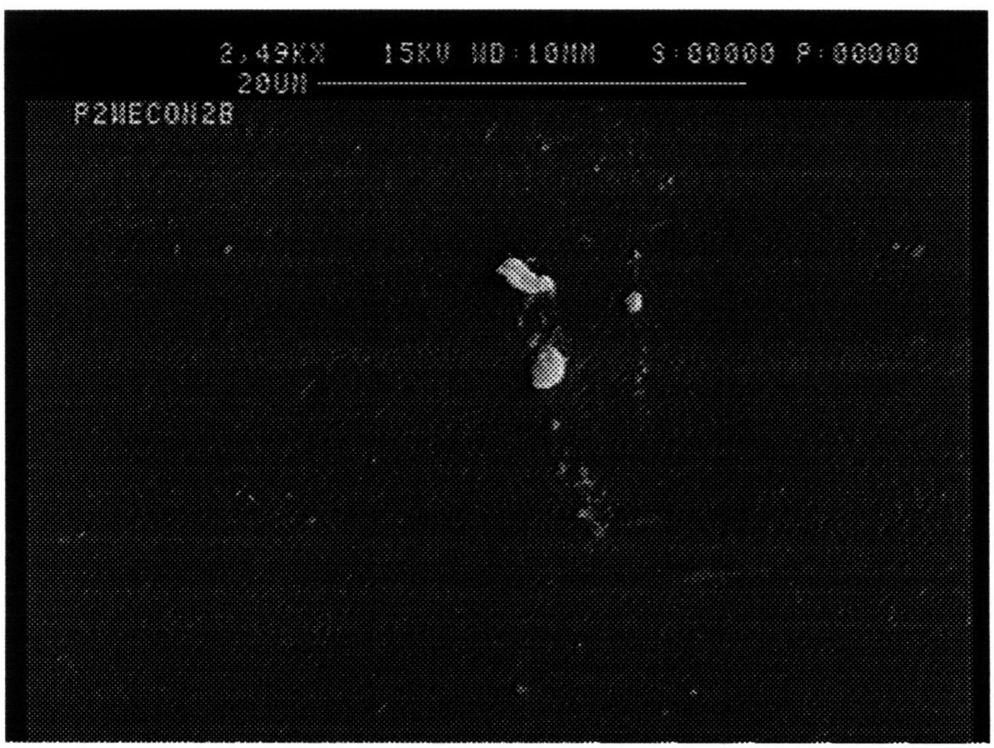


Figure 6-79: The Polyimide-coated optical-fiber inside the cement paste for two weeks (2490 X).

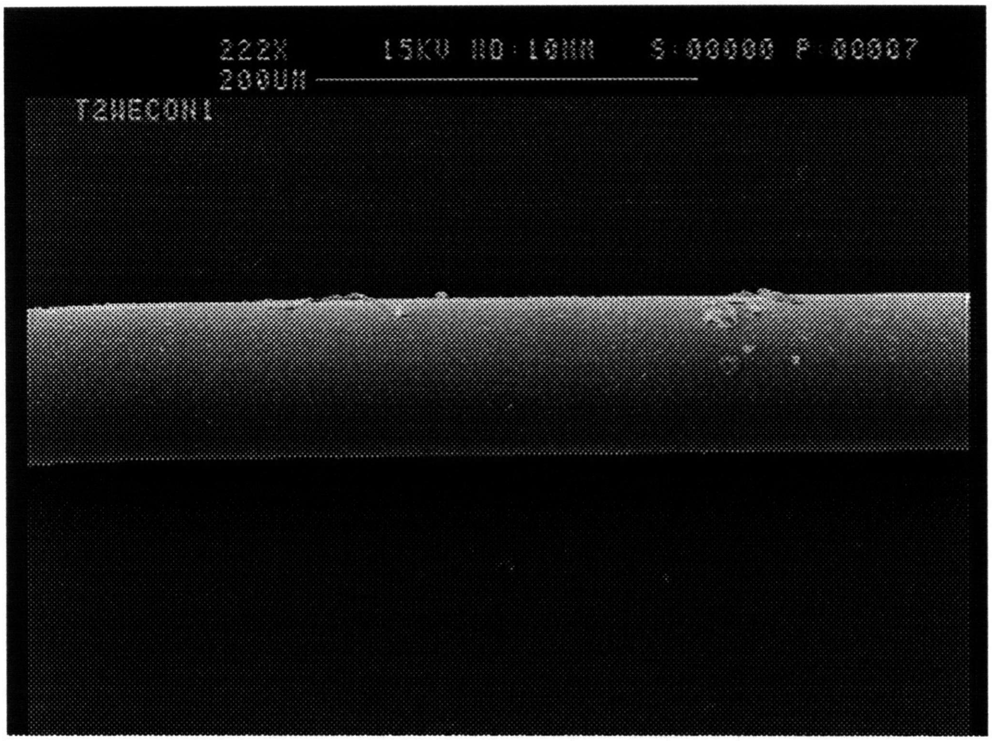


Figure 6-80: The Teftzel-Silicone-coated optical-fiber inside the cement paste for two weeks (222 X).

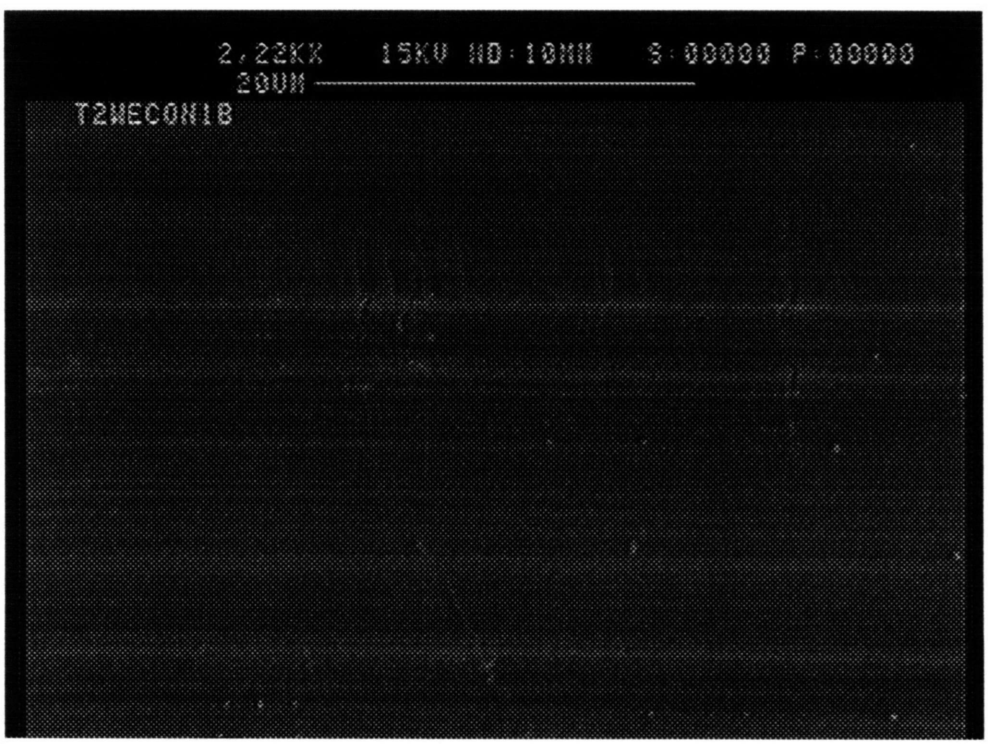


Figure 6-81: The Teftzel-Silicone-coated optical-fiber inside the cement paste for two weeks (2220 X).

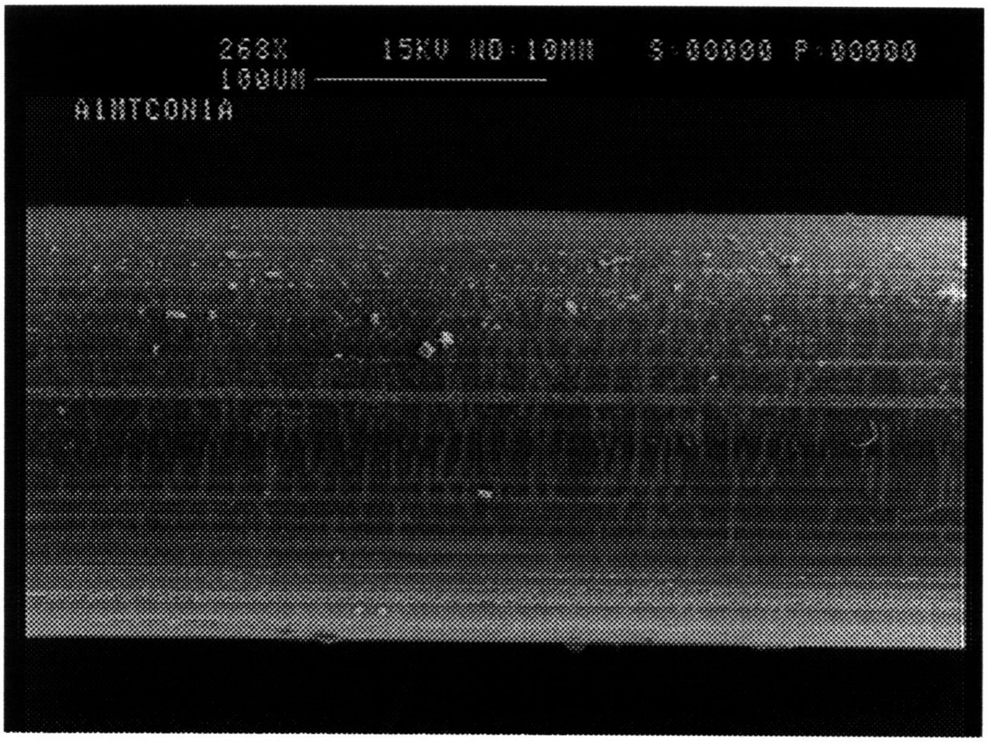


Figure 6-82: The Acrylate-coated optical fiber inside the cement paste for 1 month (268 X).

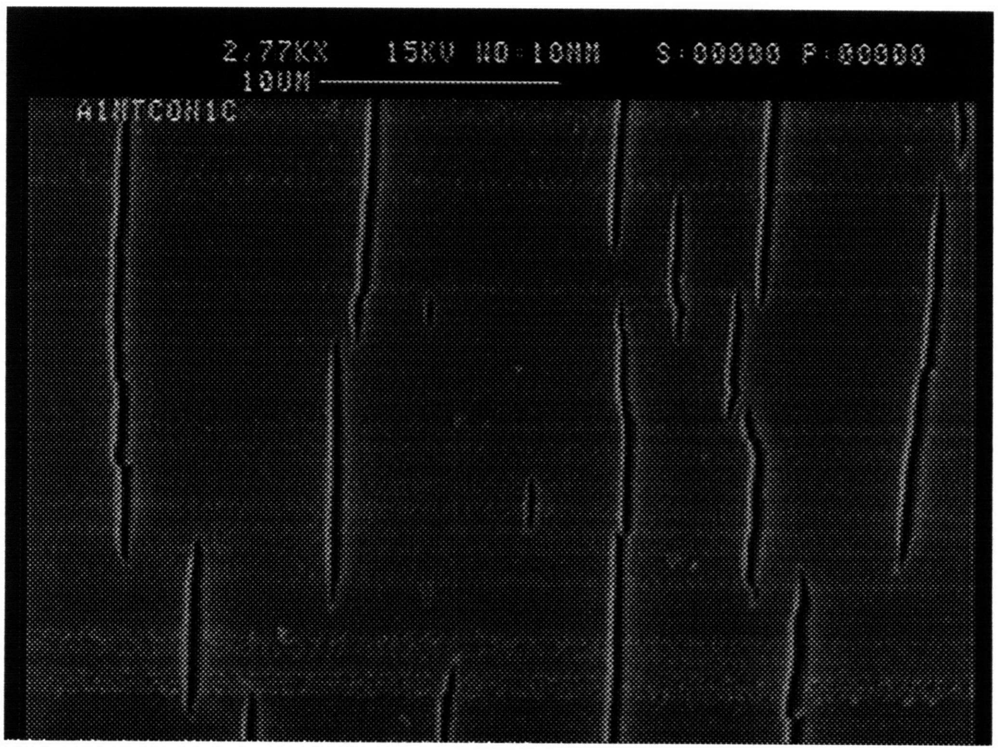


Figure 6-83: The Acrylate-coated optical fiber inside the cement paste for 1 month (2770 X).

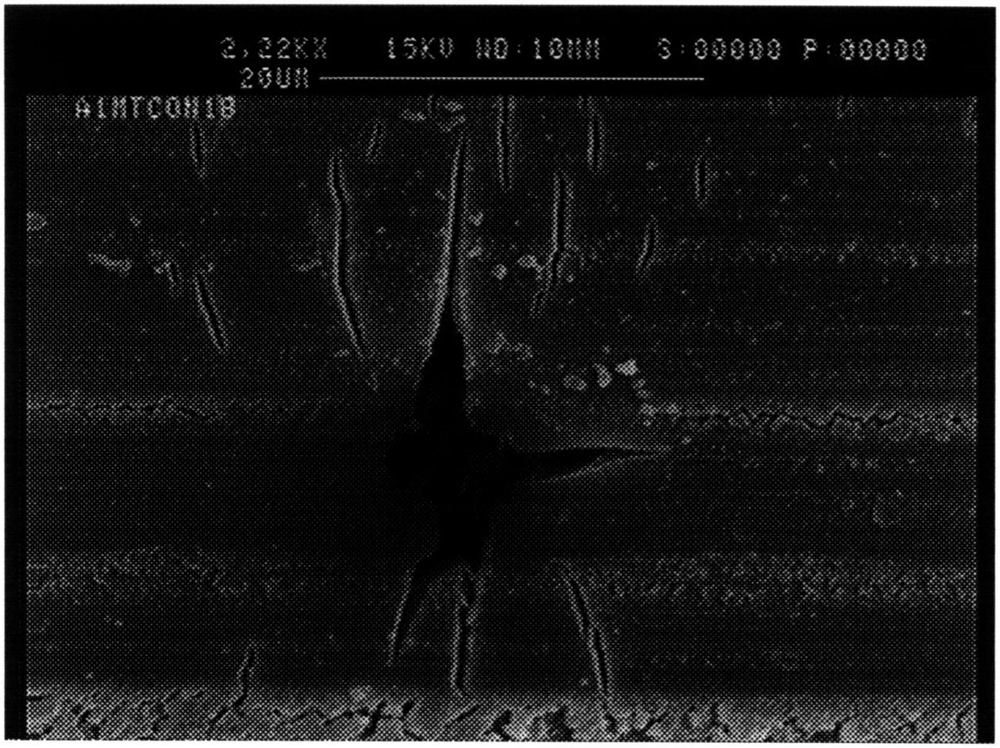


Figure 6-84: The Acrylate-coated optical fiber inside the cement paste for 1 month (2220 X).

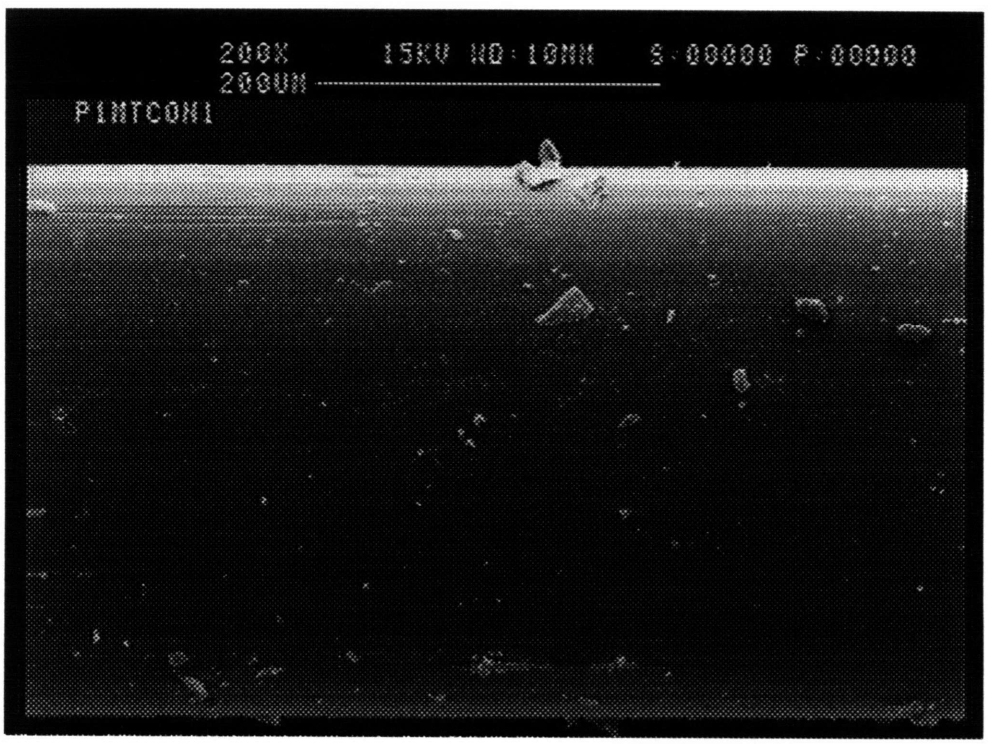


Figure 6-85: The Polyimide-coated optical-fiber inside the cement paste for1 month (200 X).

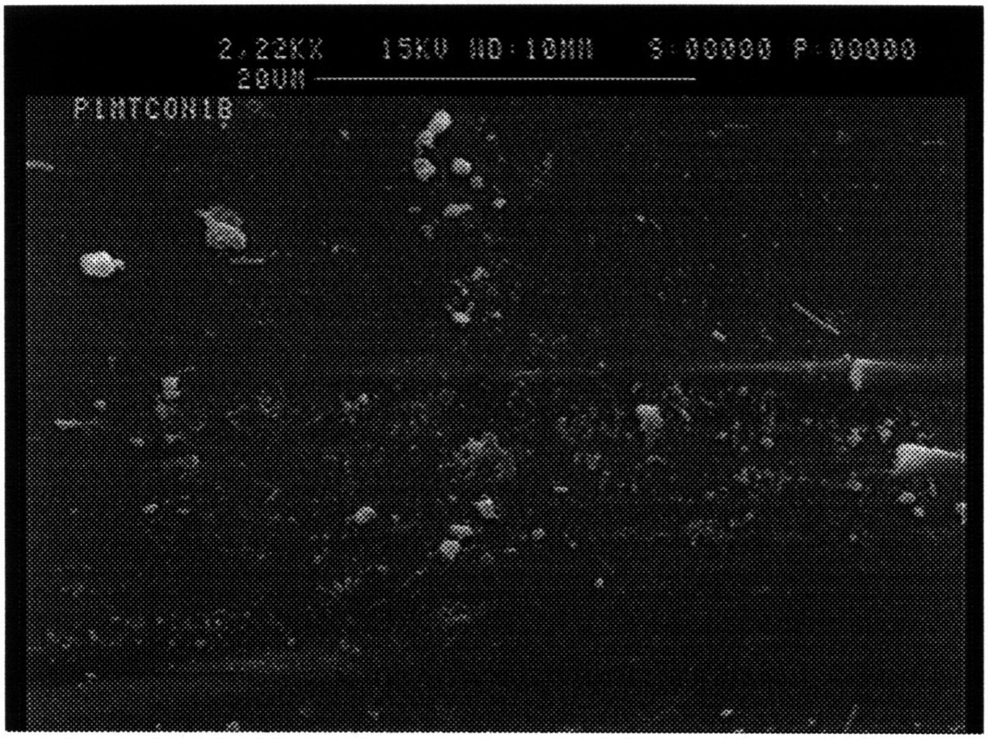


Figure 6-86: The Polyimide-coated optical-fiber inside the cement paste for 1 month (2220 X).

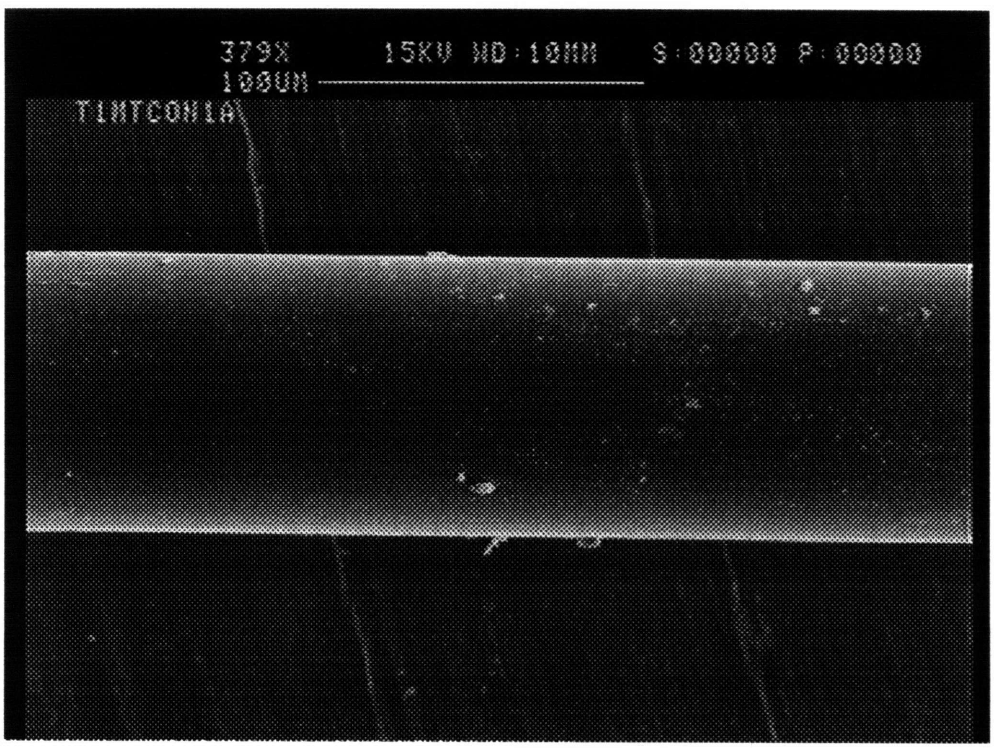


Figure 6-87: The Teftzel-Silicone-coated optical-fiber inside the cement paste for 1 month (379 X).

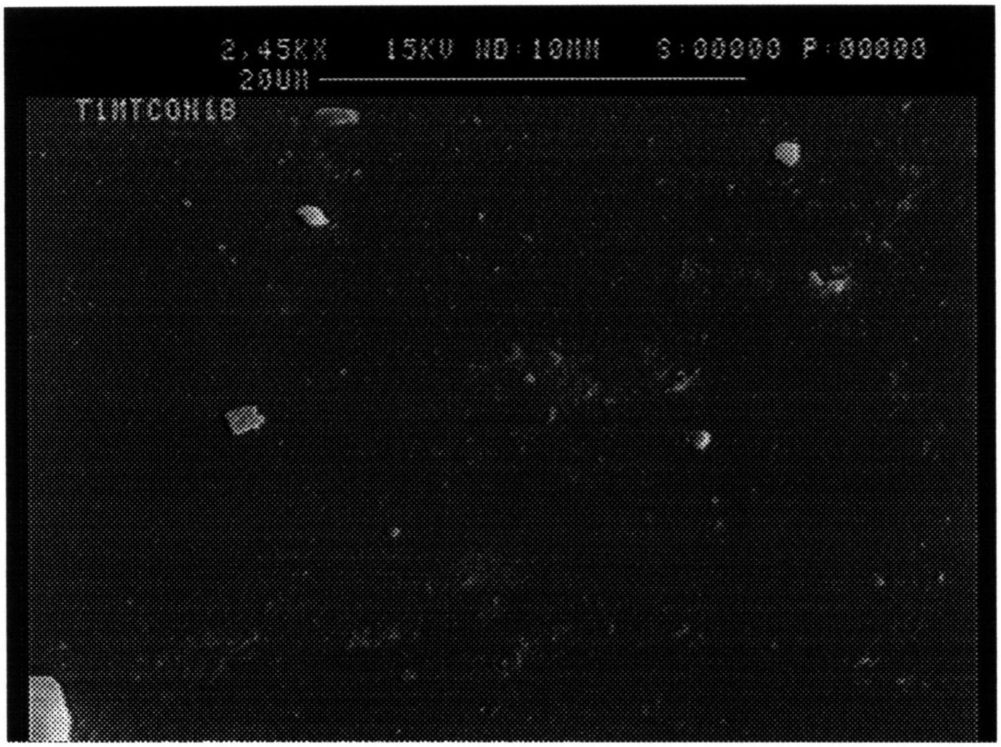


Figure 6-88: The Teftzel-Silicone-coated optical-fiber inside the cement paste for 1 month (2450 X).

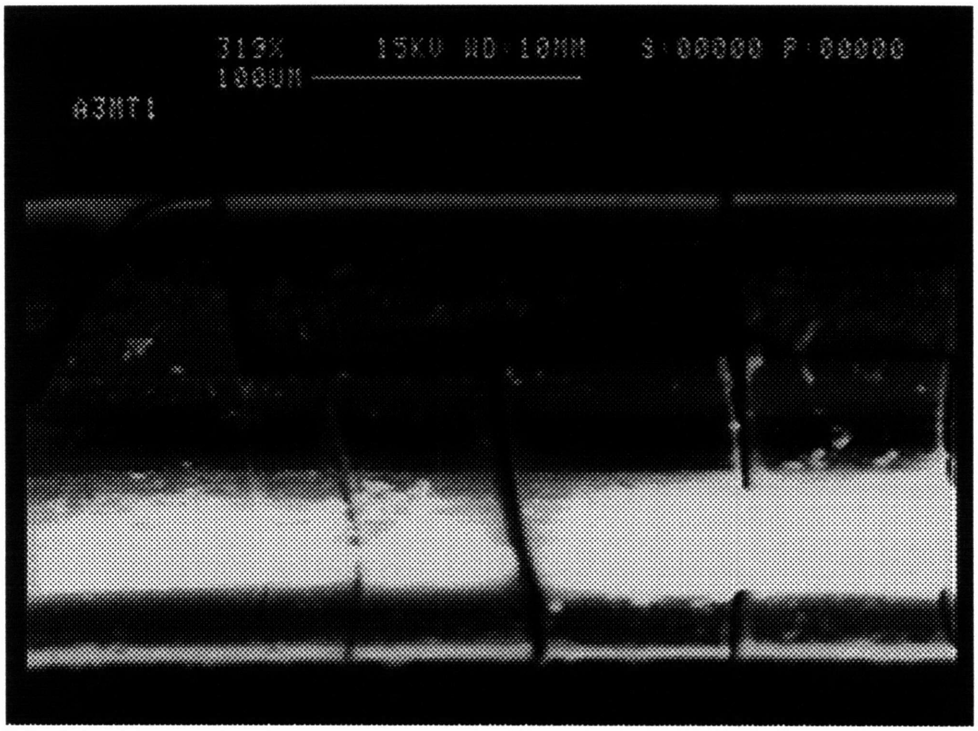


Figure 6-89: The Acrylate-coated optical-fiber inside the cement paste for 3 months (319 X).

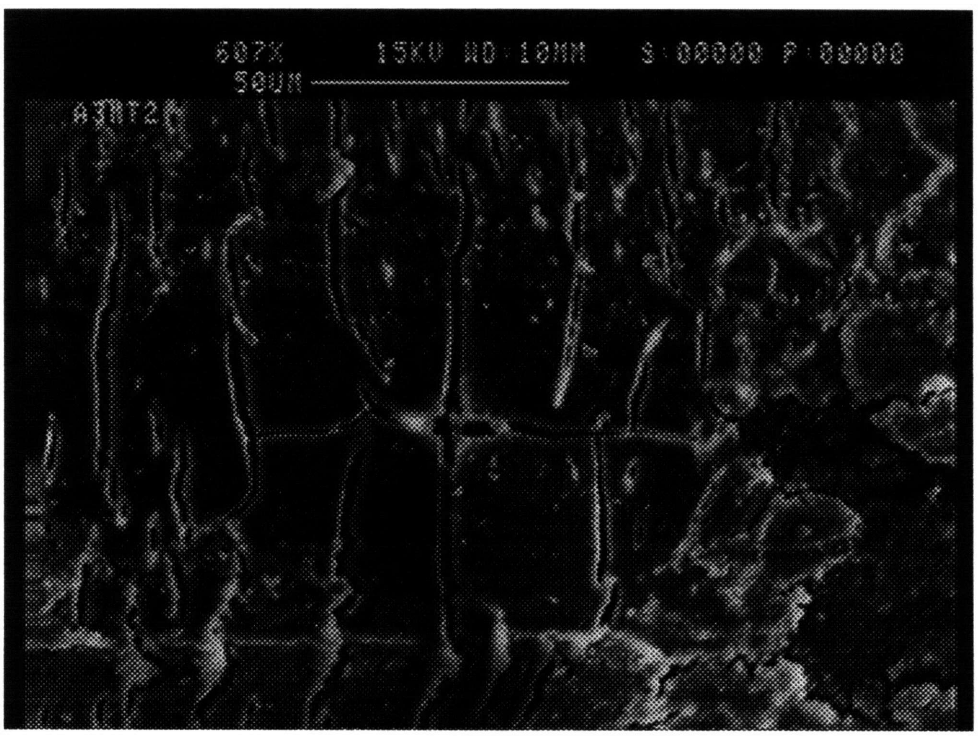


Figure 6-90: The Acrylate-coated optical-fiber inside the cement paste for 3 months (607 X).

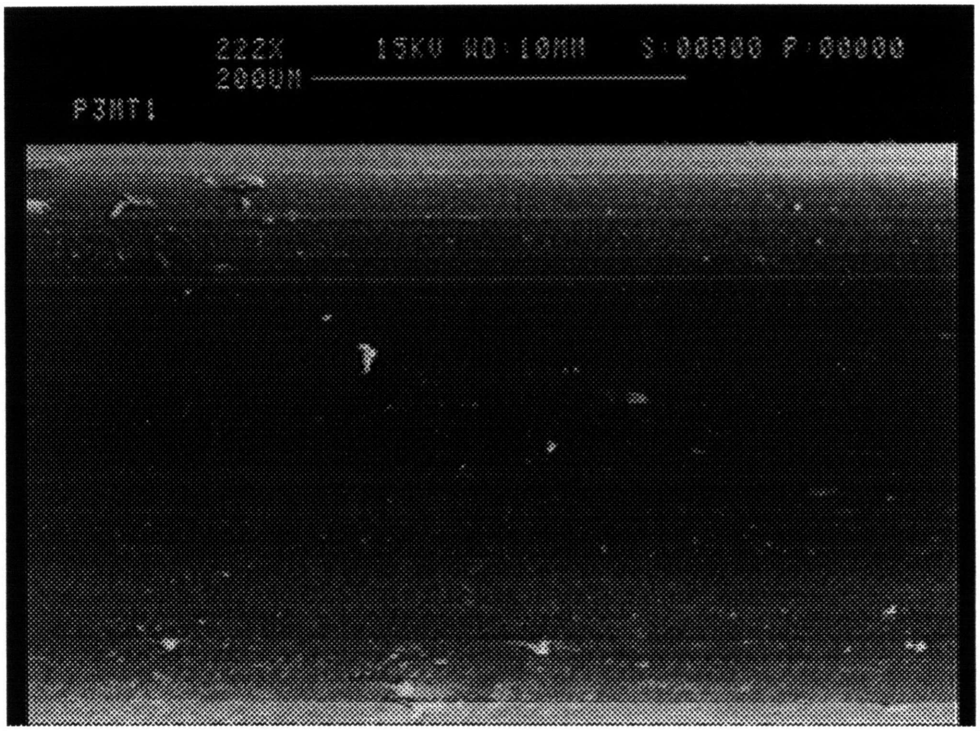


Figure 6-91: The Polyimide-coated optical-fiber inside the cement paste for 3 months (222 X).

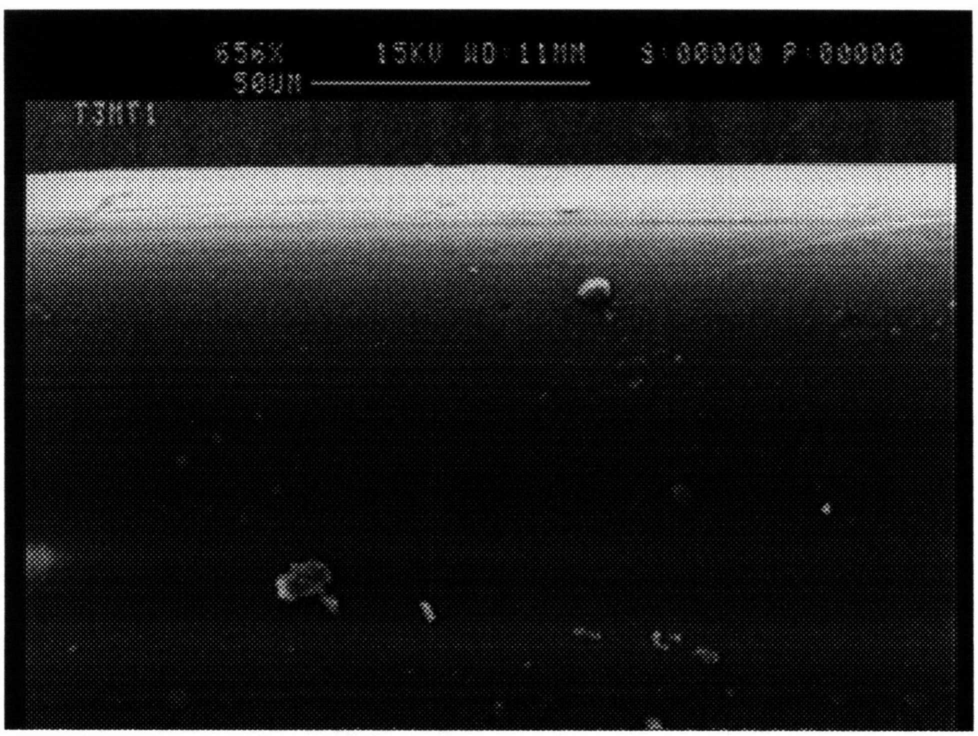


Figure 6-92: The Teftzel-Silicone-coated optical-fiber inside the cement paste for 3 months (656 X).

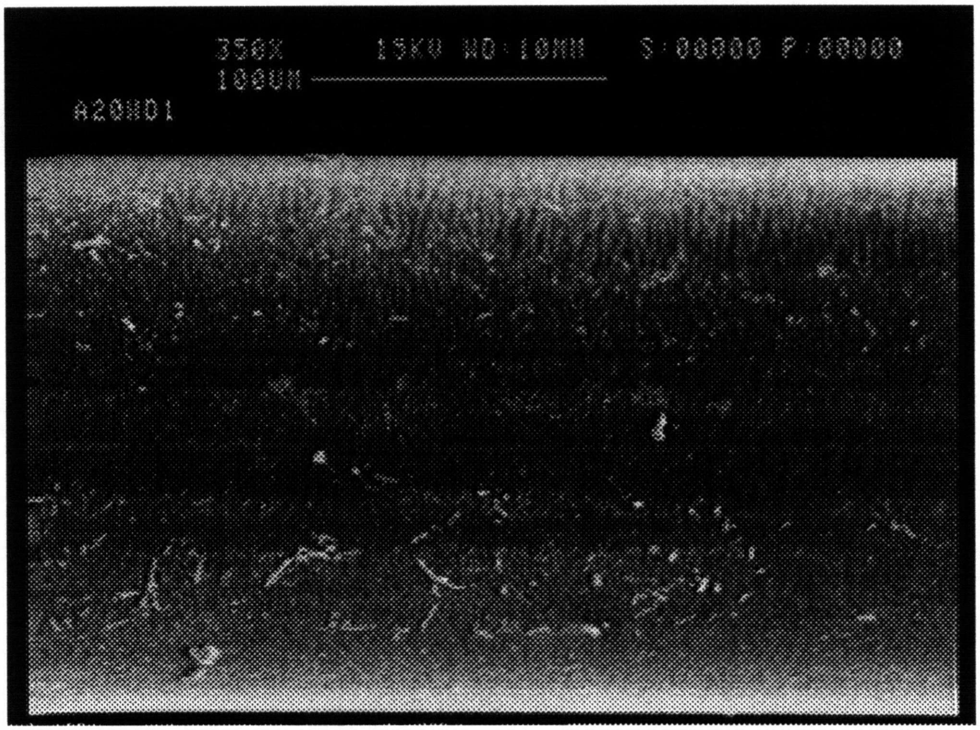


Figure 6-93: The Acrylate-coated optical-fiber under 20 wet-dry cycles (350 X).

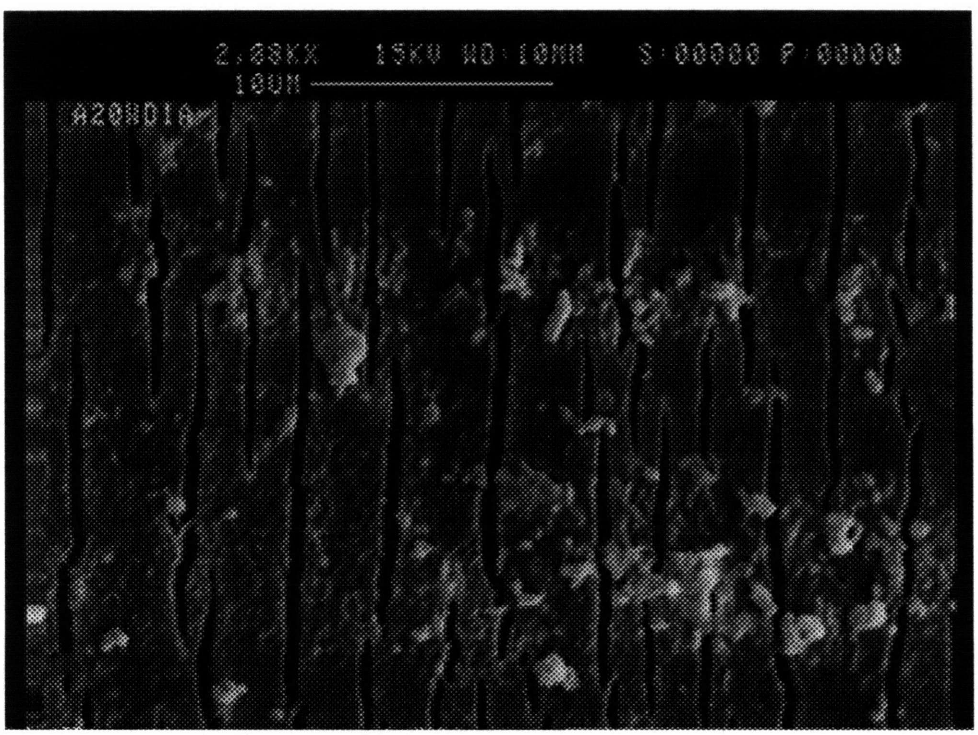


Figure 6-94: The Acrylate-coated optical-fiber under 20wet-dry cycles (2,880 X).

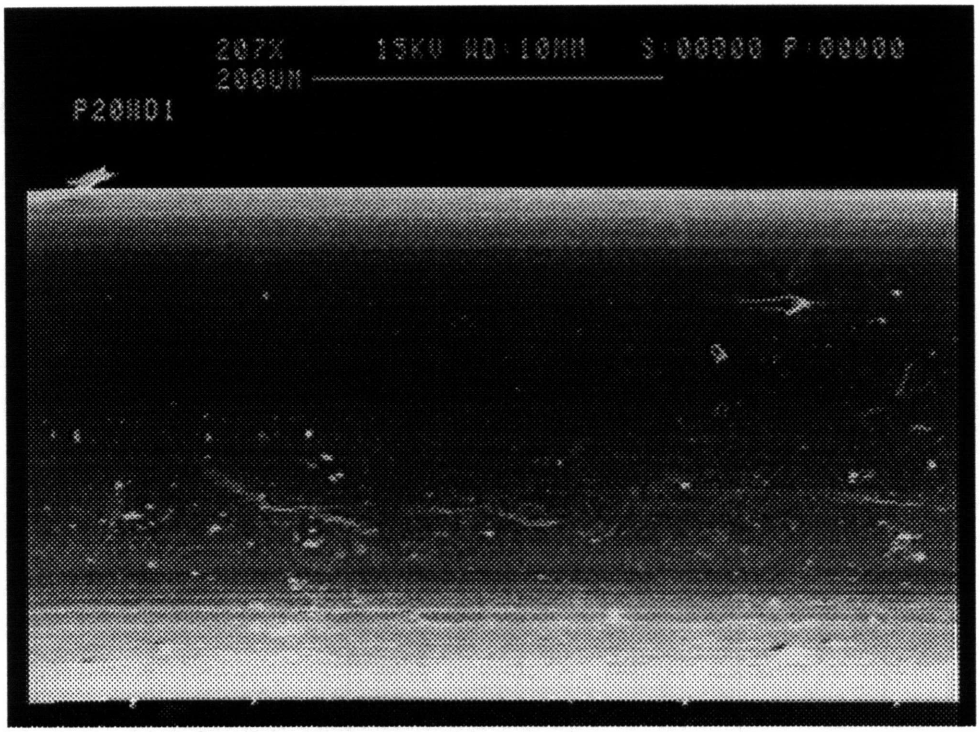


Figure 6-95: The Polyimide-coated optical-fiber under 20wet-dry cycles (207 X).

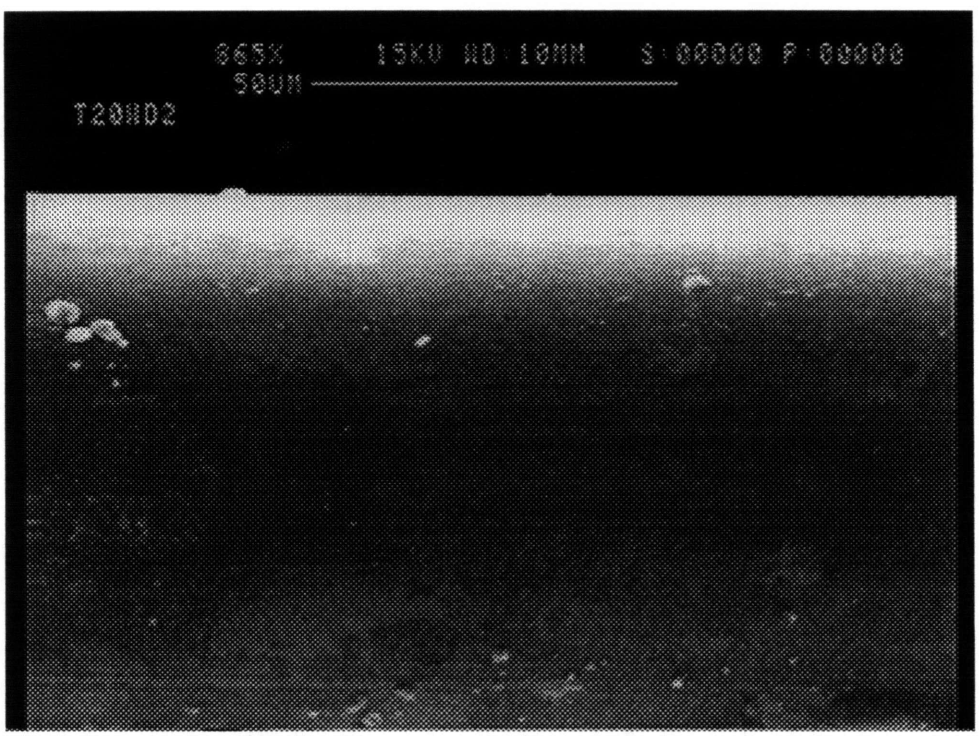


Figure 6-96: The Teftzel-Silicone-coated optical-fiber under 20 wet-dry cycles (865 X).

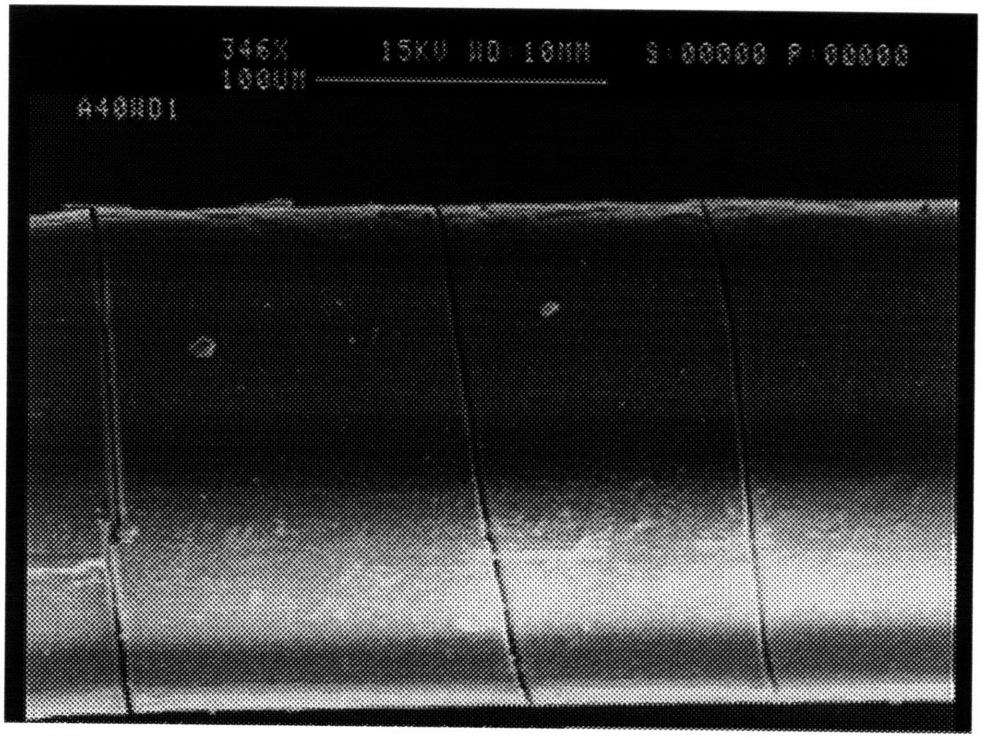


Figure 6-97: The Acrylate-coated optical-fiber under 40 wet-dry cycles (346 X).

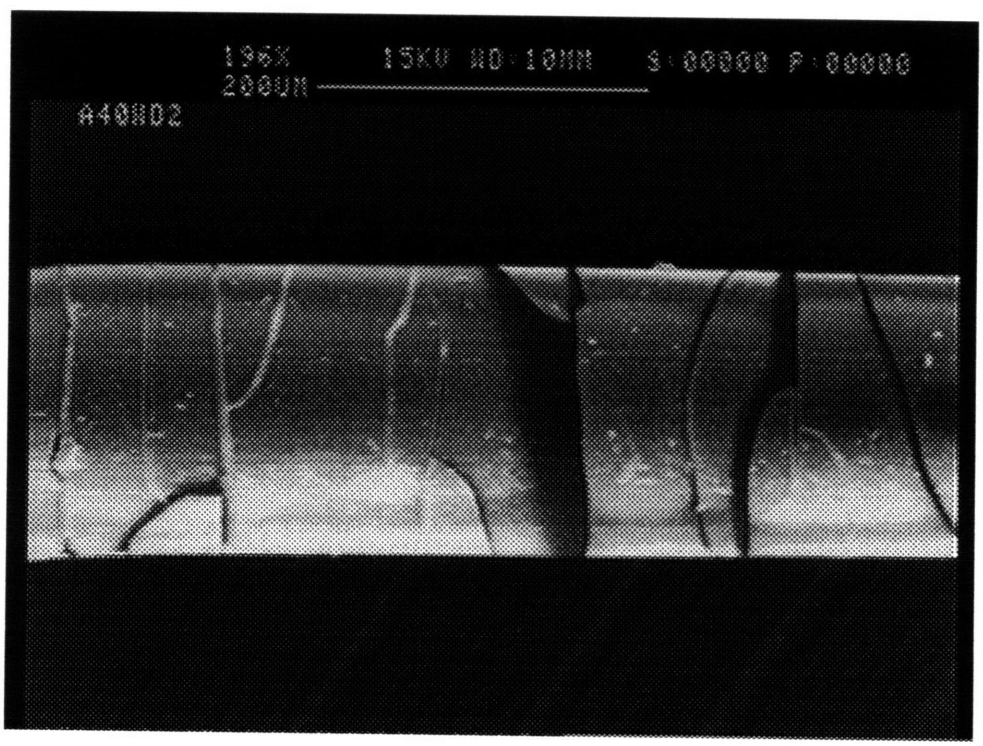


Figure 6-98: The Acrylate-coated optical-fiber under 40 wet-dry cycles (196 X).

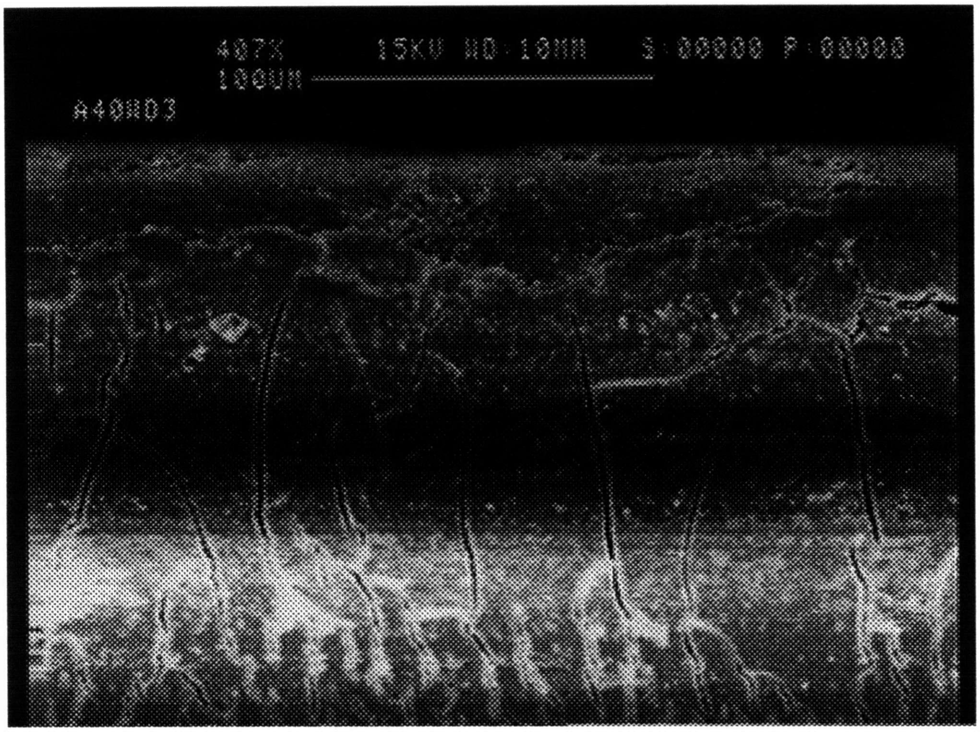


Figure 6-99: The Acrylate-coated optical-fiber under 40 wet-dry cycles (407 X).

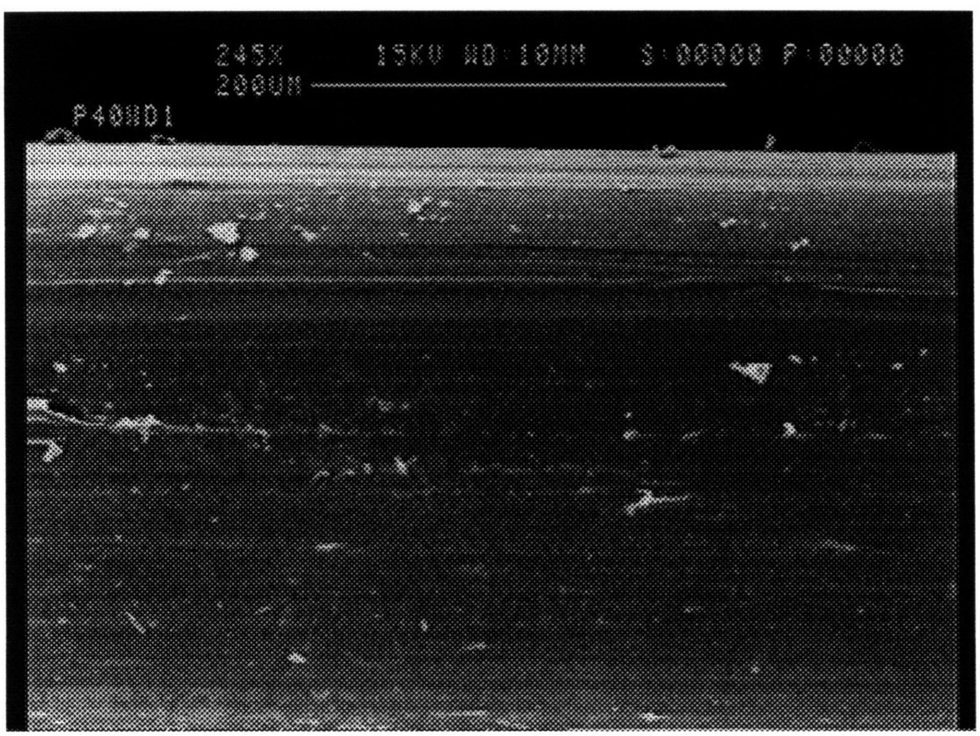


Figure 6-100: The Polyimide-coated optical-fiber under 40 wet-dry cycles (245 X).

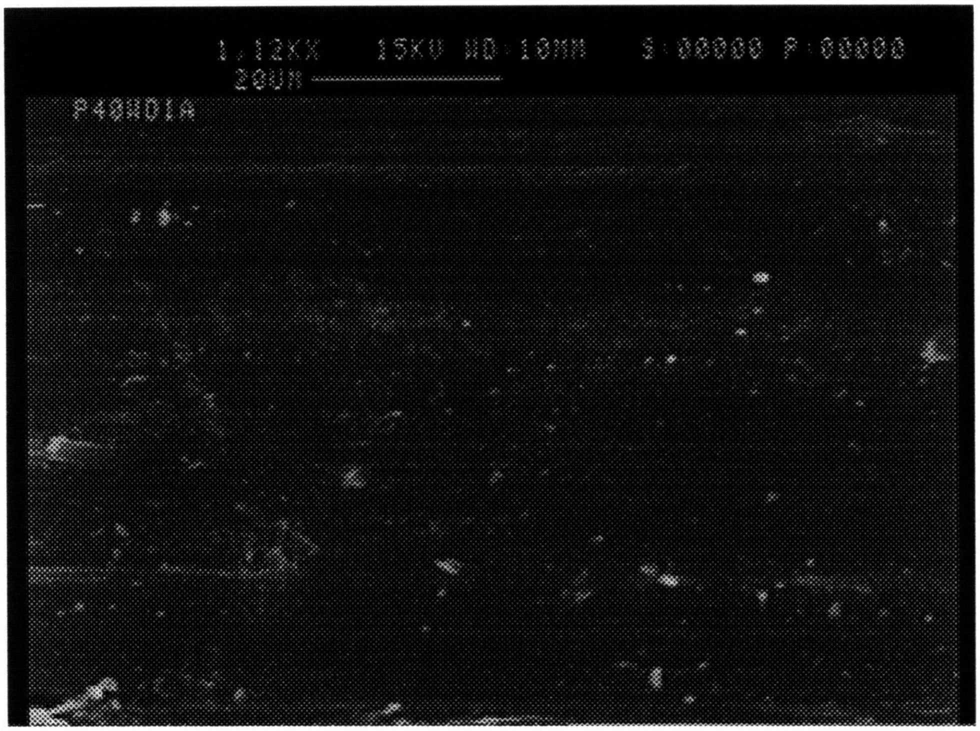


Figure 6-101: The Polyimide-coated optical-fiber under 40 wet-dry cycles (1,120 X).

Figure 6-102: The Teftzel-Silicone-coated optical-fiber under 40 wet-dry cycles (925 X).

Figure 6-103: The Acrylate-coated optical-fiber under 30freeze-thaw cycles (467 X).

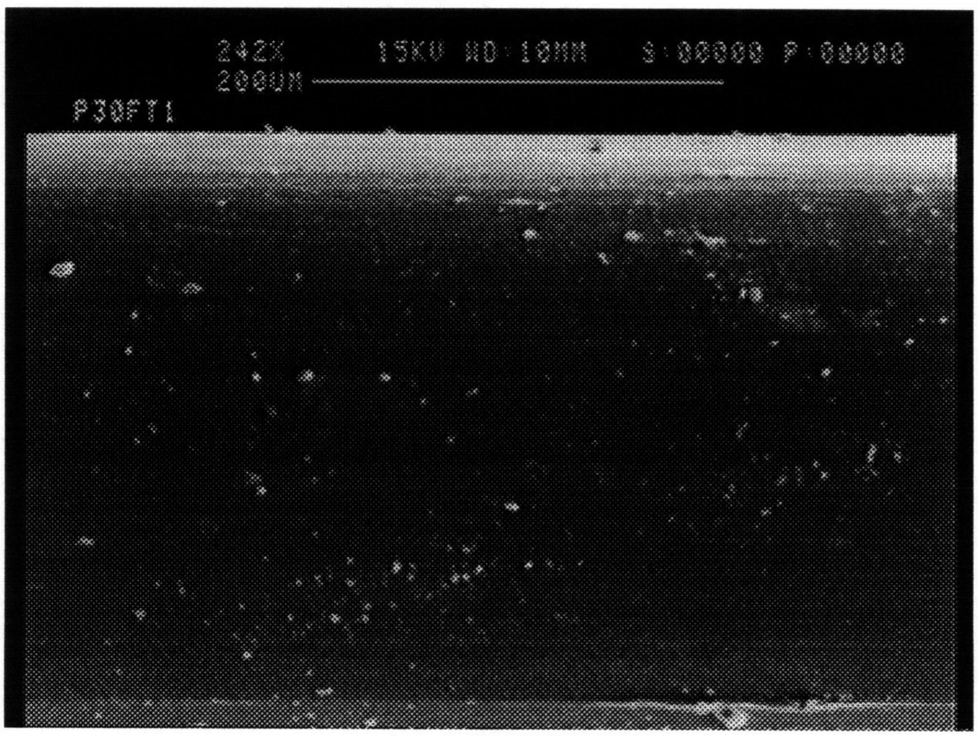


Figure 6-104: The Polyimide-coated optical-fiber under 30 freeze-thaw cycles (242 X).

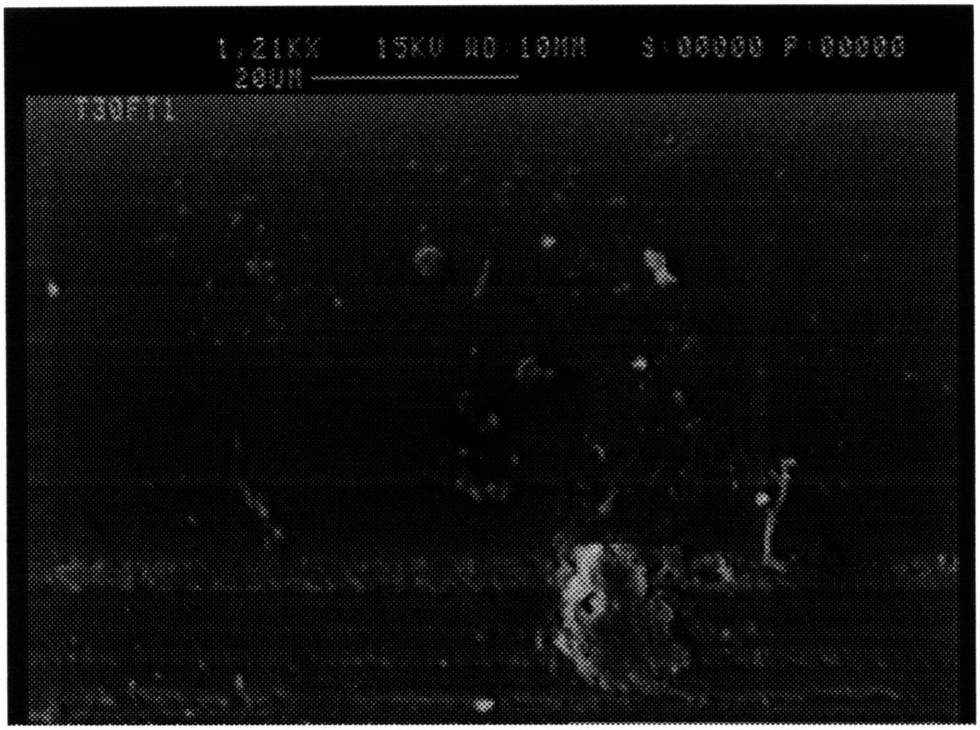


Figure 6-105: The Teftzel-Silicone-coated optical-fiber under 30 freeze-thaw cycles (1,210 X).

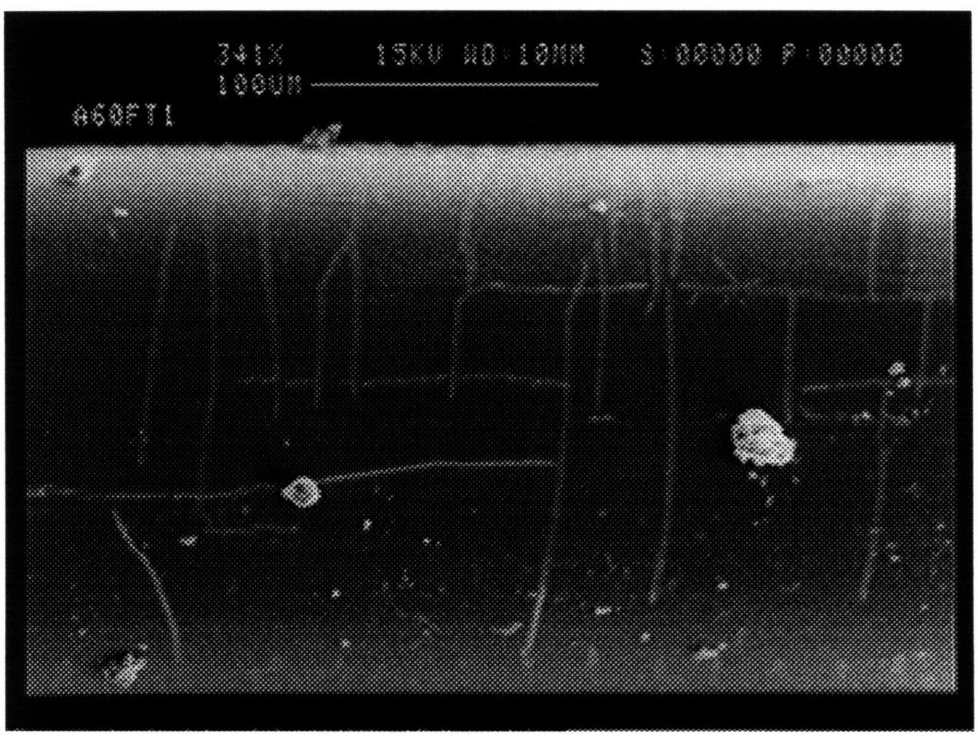


Figure 6-106: The Acrylate-coated optical-fiber under 60 freeze-thaw cycles (341 X).

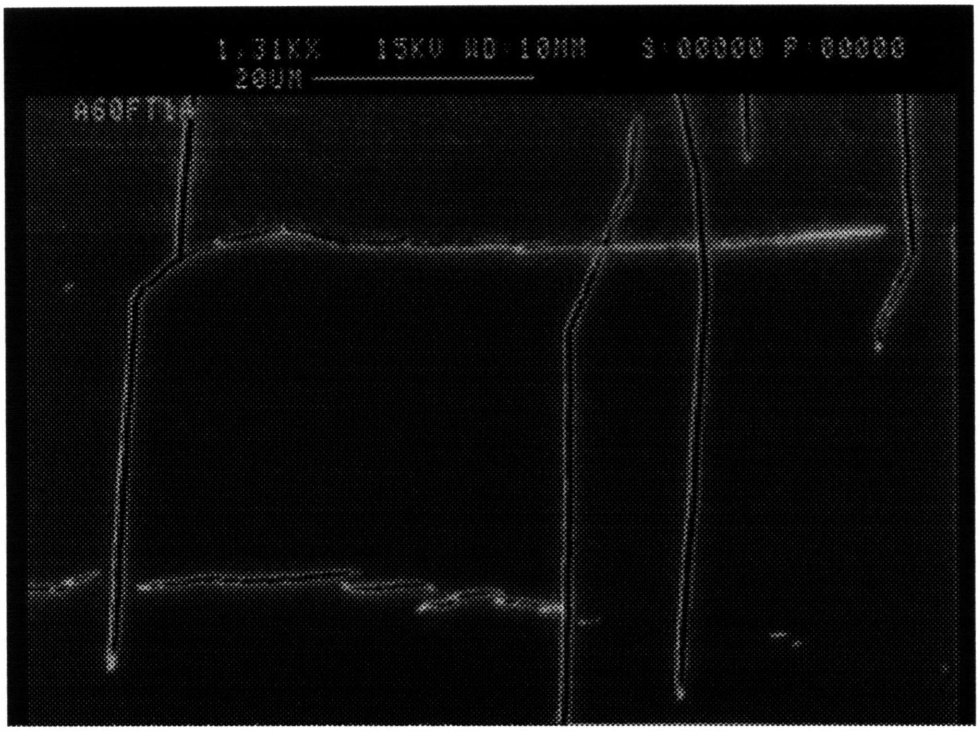


Figure 6-107: The Acrylate-coated optical-fiber under 60 freeze-thaw cycles (1,310 X).

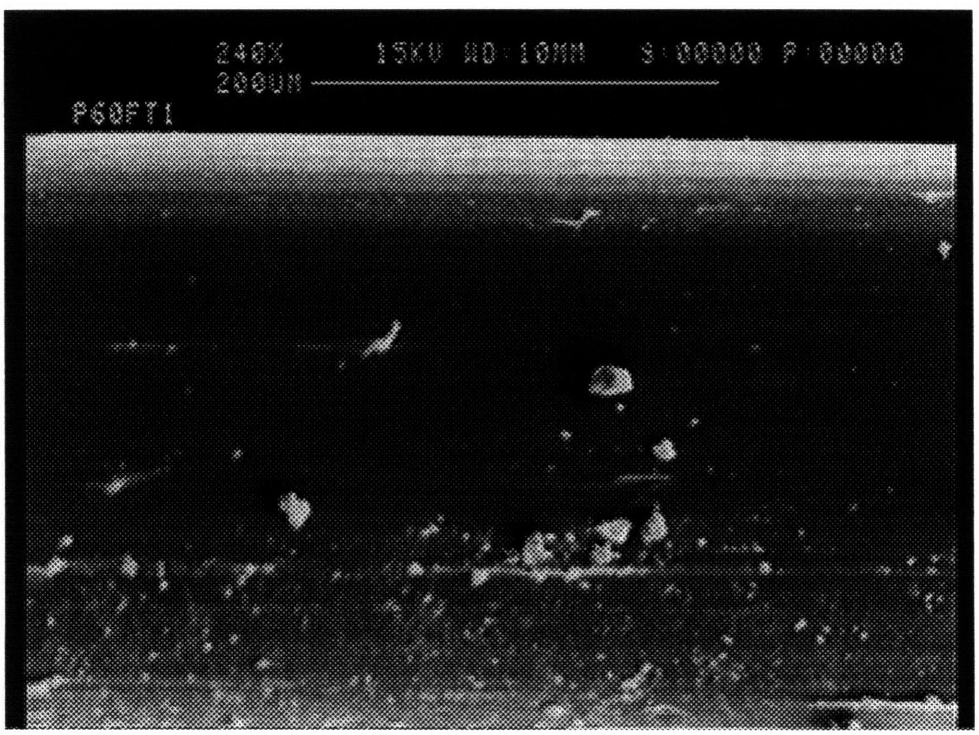


Figure 6-108: The Polyimide-coated optical-fiber under 60 freeze-thaw cycles (240 X).

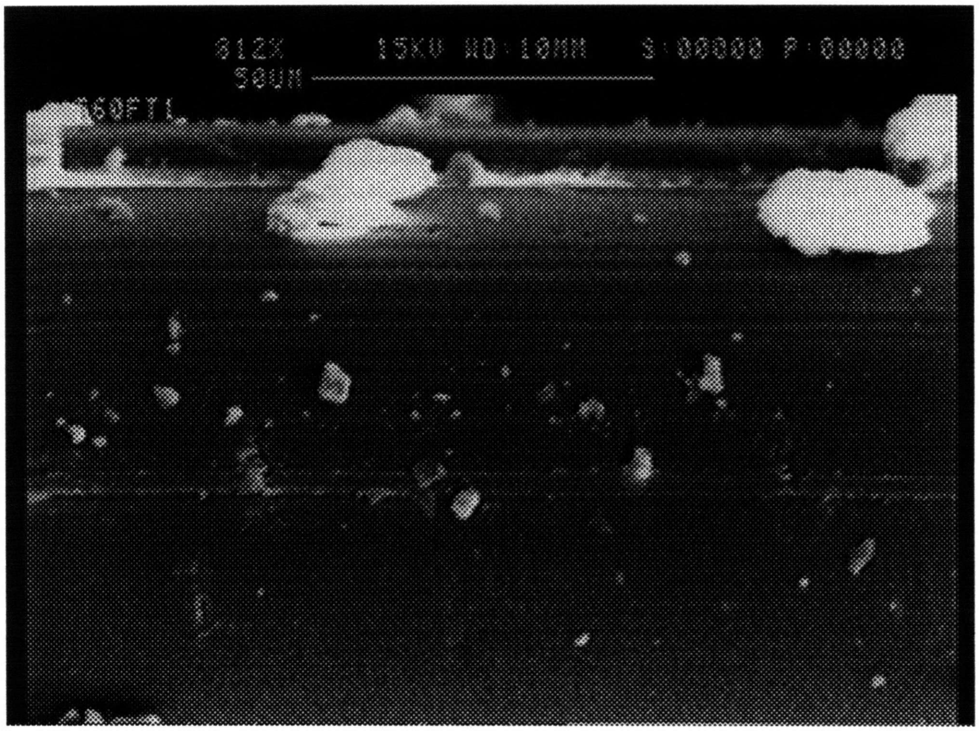


Figure 6-109: The Teftzel-Silicone-coated optical-fiber under 60 freeze-thaw cycles (812 X).

Figure 6-110: The Acrylate-coated optical-fiber 3month inside the cement paste (pull-out extraction).

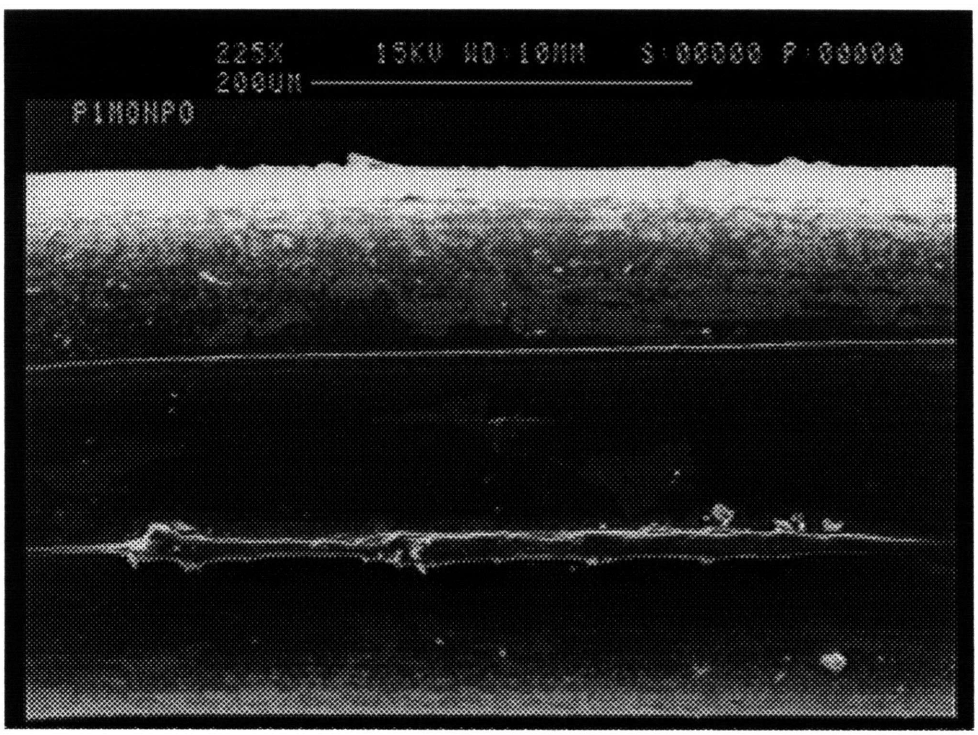


Figure 6-111: The Polyimide-coated optical-fiber 1 month inside the cement paste (pull-out extraction).

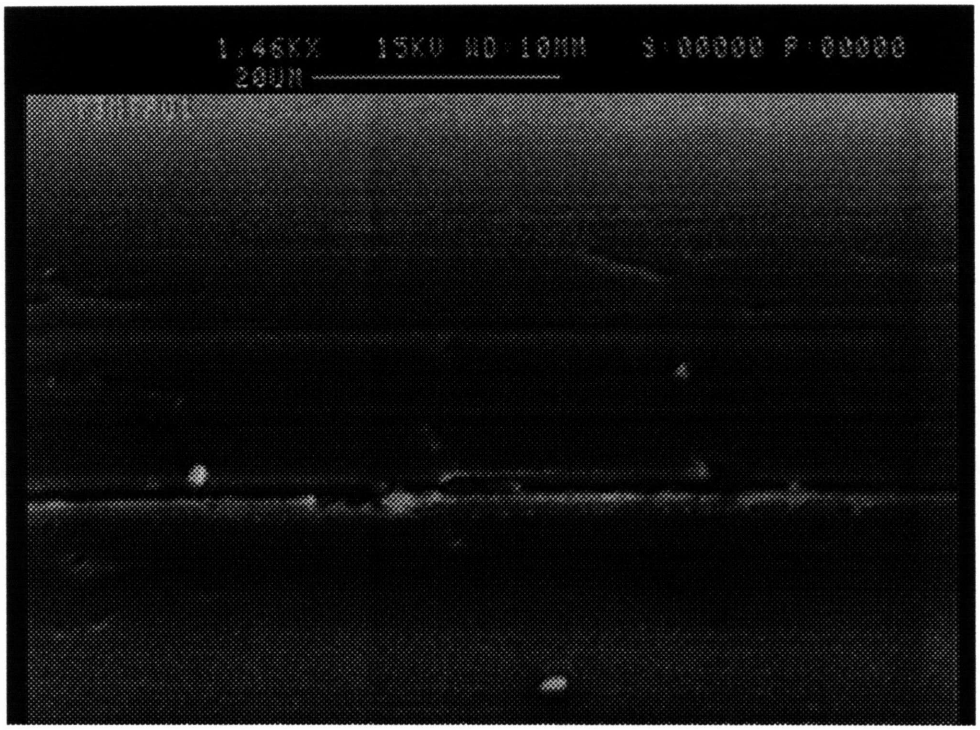


Figure 6-112: The Teftzel-Silicone-coated optical-fiber 3 month inside the cement paste (pull-out extraction).

Chapter 7

Conclusions and Future Work Recommendations

The practical application of fiber optic sensing for concrete structures requires several technical advances. These include: successful embedment of the optical fiber without affecting either the design performance of the structure or the integrity of the fiber; accurate coupling of structural parameters to the fiber through appropriate fiber coatings compatible with the composite matrix; selection of optimum fiber optic sensor signal conditioning and signal processing techniques to convert the sensed information into usable form. [Spillman, 1988]

7.1 Summary of Experimental Results

Fiber pull-out behavior is affected by environmental conditions which have been studied extensively in this thesis. It was found that acrylate performed poorly compared to polyimide and teftzel-silicone fibers. For the acrylate coating, there was a general reduction in the peak pull-out loads except for the wet/dry cycling case where the interfacial strength increases with the number of cycles introduced to the specimens. For polyimide and teftzel-silicone, the pull-out loads either increased or remained the same as the first month period inside the cement paste. These fiber coatings prove to be more effective compared to the acrylate fibers.

For the second part of the program, extensive studies of surface damage were carried out with the help of SEM. The degradation of acrylate coating was obvious during most of the environmental condition, except the case where they were stored in the water tank under calcium hydroxide solution. In this case, the formation of calcium hydroxide crystals on the fiber surface prevents observations of the surface. Nonetheless, after 3 months in the water tank thin cracks on the surface are developed. The results agreed with the finding of Habel et al. [1995] which concluded that cracks as wide as 1100 nm could form in the acrylate-coated fiber. Thus implementation of the acrylate-coated fibers embedded in concrete structure should be avoided. The overall performance of polyimide and teftzel silicone again showed promise of surviving in harsh environments like concrete. Damages occurred but mainly due to mishandling of the fibers. However, the results for polyimide-coated optical fibers did not come in agreement with Habel et al. [1995]. In their paper, they observed the swelling deterioration in fiber in alkaline condition and suggested that polyimide-coated fibers should not be used for embedment in concrete. However, the SEM results herein did not observe that kind of condition. Polyimide fibers showed good integrity inside alkaline condition. The results of teftzel-silicone-coated optical fibers agreed with Escobar et al. [1992]. They showed excellent performance of teftzel-silicone optical fibers after five years of embedment inside a concrete beam. Results of both the pull-out tests and SEM investigation show the possibility of using these types of fibers in the near future. There is an agreement between the pull-out test results and SEM observations regarding the acrylate-coated fibers condition. The pull-out tests showed a decrease in interfacial strength due to aging and freeze thaw cycles. SEM confirmed this weakness by showing large surface cracks. Thus, it is not recommended to use this type of optical fiber in concrete structures.

For the third part of the study, the crack opening measurement were undertaken. It illustrates that the sensitivity increases with increasing angle from 15 to 45 degrees. Both 30 and 45 degree angles show higher dynamic range compared to the 15 degree. However, for the 45 degree, the results are more scattered and this may be due to the heterogeneous nature of the material.

7.2 Recommendation of Future Studies

Further durability studies and quantitative study of optical fibers should be carried out. Several suggestions for further studies are as follows:

1. The embeddment of optical fibers inside larger specimen (i.e. concrete block) to demonstrate its applicability for real structures.
2. In this work, one found that teftzel-silicone-coated fiber showed significant strength compared to acrylate-coated fiber. One needs carried out longer term studies with the teftzel-silicone fiber to ensure its durability under practical conditions.

3. Besides fiber pull-out and SEM studies, optical measurements (for the determination of strain) should be carried out to assess the actual performance of the optical fiber as a sensor.
4. For the inclined fiber crack sensor, more experimental work needs to be done to obtain consistent results.

Appendix A

Derivation of the Maxwell's Equation for Snell's Law

Fiber optic sensor testing of materials makes use of electromagnetic waves in contrast to ultrasonic techniques which use mechanical waves. A successful application of fiber optics sensor to concrete structures for nondestructive testing requires a clear understanding of the theories behind this technique, thus Maxwell's equation is presented.

A.1 Maxwell's Equation

The Maxwell's equations are given here to show how these equations lead to the Snell's reflection theory and total internal reflection which is the basic theory of wave propagation in optical fibers.

Maxwell's equations written in differential forms are as follows :

$$\nabla \times E = -\frac{\partial B}{\partial t} \qquad \text{(a)} \tag{A.1}$$

$$\nabla \times H = J + \frac{\partial D}{\partial t} \quad \text{(b)}$$

$$\nabla \bullet D = \rho \qquad \text{(c)}$$

$$\nabla \bullet B = 0 \qquad \text{(d)}$$

These four equations contain five vector fields, where **E**, **B**, **H**, **J**, and **D**[1] are the electric field intensity, the magnetic flux density, the magnetic field intensity, the current density, the electric flux density, respectively ρ is the scalar field which represents the electric charge density. The del operator is ∇ . In rectangular coordinates the del operator ∇ = x **i** + y **j** + z **k** , where **i** , **j** , **k** are unit vectors in the x, y, and z directions.

To be able to solve the above equations for the unknown, one need three more equations. The three constitutive relations are as follows :

$$\mathbf{J} = \sigma\mathbf{E},\ \mathbf{D} = \varepsilon\mathbf{E},\ \mathbf{B} = \mu\mathbf{H} \qquad \text{(A.2)}$$

where the parameters σ, ε, and μ depend on the medium in which the field exist. In the case of the source regions are air or glass where there is no free charge, **J** = 0 and ρ = 0. thus for the medium which is time invariant, homogeneous, isotropic, and linear, the constitutive relations become **B** = μ**H** and **D** = ε**E** , where the permeability (μ) , and the permittivity (ε) , are the scalar quantities that do not vary in space or time. Thus, under these conditions Maxwell's equations become :

$$\nabla \times E = -\mu \frac{\partial H}{\partial t} \qquad \text{(a)} \qquad \text{(A.3)}$$

[1] The bold characters mean that the variables are vector quantities.

$$\nabla \times H = \varepsilon \frac{\partial E}{\partial t} \qquad \text{(b)}$$

$$\nabla \bullet E = 0 \qquad \text{(c)}$$

$$\nabla \bullet H = 0 \qquad \text{(d)}$$

In order to obtain the wave equation, one needs to combine equations A.3(a) and A.3(b), but before combining these equations, first take the curl of equation A.3(a).

$$\nabla \times (\nabla \times E) = \nabla \times \left(-\mu \frac{\partial H}{\partial t} \right) \qquad \text{(A.4)}$$

By interchanging the differentiation order with respect to time and space, and moving constant μ out of the derivative

$$\nabla \times (\nabla \times E) = -\mu \frac{\partial}{\partial t} (\nabla \times H) \qquad \text{(A.5)}$$

Now, substitute equation A.2(b) into A.5 for $\nabla \times H$.

$$\nabla \times (\nabla \times E) = -\mu\varepsilon \frac{\partial^2 E}{\partial t^2} \qquad \text{(A.6)}$$

Recall the vector identity $\nabla \times (\nabla \times E) = \nabla(\nabla \bullet E) - \nabla^2 E$. Using this identity expands equation A.6. From equation A.3(c) the first term on the right hand side is equal to zero. Thus the vector wave equation can be obtained.

$$\nabla^2 E = \mu\varepsilon \frac{\partial^2 E}{\partial t^2} \qquad \text{(A.7)}$$

It is convenient to use phasor components since the field vectors have sinusoidally varying components.

$$\mathbf{E} = A \cos(\omega t + \theta_x)\, \underline{\mathbf{i}} + B \cos(\omega t + \theta_y)\, \underline{\mathbf{j}} + C \cos(\omega t + \theta_z)\, \underline{\mathbf{k}} \qquad \text{(A.8)}$$

The x, y, and z components vary sinusoidally at the same frequency where each component may have a different amplitude and phase. When phasor are used to represent the sinusoidally varying components, the following phasor vector results

$$\mathbf{E} = E_x \underline{\mathbf{i}} + E_y \underline{\mathbf{j}} + E_z \underline{\mathbf{k}} \quad (A.9)$$[2]

where the complex numbers $E_x = A < \theta_x$, $E_y = B < \theta_y$, and $E_z = C < \theta_{z,}$. These complex numbers are the phasor representations of the components of the vector.

Taking the derivative of a sinusoid with respect of time corresponds to multiplying its phasor representation by $j\omega$. The wave equation becomes

$$\nabla^2 E = -\omega^2 \mu \varepsilon E \quad (A.10)$$

A.2 Plane Waves

Plane waves are waves which have planar constant wave and they are simple in term of mathematical form. The plane waves are the most basic of waveforms and the sum of them could represent complex waves. In the case of uniform plane wave both the amplitude and phase of field quantity are constant in a plane. Equation A.10 shows a uniform plane wave which polarized in the x direction and propagating in the z direction. A wave polarized in the x direction has electric field components only in the x direction. Assume the phasor vector representation of the electric field is only a function of z

$$\mathbf{E} = E_x \underline{\mathbf{i}} \ (z) \quad (A.11)$$

[2] The vector terms of i, j, and k are interchangeably used with x, y, and z in this context.

Since the function **E** has no dependency on x and y, thus the Laplacian operator reduces to, $\nabla^2 = \frac{\partial^2}{\partial z^2}$. The wave equation becomes

$$\frac{\partial^2 E_x}{\partial z^2} = \omega^2 \mu \varepsilon E_x \tag{A.12}$$

The solution of E_x in equation (A.12) is in the exponential function form of

$$E_x = E_0 e^{\pm jkz} \tag{A.13}$$

where $k = \omega\sqrt{\mu\varepsilon}$. $E_0 = A < \theta_x$ is a complex constant which depends on the boundary conditions. One can transform the equation A.13 into a phasor quantity that corresponds to the following time function

$$\mathbf{E}_x(t, z) = A \cos(\omega t \pm kz + \theta) \tag{A.14}$$

For a constant phase, $\omega t \pm kz$ = constant. One can find phase velocity by differentiation. The velocity of a constant phase point is then given by:

$$v_p = \frac{dz}{dt} = \pm\frac{\omega}{k} = \pm\frac{1}{\sqrt{\mu\varepsilon}} \tag{A.15}$$

The index of refraction of a medium is the ratio between the phase velocity in free space to the phase velocity in the medium. Thus the refractive index of a medium (n) is

$$n = \frac{v_{vacuum}}{v_{medium}} = \frac{k_{medium}}{k_{vacuum}} = \sqrt{\frac{\varepsilon_{medium}}{\varepsilon_{vacuum}}} = \sqrt{\varepsilon_r} \tag{A.16}$$

where $k_{vacuum} = \omega\sqrt{\mu_0\varepsilon_0}$[3], ε is the permittivity of free space, and ε_r is the dielectric constant. Note that one has assumed the medium to be non-magnetic hence $\mu = \mu_0$.

[3] The subscripts "vacuum" and "0" are used interchangeably in this context.

A.2.1 Generalized Plane Waves

Generalized plane waves introduce the same wave propagating with equation A.12 however in some directions other than the z axis. The rotation of coordinates changes is denoted by a plane described by $k_x \underline{\mathbf{i}} + k_y \underline{\mathbf{j}} + k_z \underline{\mathbf{k}} = \phi$ = constants. Thus, a field quantity corresponded with this wave is

$$E = E_0 \, e^{-j(k_x x + k_y y + k_z z)} \tag{A.17}$$

where E_0 is a constant phasor vector. Since **r** is the vector position of any point in space, the equation A.17 could be written as

$$E = E_0 \, e^{-j(k.r)} \tag{A.18}$$

By taking the derivative of equation A.18 with respect to x, y, and z of plane field quantities is equivalent to multiplying by -j**k**. This allow the del operator, which in rectangular coordinates is $\nabla = \bar{x}\frac{\partial}{\partial x} + \bar{y}\frac{\partial}{\partial y} + \bar{z}\frac{\partial}{\partial z}$, to be substituted by -jk while the Laplacian operator which in rectangular coordinates is $\nabla^2 = \bar{x}\frac{\partial^2}{\partial x^2} + \bar{y}\frac{\partial^2}{\partial y^2} + \bar{z}\frac{\partial^2}{\partial z^2}$, is substituted by

$$\nabla^2 = -k_x^2 - k_y^2 - k_z^2 = -k^2 \tag{A.19}$$

where k^2 is the magnitude of **k** squared. By substituting **k** into ∇ in the equation A.3 , the new representation of Maxwell's equations are as follows

$$k \times E = \mu \, \omega H \qquad \text{(a)} \tag{A.20}$$

$$k \times H = -\varepsilon\, \omega \mathrm{E} \qquad \text{(b)}$$

$$k \bullet E = 0 \qquad \text{(c)}$$

$$k \bullet H = 0 \qquad \text{(d)}$$

The magnitude of k could be found by substituting equation A.19 into equation A.10 :

$$k = \omega\sqrt{\mu\varepsilon} \tag{A.21}$$

The magnetic field associated with the plane wave is simply obtained from equation A.20(a):

$$H = \frac{1}{\omega\mu}\,\mathrm{k} \times \mathrm{E} \tag{A.22}$$

Also from equations A.20, one could find that **E** is perpendicular to both **k** and **H**. Since **k** and **E** are perpendicular, the magnitude of **H** is the product of the magnitudes of k and **E** divided by ωμ. Using equation A.22 and A.21 it follows that

$$E^* = \sqrt{\frac{\mu}{\varepsilon}}H^* \tag{A.23}$$

where E* and H* are both the magnitudes of **E** and **H** and $\sqrt{\mu/\varepsilon}$ is the characteristic impedance of the medium. Another equation for characteristic impedance is

$$Z = \sqrt{\frac{\mu}{\varepsilon}} = \frac{Z_0}{n} \tag{A.24}$$

where n is the index of refraction and Z_0 is the characteristic impedance of free space.

From equations A.20(a) and (b), **E**, **H**, and **k** form an orthogonal set of vectors. Since **E** and **H** are perpendicular, the magnitude of **E** x **H** is the magnitude of **E** multiplied by the magnitude of **H**. Substituting the value of H* from equation A.23, **E** x **H** becomes

$$E \times H = \frac{E^2}{Z} k' \tag{A.25}$$

where k' is the unit vector in the direction of **k** and **E** x **H** is the Poynting vector. Its units are watts per square and its direction parallel with the direction of energy flow in isotropic media.

A.3 Propagation of Light in Two Media

When the propagation of light wave takes place in two different medium, the amount of light reflected at a dielectric interface depends on the incidence angle, polarization, as well as the indices of the two media. In order to obtain the reflection and transmission coefficient, the boundary conditions should be satisfied i.e. the tangential components of both the E and H vectors are continuous at the interface. Thus the incident, reflected and transmitted plane waves shown in Figure A1-1 are

$$\mathrm{E}_{\imath} = E_{\imath} \bullet e^{-jk_{\imath} \bullet r} \tag{A.26}$$

$$\mathrm{E}_{R} = E_{R} \bullet e^{-jk_{R} \bullet r}$$

$$\mathrm{E}_{t} = E_{t} \bullet e^{-jk_{t} \bullet r}$$

Snell's law follows from the boundary conditions and states that the phase variation along the interface must be the same for the incident, reflected, and transmitted fields. At the interface:

$$\bar{k}_{\imath} \bullet \bar{r} = \bar{k}_{R} \bullet \bar{r} = \bar{k}_{t} \bullet \bar{r} \tag{A.27}$$

At the interface where z = 0, equating the phases of the incident, reflected, and transmitted waves at interface

$$n_1 k_0 \sin\theta_i = n_1 k_0 \sin\theta_R = n_2 k_0 \sin\theta_t \qquad \text{(A.28)}$$

From equation A.28, it turns out that the angle of incidence equals to the angle of reflection, $\theta_i = \theta_R$, and the next relationship is the familiar form of Snell's law

$$n_1 \sin\theta_i = n_2 \sin\theta_t \qquad \text{(A.29)}$$

Total internal reflection occurs at the interface between two media where n_2 is less than n_1 and also when the incidence angle is larger than the critical angle of the incidence wave, no light propagates into medium 2. The increase in the incidence angle leads to the increase with the transmitted angle. When $n_1 > n_2$, θ_t is greater than θ_i and there is critical incidence angle for θ_t which = 90°.

The propagation vector into medium 2 can be described in x and z vector directions

$$\overline{k_t} = n_2 k_0 (\sin\theta_t \; \bar{x} + \cos\theta_t \; \bar{z}) \qquad \text{(A.30)}$$

and using Snell's law and trigonometric identity, the transmitted vector could be write in terms of incident angle such as $\cos\theta_t = \left[1 - \left(\frac{n_1}{n_2}\right)^2 \sin^2\theta_i\right]^{\frac{1}{2}}$. If the incident angle is greater than critical angle of transmitted angle, there will be no refracted light into the medium 2 except of surface wave propagation which is described as a decay exponentially with z-direction. Thus the expression for the electric field associated with the wave in the medium 2 is

$$E_t = E_t \bullet e^{-z/\delta} \, e^{-j(n_2 k_0 \sin\theta_t)x} \qquad \text{(A.31)}$$

where $\delta = \left(\frac{1}{k_0}\right)\left(n_2^2 - n_2^2 \sin^2 \theta_i\right)^{-\frac{1}{2}}$ is the depth of penetration of the light into the second medium.

Another interesting point about the light propagation into different media is the reflected and transmitted waves in terms of the incident wave by using boundary conditions at the interface. The tangential E and H fields are continuous throughout the interface. For parallel polarization, based on equilibrium in the tangential components of electric field and the tangential components of magnetic fields in both media, the following equations can be obtained:

$$E \cos\theta_i + E_R \cos\theta_R = E_t \cos\theta_t \tag{A.32}$$

$$H - H_R = H_t \tag{A.33}$$

Two other equations with similar to those in equations A.32 and A.33 could also be obtained for perpendicular polarization. Since E and H for the three waves are related by the characteristic impedance of the medium, equation A.33 can be written in terms of electric fields as follows,

$$n_1(E_i - E_R) = n_2 E_t \tag{A.34}$$

Substituting equation A.34 into the equilibrium of tangential components of electric field in the equation A.32 results in the following

$$(E_i + E_R) n_2 \cos\theta_i = (E_i - E_R) n_1 \cos\theta_t \tag{A.35}$$

Reflection coefficient is defined as the ratio of E_R to E_i , using equation A.35 for both parallel and perpendicular reflection coefficients and the trigonometric identity of $\cos\theta_t = \left[1 - \left(\frac{n_1}{n_2}\right)^2 \sin^2\theta_i\right]^{\frac{1}{2}}$, one can obtain

$$R_{Parallel} = \frac{n_1\left[1-\left(\frac{n_1}{n_2}\right)^2 \sin^2\theta_i\right]^{\frac{1}{2}} - n_2\cos\theta_i}{n_1\left[1-\left(\frac{n_1}{n_2}\right)^2 \sin^2\theta_i\right]^{\frac{1}{2}} + n_2\cos\theta_i} \tag{A.36}$$

$$R_{\perp} = \frac{\cos\theta_i - \left[\left(\frac{n_1}{n_2}\right)^2 - \sin^2\theta_i\right]^{\frac{1}{2}}}{\cos\theta_i + \left[\left(\frac{n_1}{n_2}\right)^2 - \sin^2\theta_i\right]^{\frac{1}{2}}} \tag{A.37}$$

The transmission coefficient is the ratio of the phasor representing the transmitted wave (E_t) to the phasor representing the incident wave (E_i). The boundary conditions for the transmission coefficients are found similar to those used to obtain the reflection coefficients. The transmission coefficients for parallel and perpendicular polarizations are

$$T_{Parallel} = \frac{2n_1\cos\theta_i}{n_1\left[1-\left(\frac{n_1}{n_2}\right)^2 \sin^2\theta_i\right]^{\frac{1}{2}} + n_2\cos\theta_i} \tag{A.38}$$

$$T_{\perp} = \frac{2\ \cos\theta_i}{\cos\theta_i + \left[\left(\frac{n_1}{n_2}\right)^2 - \sin^2\theta_i\right]^{\frac{1}{2}}} \tag{A.39}$$

References

[1] Tripler, A. Paul, Physics , Volume 2 , Worth Publishers, Inc., 1976.

[2] Brancazio, J. Peter, The Nature of Physics, Macmillan Publishing Co. Inc, 1975.

[3] Resnick, Robert., Halliday, David., The Fundamental of Physics, John Wiley & Sons, 1978.

[4] Seippel, Robert G., Fiber Optics, Reston Publishing Co. Inc, Reston, Virginia, 1983.

[5] Giancoli, C.Douglas., Physics for scientists and engineers, 2nd ed., Prentice Hall, New Jersey, 1988.

[6] Ditchburn, R.W., Light , 3rd ed., Academic Press Inc.(London) Ltd., 1976.

[7] Richtmyer, F.K., Kennard, E.H., Lauritsen, T., Introduction to Modern Physics, 5th ed., McGraw-Hill Book Company, Inc., 1955.

[8] Kao, Charles K., Optical Fibre, Peter Peregrinus Ltd., 1988.

[9] Briley, Bruce E., An Introduction to Fiber Optics System Design, Elsevier Science Publishing Company, Inc., 1988.

[10] Udd, Eric., Fiber Optic Sensors : An Introduction for Engineers and Scientists, John Willey & Sons, Inc. New York, 1991.

[11] Ungar, Serge., Fibre Optics : Theory and Applications, John Willey & Sons Ltd., England, 1990.

[12] Christian, N.L., Passauer, L.K., Fiber Optic Component Design, Fabrication, Testing, Operation, Reliability, and Maintainability, Noyes Data Corporation, Park Ridge, New Jersey, 1989.

[13] Jeunhomme, Luc B., Single-Mode Fiber Optics: Principles and Applications, Marcel Dekker, Inc., New York, 1983.

[14] Chester, A.N., Matellucci, S., Verga, A.M., Optical Fiber Sensors, Martinus Nijhoff Publishers, Dordrecht, Netherlands, 1986.

[15] Taylor, Henry F.,. "Novel Applications of Fiber Optics," Fiber Optics: Advances in Research and Development, Editors, Bendow, B., Mitra, S.S., University of Rhode Island, Plenum Press, New York, 1978.

[16] Schultz, Peter C.,. "Vapor Phase Materials and Processes For Glass Optical Waveguides", Fiber Optics: Advances in Research and Development, Editors, Bendow, B., Mitra, S.S., University of Rhode Island, Plenum Press, New York, 1978.

[17] Basch, E.E., Carnes, H.A., "Digital Optical Communication Systems," Fiber Optics, Editor, James C.Daly, CRC Press,Boca Raton, Florida, 1984.

[18] Olsen, G. Robert, Rogers, A. David, "Propagation in Optical Fibers," : Fiber Optics, Editor, James C.Daly, CRC Press,Boca Raton, Florida, 1984.

[19] Aggarwal, D. Ishwar, "Optical Waveguide Manufacturing", Fiber Optics, Editor, James C.Daly, CRC Press,Boca Raton, Florida, 1984.

[20] Horiguchi, M., Osanai, H., Electronics Letter 12, pp 310 (1976).

[21] Kawana, A., Kawachi, M., Miyashita, T., Fourth European Conference on Optical Communication, Genova, Italy, p.23-29 (Sept. 12-15, 1978).

[22] Izawa, T., Kobayashi, S., Sudo, S., and Hanawa, F., "Continuous Fabrication of High Silica Fibre Preform," Proc. Int. Conf. Int. Opt. & Opt. Fiber Communication, pp 375, Tokyo,1977.

[23] Lengyel, G., "Optical Sources," Fiber Optics, Editor, James C.Daly, CRC Press,Boca Raton, Florida, 1984.

[24] Mehta, P. Kumar, Monteiro, Paulo J.M., Concrete : Structure, Properties, and Materials, Second Edition, Prentice Hall, New Jersey, 1993.

[25] Anshari, F., Sture, S., Nondestructive Testing of Concrete Elements and Structures, Proceedings of Engineering Mechanics Division of ASCE, San Antonio, 1992.

[26] Stevens, A., "Design Life in Practice," The Design Life of Structures, Editor, Somerville, G., pp 25-29, Blackie and Son Ltd., Glasgow, 1992.

[27] Sansalone, M., Carino, N.J., "Impact Echo: A New Method For Inspecting Construction Materials," Non-destructive Testing and evaluation for Manufacturing and Construction Conference, Editor, Henrique L.M. dos Reis, pp 209-223, University of Illinois at Urbana Champaign, Hemisphere Publishing Corporation, 1990.

[28] Spillman Jr., W.B., "Fiber Optic Sensors for Composite Monitoring", Fiber Optic Smart Structures and Skins, Eric Udd, Editor, Proc. SPIE 986, pp. 6-9, 1989.

[29] Spillman Jr., W.B., "Instrumentation architecture development for smart structures", Richard O. Claus, Editor, SPIE Vol. 1918 Smart Sensing, Processing, and Instrumentation, pp 165-171, 1993.

[30] Hecht, J.,Understanding Fiber Optics, 2nd edition, Sams Publishing, 1993.

[31] Corke, M., Kersey, A.D., Jackson, D.A., and Jones, J.D.C. (1983). All fiber Michelson thermometer, Electron Letter.,19, pp.471.

[32] Lee, C.E., Taylor, H.F., Marcus, A.M., Proc. SPIE 1489 (1991).