Mechanical Behavior of Optical Fibers Removed From a Field-Aged Cable

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Abstract

Optical fiber handleability after exposure to field conditions is an important aspect for long term reliability. The attributes that control handleability of a fiber are mainly strength and strippability. In the present study optical fibers were removed from a nine year old cable that had been aged in the field for five years. The effect of zero stress aging on the strength of these fibers in these field conditions is studied. The surface roughness was measured using an Atomic Force Microscope (AFM). In addition, the strip force and Dynamic Mechanical Analysis (DMA) on coating materials was performed. Results show that these fibers are as handleable as their as-manufactured counterparts and the zero stress aging of the cabled fibers is not a reliability concern.

Introduction

Based on a 1993 Bellcore study, cable failures account for nearly 1/3 of the total telecommunication outages[1]. About 59% of these cable failures occurred as a result of accidental dig-ups. However, this paper is concerned with failure mechanisms for optical fiber that can be considered related to the long-term glass and coating degradation; namely, strength degradation due to fatigue eventually causing fiber breakage and the inability to handle the fiber in the field during stripping, cleaving, and splicing.

There are no cases reported so far where fiber fatigue was responsible for a network failure. This is indicative of the conservatism built into current cable designs and the care taken in avoiding stresses during cable deployment. It is still important to understand whether or not fibers would be handleable during re-entry and repair after several years of field aging.

The purpose of this study was to examine the handleability of fibers aged in a cable and to reflect on the significance of the results as they pertain to handleability of fibers during cable repair and re-entry. The role of coating and the cable components in protecting the fibers from aging and strength degradation was also studied. Results are found to be consistent with studies[2] where fibers were aged in a cabled condition.

Background

Whereas there is an abundance of strength data on short fiber lengths after laboratory aging, there are only a few publications that examine the strength of fiber in the field-aged state.[2,3] Since there are no industry accepted models for translating accelerated laboratory aging behavior to field aging behavior, it is difficult to predict functional field performance from laboratory data. To study the degradation over time, an empirical approach should be followed and fibers from a field-deployed cable should be removed and tested.

An earlier study,[2] where fibers were removed from a severely aged cable, showed almost no degradation of mechanical characteristics of the optical fibers due to aging. Other recent studies have shown strength degradation of optical fiber due to accelerated laboratory aging[4,5]. These reports may seem contradictory, but a close examination of the experimental procedures reveals that most of the studies are based on the testing of uncabled fibers aged in environments not commonly encountered in the field. Unfortunately, the results of such studies are almost always interpreted in terms of real field conditions which is misleading.

For example, in a 1988 work[4] a drop in strength was observed after aging in water.

Fibers were tested in a 2-pt bend configuration after aging the uncabled fibers in 100°C water. In a more recent study[5] uncabled fibers were tested in 25°C, 40°C, 60°C, 80°C and 100°C water and a drop in strength was noted. Based on this work, an aging model was proposed which has the Arrhenius form,

$$t = t_0 \exp(E/RT) \qquad ....(1)$$

where t is time required for a specific strength degradation, t_o is a pre-exponential term, E is the activation energy of the reaction causing strength degradation, R is the gas constant, and T is the absolute temperature of the water. Another complication comes from the fact that different fibers yield different rates of strength degradation. After aging in ~40°C water, a more than 40% drop in strength was seen for the fiber tested by Kurkjian et. al.[5], whereas a less than 10% strength drop was observed for the fiber tested by Carr[6]. The strength degradation model proposed by Carr[6]. The strength degradation model proposed by Carr[6] has the following form.

$$S = S_o \exp(-\alpha \ t^{1/2}) \qquad ....(2)$$

Where S_o is the initial strength and S is the strength after aging for time, t, in water, and α is a constant for a given material and aging condition.

Most aging models[5,6] suggested so far are based on aging studies of uncabled fiber in the liquid water (25-100°C) which is not a common environment for most applications. The results of the present study would be used to assess the handleability of field-aged fibers during re-entry and repair as well as to test the applicability of the proposed aging models to commonly encountered field conditions.

Cable Design

A schematic of the cable design used for this study is illustrated in Figure 1. The cable consisted of four gel-filled buffer tubes and one filler tube. Each buffer tube contained six fibers. Two of the buffer tubes contained single-mode fibers while the remaining two tubes contained multimode fibers. Only the single-mode fibers were use for the present study since mechanical attributes of optical fibers area assumed to be independent of their refractive index profiles. All fibers were coated with a dual layer acrylate coating and overcoated with a thin layer of thermally cured coloring ink. The loose tube cable design was an unarmored construction with interstitial compound for water blocking.

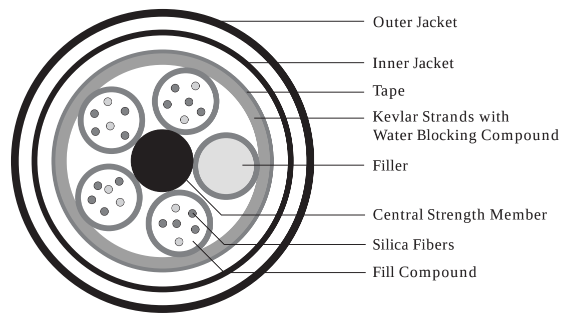

Figure 1: Schematic of the cable design.

Cable History

The cable tested in the present study was installed in an underground conduit between buildings in Corning, NY. The cable was manufactured in 1985 and left in a warehouse in an uncontrolled environment for just over two years. It was first installed in September 1987, and then re-routed in April 1992. The segment tested in the present study was an excess piece that was removed during this re-routing. The underground conduit which held the cable is located within 150 meters of a river. Based on periodic inspections of the manhole, this conduit would frequently fill with water, often submerging the cable (Figures 2 & 3). The cable was dissected and fibers were carefully removed in 1994 for mechanical testing. At the time of testing, the fibers had been in the cable for about nine years and the cable had been in a field installed state for a period of five years. According to the National Weather Service, the average lowest temperature in the Corning NY region is 14°F and average highest temperature in 80°F.

Figure 2: Conduits submerged in water inside the manhole.

Figure 3: Water being removed from the manhole using a water pump.

Additional samples were also included in this study for comparative purposes. Three fibers that were manufactured in the same time frame as the cabled fibers were archived on fiber shipping spools. These archived fibers were stored in a box in a warehouse with uncontrolled temperature and humidity and were tested at the same time as the cable-aged fiber. The results were compared with those of a recently manufactured fiber with the same glass and coating design. For simplicity these fibers will be referred to as "Cable-Aged", "Archived", and "Recently Manufactured," respectively, in the following discussion.

Experimental Testing

Fiber Removal:

The two buffer tubes containing the single-mode fibers were removed from an approximately 90-meter length of field-aged cable described above. The buffer tubes were cut into two-meter lengths to allow for easier fiber removal. The fibers were carefully pulled out of the buffer tubes, ensuring no coating or glass damage due to fiber removal. The filling compound was removed from the fibers by soaking as Kimwipe™ with D-Gel™ and carefully sliding the fiber through the wipe. After the fibers were cleaned, they were coiled and taped on the inner side of a cardboard folder. All specimens were prepared, preconditioned, and tested in a controlled environment of 50% Relative Humidity (RH) and 23°C.

Atomic Force Microscopy:

The surfaces of the aged and archived fibers were examined using an atomic force microscope (AFM). Optical fiber coatings were chemically removed by dipping in methylene chloride, boiling sulfuric acid, and water. A 2x2 μm^2 area was scanned. Surface topography and average surface roughness were recorded.

Strength Testing:

Strength testing was performed on a Rotating Capstan FiberTester (RCFT). Testing was done according to FOTP-28B[7] with a gauge length of 0.5 meter and a strain rate of 5%/min. Fibers were attached to the testing apparatus by wrapping the fiber a minimum of two times around 4 inch diameter capstans at each end of the gauge length.

Strip Force Testing:

Peak strip force was measured to determine the coating integrity and strippability after field aging. Strip force was performed according to FOTP-178[7] with a strip length of 30 mm, a stripping speed of 500 mm/min, and a data acquisition rate of 200 Hz.

Dynamic Mechanical Analysis (DMA):

Mechanical properties of viscoelastic materials such as optical fiber coatings are best characterized by Dynamic Mechanical Analysis (DMA). The response of a viscoelastic material to cyclic stress contains two elements, a) viscous, and b) elastic. The response varies with the frequency of the cyclic field. Though the detailed description of the fundamentals of dynamic mechanical testing can be found elsewhere[8,9], it is important to note that the mechanical response of a viscoelastic material is most commonly characterized by a complex modulus

$$E^* = E' + E'',$$

where E' is the storage modulus associated with the elastically stored energy, whereas E" is the loss modulus associated with the energy loss due to viscous relaxation. The peak of E" vs. temperature curve typically exhibits a maxima at the glass transition temperature (T_g) of the glassy materials.

Composite tubes made of both inner and outer primary coating were removed by stripping under liquid nitrogen temperature. These tube samples have several advantages[10] over films commonly used for dynamic mechanical characterization of optical fiber coating. Dynamic mechanical testing was performed at a stress field frequency of 1Hz on the composite tubes obtained from field-aged cabled fiber, archived fiber, and a recently manufactured fiber.

Visual Examination/Microscopy:

All specimens were examined both visually and microscopically. Microscopic examinations were done using 200X magnification on samples immersed in index matching liquid.

Results and Discussion

Atomic Force Microscopy (AFM):

AFM images of a cable-aged, and archived, and a recently manufactured fiber are shown in Figures 4, 5, and 6 respectively. As shown in Table 1, and Figures 4, 5, and 6, the average surface roughness values for all fibers measured in the present study are found to be within a narrow range.

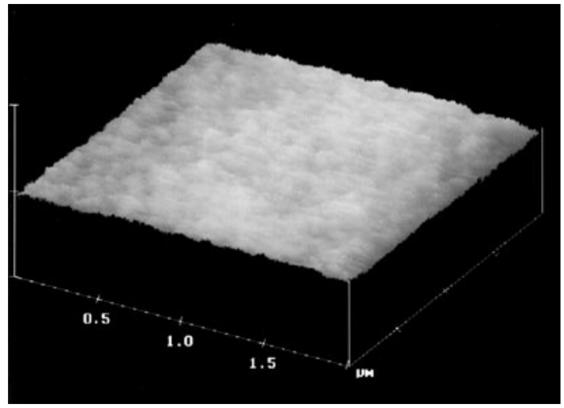

Figure 4: Auto-flattened and Plane-fit AFM scan of cable-aged fiber.

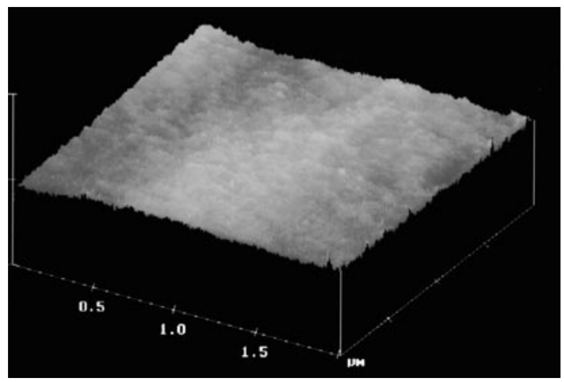

Figure 5: Auto-flattened and Plane-fit AFM scan of archived fiber.

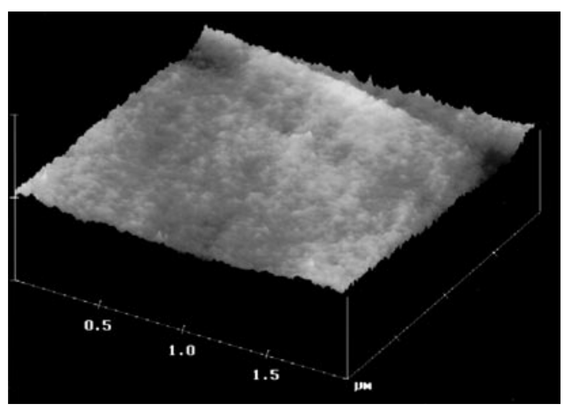

Figure 6: Auto-flattened and Plane-fit AFM scan of a recently manufactured fiber.

The original three dimensional AFM plots showing the curved fiber surfaces have been Auto-flattened (the average horizontal offset is calculated and subtracted from each line) and Plane-fit in both X and Y directions (an average S and Y value has been measured and subtracted from the entire image). The Flattening and Plane-fit processing is necessary to avoid including the vertical distances resulting from curvature into the calculations for surface roughness.

Based on the surface roughness and the AFM micrographs, the surface topography was equivalent for the cable-aged, archived, and recently manufactured fibers.

Strength Experiments:

Several specimens were tested for strength immediately after 24-hour preconditioning in 23°C/50%RH. The strength values are shown in Figure 7 and Table 1 for fibers of different colors. The results show no dependence of fiber strength on various ink colors. The measured strength distribution for the cable-aged samples, with a median value range of 655-658 kpsi, is statistically the same as the archived samples, with a median value range of 656-669 kpsi. The median strength of recently manufactured fibers was found to be in the range 633-675 kpsi. It is therefore concluded that the aging of this cable has not degraded the strength distribution of the fibers contained within. The strength of these fibers is more than sufficient to handle the common field handling scenarios encountered during cable repair.

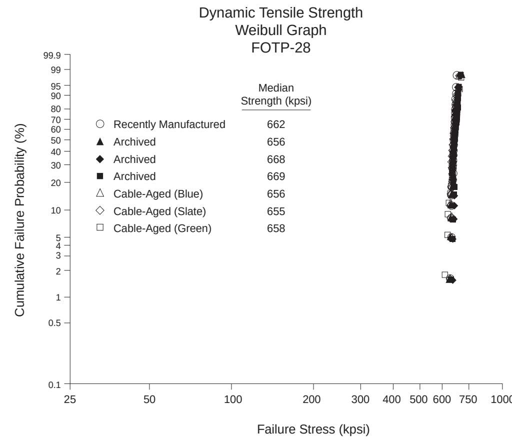

Figure 7: Strength distributions of cable-aged, archived, and recently manufactured fibers.

Results from the present study are schematically shown in Figure 8 along with the strength degradation plots reported in an earlier work[5]. Figure 8 illustrates the dramatic difference between the degree of strength degradation in liquid water as compared to degradation in field-age cable. No strength degradation is observed in the field aged cables. Whereas, about 25% of the original strength degradation would be predicted from the room temperature liquid water aging data[5]. This suggests that to use an Arrhenius model such as described in Equation 1, for predicting ZSA, the application-specific pre-exponential term (t_o), and activation energy (E_a) must be obtained. Similarly, the constant α in Carr's model[6] need to be determined for specific application.

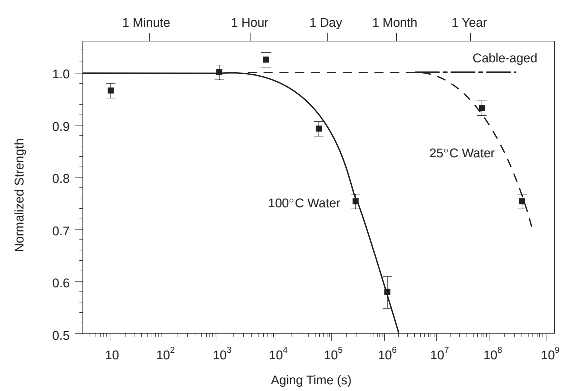

Figure 8: Comparison of strength degradation results obtained from fibers aged in the field and in laboratory[5] (liquid water).

Table 1. Summary of test results

Fiber Type and Aging	Peak Strip Force (lbf)	Median Strength (kpsi)	Surface Roughness (nm)
Colored, cable-aged	0.88 - 0.99	655 - 658	0.26 - 0.50
Uncabled, archived	0.67 - 0.89	656 - 669	0.26 - 0.34
Recently manufactured	0.60 - 0.80	633 - 675	0.26 - 0.49

Strip Force Experiments:

The strip force results are summarized in Figure 9, and Table 1. The results indicate that there is no dependence of strip force between various ink colors. The mean peak strip force range for the colored cable-aged fibers, 0.88 - 0.99 lbf. was slightly higher than typical strip force values for uncabled archived fibers, 0.67 - 0.89 lbf, and a recently manufactured fiber, 0.60 - 0.80 lbf. The slightly higher strip force of cable-aged samples could be attributed to the coloring ink.

As shown in Figure 9, all measured strip force values were well within Bellcore's recommended range[11] of 0.3 - 2.0 lbf.

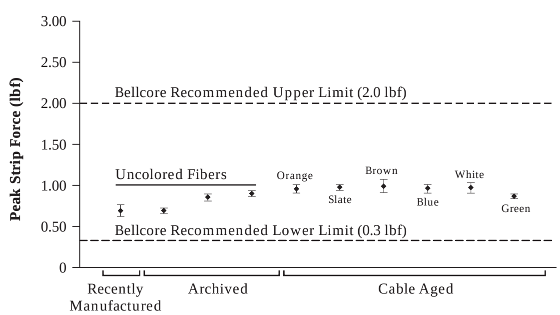

Figure 9: Peak strip force results for various fibers.

DMA Experiments:

Storage modulus (E'), and loss modulus (E") were measured in the temperature range - 60°C to 60°C, at 1 Hz. Typical results are shown in Figures 10 and 11. No change in the viscoelastic properties of various coating samples could be concluded from these DMA results. The glass transition temperature (T_g) of the inner primary coating for each sample was determined from the peak of the E" vs. temperature plot, the results of which are summarized in Table 2. All T_g values were found to fall within a narrow temperature range.

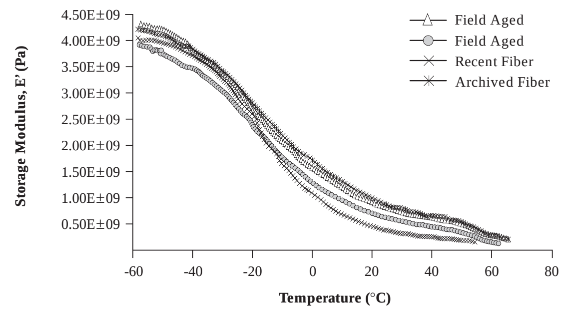

Figure 10: Coating Storage modulus (E') vs. temperature from DMA.

Table 2: T_g of inner primary coating obtained from DMA

Aging	T_g (°C)
Cabled, field-aged	-18.5
Cabled, field-aged	-20.3
Cabled, field-aged	-21.6
Cabled, field-aged	-16.8
Cabled, field-aged	-20.9
Cabled, field-aged	-19.3
Uncabled, archived	-16.5
Uncabled, archived	-16.7
Uncabled, archived	-17.1
Uncabled, Recently manufactured	-18.0

Visuals/Microscopy Experiments:

There were no coating defects observed during visual inspection of any of the cable-aged fibers. Also, there were no anomalies found in the coating during microscopic examination.

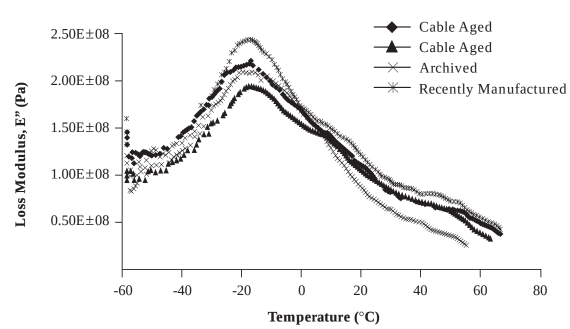

Figure 11: Coating Loss modulus (E") vs. temperature from DMA.

Summary of Conclusions

Actual field aging of a fiber-optic cable showed no degradation of the handleability of mechanical behavior of the optical fibers. All of the fiber coatings were handleable as shown by normal peak strip force, unchanged viscoelastic properties, and no observable coating anomalies. No degradation was observed for either fiber strength of fiber surface roughness even after five years of field aging and nine years after cabling. Based on the strength and AFM data obtained in this study, zero-stress-aging is not a reliability or handleability concern for fibers field-aged and protected by fill compound and other typical cable components. Models based on the strength of uncabled fibers after aging in liquid water, temperature ranging from 25-100°C, overestimate the strength degradation of fibers in normal field conditions. In conclusion, the cable-aged fibers remained handleable for cable repair nine years after the manufacture of the cable. These fibers were in the field for more than half of this nine year period.

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