Examination of failure of fibers from synthetic rope with foreign inclusions using polarized light microscopy

Dr. Isaac Slaven* and Dr. Barbara Carlsward**
*Eastern Illinois University School of Technology, Charleston, Illinois
**Eastern Illinois University Department of Biological Sciences, Charleston, Illinois

Introduction

It is nearly impossible to predict exactly what will happen in a rope system. Many of the influences that can diminish the strength of a system have been observed in both practice and through empirical studies. When all factors are combined it becomes increasingly difficult to predict how it will fail, at what point the failure will occur, or what the unintended consequences resulting in a system failure may be.

In some cases the experience a person has with these influences or even an interpretation of a research experience goes further to complicate the understanding of how the complexities of a system are interrelated. One could easily interpret an experience where no failure occurred or the findings of a study and inadvertently over-simplify a conclusion creating misleading information in his or her own thinking or in that which he or she advertises.

This study aims to examine two methods of nylon kernmantle rope degradation: sand and limestone. Then, it examines the line breakages on the microscopic level by using polarized light to highlight internal stresses in the polymer fibers. These images can aid in the visualization of what is occurring to ropes under outside influences.

Background

When doing casual research on the internet, the researchers came across a website that had several "myths" about rope use and care. One, in particular, struck the eye of the researchers: "Myth #9: Walking on a rope damages it" [1]. In the interpretation of research presented at the International Technical Rescue Symposium, it describes a study that used relatively large particles to damage rope and then performed a pull test.

When examining the initial study referenced, the author makes very clear early in the report that their testing method "presents a very limited look at the potential for damaging ropes" [2]. However, the website asserts that the "limited look" is proof that stepping on ropes is a myth, and indirectly infers that good rope maintenance may not be important. Since the rejection of this "myth" is contrary to what rope manufacturers generally recommend as good practice (i.e. keeping ropes clean and free from unnecessary wear), it was viewed as an opportunity for the researchers to take another look at ropes exposed to debris.

Another interesting part of the same webpage was the assertion of "personal proof" from the webpage's author. It reads: "Personal proof: cut off about 1 foot of old very used rope and examine the core for yourself." Here is where the research for this paper began to take form.

Objectives

This study has the following objectives:

- Determine strength degradation from exposure to sand or limestone
- Compare the strength of heavily used rope to new rope
- Examine the fiber of tested rope to observe attributes that may indicate damage

Methodology

This study was broken into two parts, each with two phases. The first part of the study was to expose rope to common jobsite materials: sand and limestone. After these ropes were exposed and tested, the fibers were examined to observe microscopic destruction and stresses. The second part of the study examined ropes used and maintained by an ROTC unit on campus to determine what effect regular use may have on the breaking strength of rope relatively independent of foreign inclusions.

Part 1: Foreign matter

A pull-test apparatus was constructed to break sections of ropes (figure 1). The apparatus allowed for sections of rope to be pulled in a straight line using a Tuf-Tug 3-ton web come-along. The peak loads were measured on a Dillion ED-Junior dynamometer. Pulling speed did not exceed 6 inches per minute.

Sections of PMI 7 mm accessory cord were cut with a hot-knife to lengths of approximately 5 feet. This length allowed for a knot on bights to be tied on either end for connections to the apparatus. Two treatments of foreign material were prepared: sand for concrete (figure 2) and ½" limestone gravel (figure 3). Additionally, two different knots were prepared within each treatment group: Figure-8 on a bight (figure 4A) and the Slaven knot on a bight with the overhand on the dead-end (figure 4B).

To apply the treatments, 50 cut sections were placed into a contractor-style refuse bag. Then, twenty-five 1-pint cups of the treatment (sand or limestone gravel) were added to the bag. The bag was tied and placed into another bag, which was then also tied. This was then placed into a compost tumbler with an eccentric pipe as an agitator. The tumbler was slowly turned for 200 rotations.

When the pull test was assembled, a slow pull was performed with the come-along. After the failure of the line, the maximum load was recorded. A two-way ANOVA test was performed on these maximum load data to compare the different combinations of variables.

After breaks were performed, samples of the ropes at the breaks were collected and labeled according to the treatment and knot. Core fibers from the breaks were cut near the break. The fibers were prepared on microscope slides to gather observations about the physical characteristics of the fiber at the break. Brightfield, polarizing, and scanning electron microscopy were used for the examination. Slides were examined using a Nikon Optiphot microscope, photographs were taken with an AmScope MU300, and the images were analyzed using Adobe Photoshop CS 5.1 with ImageJ 1.49 application for scaling. Additional images were taken with a Hitachi 3500 variable pressure scanning electron microscope at a running voltage of 5 kV.

Part 2: Extensively used rope with regular maintenance

Ropes and rope logs were acquired from the campus Army Reserve Officer Training Corps. The ropes logs indicated the number of rappels that had occurred for each rope. Three used, Bluewater 11 mm Assaultline ropes were tested: one with 323 rappels (orange tag), one with 425 rappels (blue tag), and one with an unknown number of rappels (white tag). The rope with an unknown number of rappels had, according to the ROTC Rope-master, "considerably greater" rappels than either of the other two. These used ropes were compared to new rope of the same model.

The lines were tested on an in-house-made pull-test test bed (figure 5). The machine used a hydraulic cylinder for force application. A dynamometer connected to the Allen-Bradly programmable logic controller with Siemens user interface delivered a peak-load read-out. The ropes were pulled at approximately 5 inches per second.

The overall strength of these three ropes was compared to new rope of the same diameter, manufacturer, and model. Two separate knots were used: Figure-8 bend (Flemish bend) and the Slaven Bend (Slaven knot as a bend). Pairwise comparisons of each mean were performed to determine significant differences.

After breaks were performed, samples of the ropes of each were collected and labeled according to the number of rappels. The fibers were prepared for microscopy to gather observations about the physical characteristics of the fiber at the break. Both brightfield and polarizing microscopy were used for the examination. Slides were examined by a Zeiss Axioskop 40 microscope, photographs were taken with an OptixCam 3.3 ICE, and the images were analyzed using Adobe Photoshop CS 5.1 with ImageJ 1.49 application for scaling. Means of the diameters of the ropes are compared using a t-test for significance.

Results

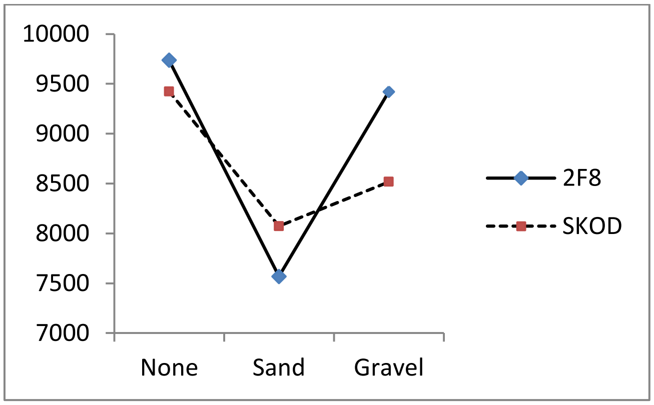
Part 1: Foreign material

The tests demonstrated different means and standard deviations for each of the treatments and knot combinations (Table 1, Chart 1). An ANOVA with a Tukey test confirmed that the sample size was significant based upon mean and variance.

Table 1: Results of foreign material

Knot: Figure-8		
No treatment, *n*=5	$\bar{x}$= 9736 N	*s* = 450
Sand, *n*=5	$\bar{x}$= 7568 N	*s* = 461
Limestone, *n*=5	$\bar{x}$= 9420 N	*s* = 782
Knot: Slaven knot, overhand on dead-end (SKOD)		
No treatment, *n*=5	$\bar{x}$= 9424 N	*s* = 469
Sand, *n*=6	$\bar{x}$= 8073 N	*s* = 323
Limestone, *n*=6	$\bar{x}$= 8517 N	*s* = 672

Chart 1: Difference in knot performance with sand and limestone treatments



The pairwise comparisons found the following:

- There is not a significant difference between knots ($p = 0.2333$)
- There is a significant difference between treatments (overall $p < 0.0001$)
  - Gravel vs. None, $p = 0.0503$ (p-values are Bonferroni corrected)
  - Gravel vs. Silica, $p = 0.0001$
  - None vs. Silica, $p < 0.0001$
- There is a significant interaction between knots and treatment (overall $p = 0.0200$)
- The double Figure-8 has a higher breaking strength for gravel and none, but it is smaller for silica.

The fibers from untreated and unstressed ropes were examined for visual baselines. Fibers appear to be relatively smooth (figures 6 & 7) and relatively free of internal stresses, other than what naturally occur from the electro-spinning process aligning the polymeric chains (figures 8 & 9). Fibers that have been pulled to failure experience a necking that results in a relaxation of the material. This results in a shallow, cup-like end that is much larger in diameter than the fiber. Figure 10 shows an image from a scanning electron microscope, figure 11 shows a visible light image of a normal failure, and figures 12-15 illustrate normal failure under polarized light. Polarized light microscopy demonstrates the extent to which plasticization (irreversible deformation) of the fiber has taken place by the amount of non-linear color-formations in the material. Figure 15 is of additional interest because it illustrates that while the fibers melt together at the break, they have independent properties beyond the break

Microscopic examination of the fibers showed that the sand treatment had much greater diametrically deleterious effects on the fibers than the other effects (figures 16-19). The shape of the cuts in the fibers is reminiscent of the shape of the sand particles (figure 2). The fibers treated with limestone gravel exhibited detriment to the fiber that was largely reminiscent of being shaved (figures 20 & 21). The limestone gravel dust images do not possess the sharp corners that the sand particles do (figures 2 & 3). In figure 3, the limestone particles appear to be powdering.

Part 2: Extensively used rope with regular maintenance

The following results were observed in the testing of the extensively used ropes. The following hypotheses were devised to compare the breaking strength of the new rope, BS_n, to the used rope, BS_i:

$$h_o: BS_n - BS_i = 0$$
$$h_a: BS_n - BS_i \neq 0$$

In other words, if the mean breaking strength of any one of the used ropes is statistically significantly different than the new rope, the null hypothesis, h_o, is rejected, and it can be said that the means are significantly different.

Table 2 compares each of the ropes to the new rope using the Slaven bend as the connection. Table 3 compares each of the old ropes to the new rope using the Figure-8 bend. Table 4 combines the data from both the Slaven bend and the Figure-8 bend data and compares each of the ropes to the new rope.

Table 2: New, blue, orange, and white tagged with Slaven knot

Comparison	*p*-value	Result	Interpretation
New vs. Blue, *n*=10	0.034	Fail to reject	Means stat. equal
New vs. Orange, *n*=10	0.189	Fail to reject	Means stat. equal
New vs. White, *n*=10	<0.0001	Reject null	Means stat. different

Table 3**:** New, blue, orange, and white tagged with Figure 8 knot

Comparison	*p*-value	Result	Interpretation
New vs. Blue, *n*=10	0.327	Fail to reject	Means stat. equal
New vs. Orange, *n*=10	0.007	Reject null	Means stat. different
New vs. White, *n*=10	0.333	Fail to reject	Means stat. equal

Table 4: New, blue, orange, and white tagged with overall strength

Comparison	*p*-value	Result	Interpretation
New vs. Blue, *n*=10	0.474	Fail to reject	Means stat. equal
New vs. Orange, *n*=10	0.476	Fail to reject	Means stat. equal
New vs. White, *n*=10	0.844	Fail to reject	Means stat. equal

When the cross-sectional diameters were compared between the unused rope and the previously used ropes, a diametric difference was observed. Polarized light showed no observable difference between the internal stresses of the old and new fibers.

Table 5: Diametric comparisons of fibers

Comparison of New and Used fibers			
New Fibers	$n = 5$	$\bar{x}$=33.90 µm	*s*=0.424 µm
Used Fibers	$n = 15$	$\bar{x}$=27.97 µm	*s*=1.746 µm
p-value	< 0.0001	Diameters statistically ≠	

A t-test with assumed unequal variance showed that the means of each the used ropes' fibers and the new ropes' fibers were statistically significantly different. This change in diameter suggests that the fibers are likely stretched into a longer shape, as one can observe from measuring the length of a new and used rope.

Conclusion and Recommendations

The overall conclusion that can be drawn from this research is that inclusion of certain foreign material has the greatest impact on the strength of ropes. More specifically, the inclusion of particles with a jagged morphology will more likely cut synthetic fibers. Additionally this damage to fibers occurs on a microscopic level, cannot be seen with the naked eye, and has a significant impact on the overall strength of the ropes. Other factors were not easily demonstrable as being significant in their detrimental effects on rope strength.

From these tests, the following conclusions can be carefully drawn:

- Sand, that caused the most significant decrease in strength, has morphology and hardness that damages rope fibers.
- Limestone appears to not have a significant effect on the rope strength, which is supported by its less crystalline morphology and inability to cut into the fibers.
- Even through repeated use, the internal stresses in rope fibers, as observed through polarized light microscopy, appear to maintain the in-line structure of new ropes.
- Rope use, within its limits, has significantly less negative impact on the strength of rope than does the inclusion of foreign materials.
- The strength degradation of the tested used lines is not statistically significantly different.
- The longitudinal change in rope fibers manifests itself through diametric loss, but no significant strength loss accompanies this.

Although these conclusions seem relatively vague, it is pernicious to make broad conclusions that could be misinterpreted. Accordingly, the following recommendations can be made with relative certainty:

- Keep ropes clean and follow the manufacturer's recommendation.
- Avoid potential contamination with particles that could work themselves into the core of the rope.
- The use of rope and rope systems should only be done under the supervision a competent person.

Future research should be done to better understand the effects on rope fibers from a variety of factors. With respect to foreign material inclusion, more research should be performed to understand what role cyclical loading has on destroying fibers. Although the tests from this research provide empirical results, it is impractical to think that users of rope would only use a rope once. Therefore, more controlled experiments of fatigue testing would be beneficial. Using images, the results from this research support the idea that silica particles are at least partially cutting through the rope fibers when they are stressed. The morphology of the double Figure-8 compared to the Slaven knot suggests that the presence of these particles is less of an impact than the fibers being forced against the particles. Perhaps a fatigue test would show that cyclical loads have an effect without forcing the particles against the fibers.

Acknowledgements

The authors would like to acknowledge the support of the following funding sources: Lumpkin College of Business and Applied Science Research Awards (Faculty Award for

Interdisciplinary Research 2013 and 2014, Faculty Research and Creative Activity Award 2013 and 2014); the Eastern Illinois University Proposal Initiative Fund 2014; and generous material donations from Pigeon Mountain Industries, Sterling Rope, and Tuf-Tug Industries. Additionally, many great thanks go to the students who worked on this project: Steven K. Wright, Craig T. Buscher, Stephany Fonseca, Nathan Rhebergen, Kyle Wathen, Daniel T. Stock, and Tyler Parks.

Works Cited

[1] On Rope 1, "On Rope 1," [Online]. Available: http://www.onrope1.com/Myth9.htm. [Accessed 20 June 2015].

[2] J. Kovach, "Never Step on a Rope," in *International Technical Rescue Symposium Proceedings*, Denver, CO, 2002.

Appendix: Figures

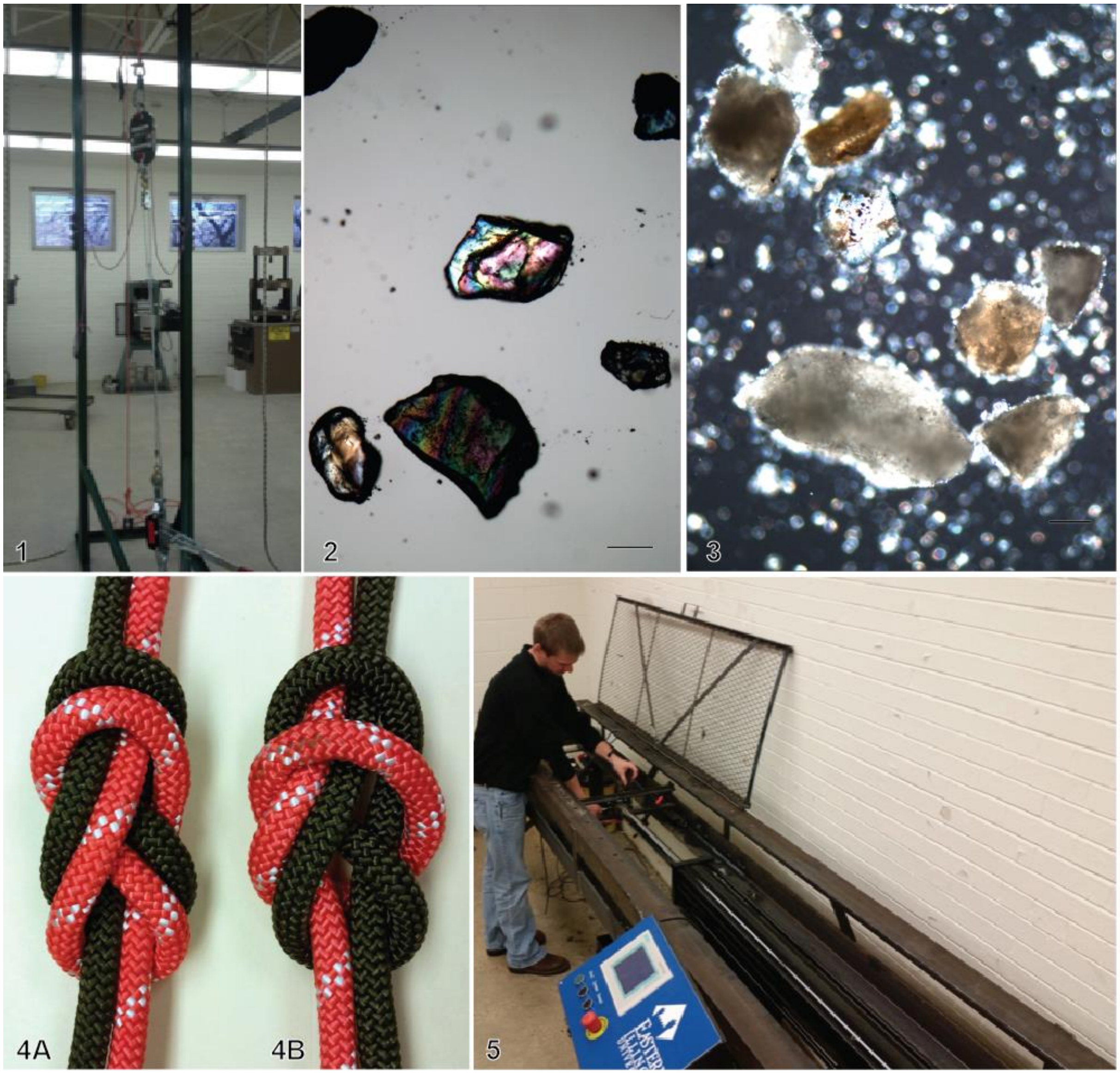
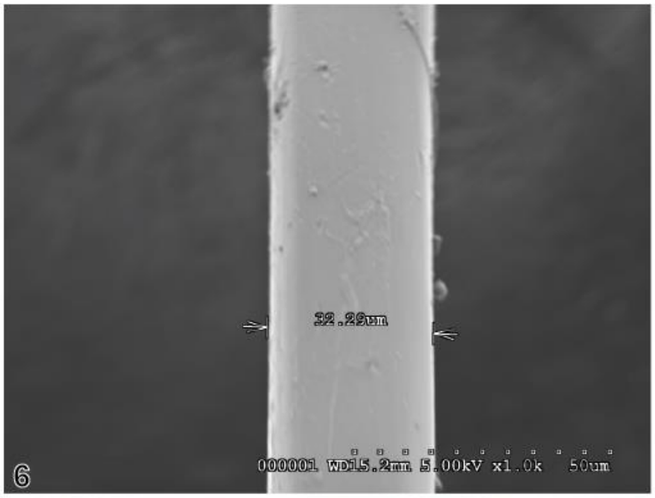
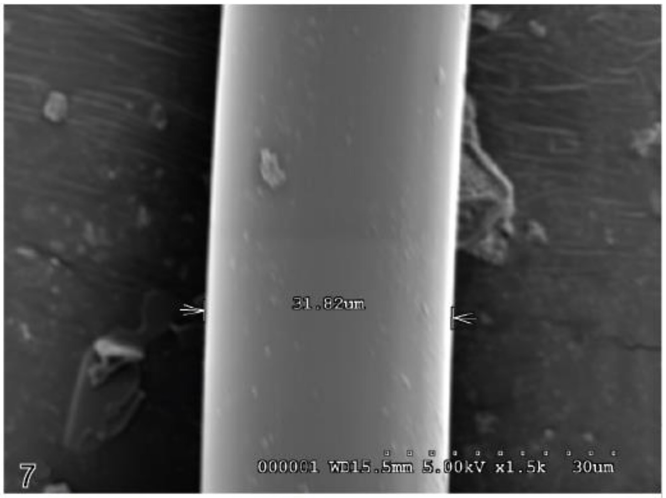
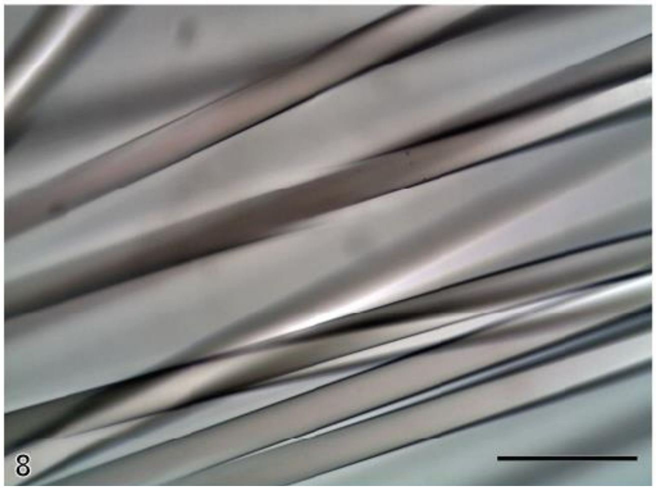


Figure 1: Pull test apparatus. **Figure 2**: Sand particles, polarized light, (50X mag., scale bar = 200 µm). **Figure 3**: Limestone dust particles, polarized light (100X mag., scale bar = 100 µm) **Figure 4**: Knots used in pull and hydraulic tests (A = Figure-8 knot & B = Slaven knot). **Figure 5**: In-house-made hydraulic test bed.







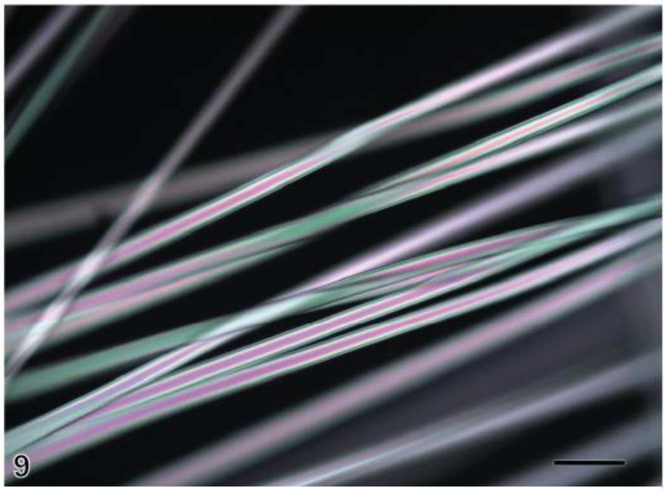
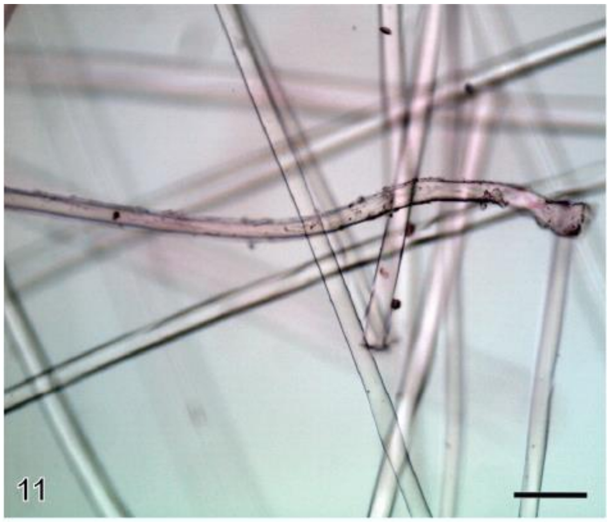
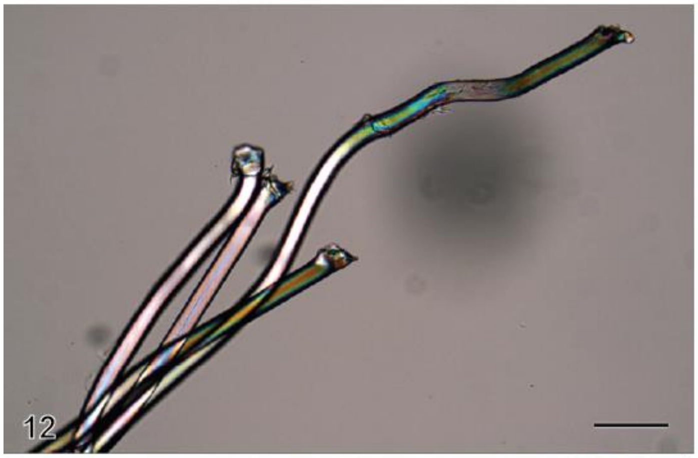
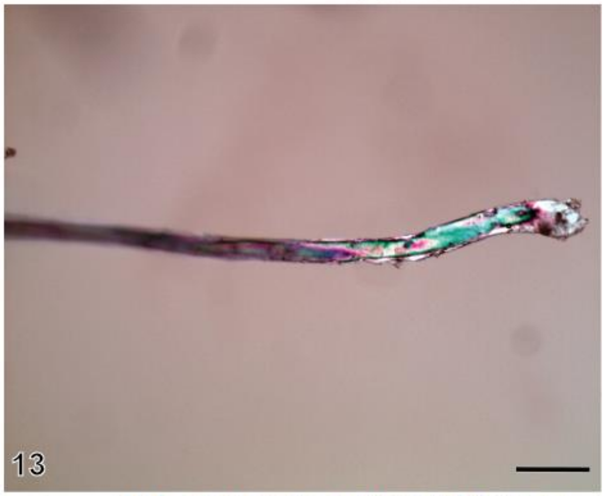
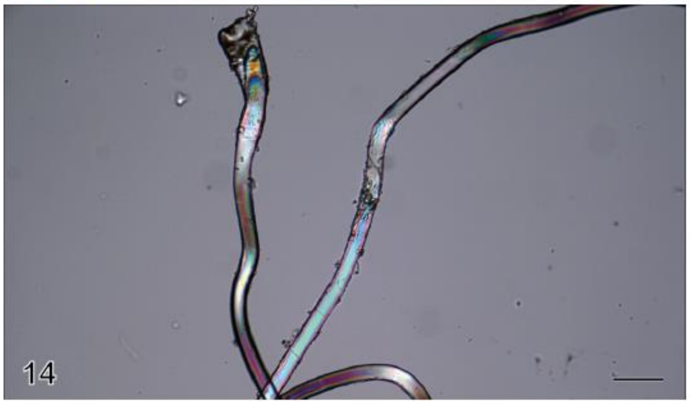


Figure 6: Nylon fiber from PMI 11 mm static core viewed with a scanning electron microscope. **Figure 7**: Nylon fiber from PMI 11 mm static core viewed with a scanning electron microscope. **Figure 8**: Examination of unstressed and untreated fibers from 7 mm PMI accessory cord core using brightfield microscopy (200X mag., scale bar = 100 µm). **Figure 9**: Examination of unstressed and untreated fibers from 7 mm PMI accessory cord core using a polarization filter (100X mag., scale bar = 100 µm).









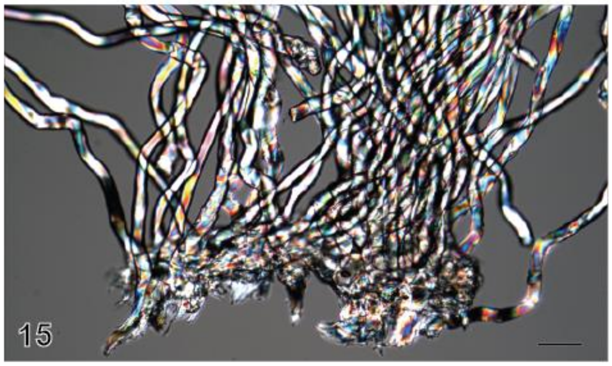
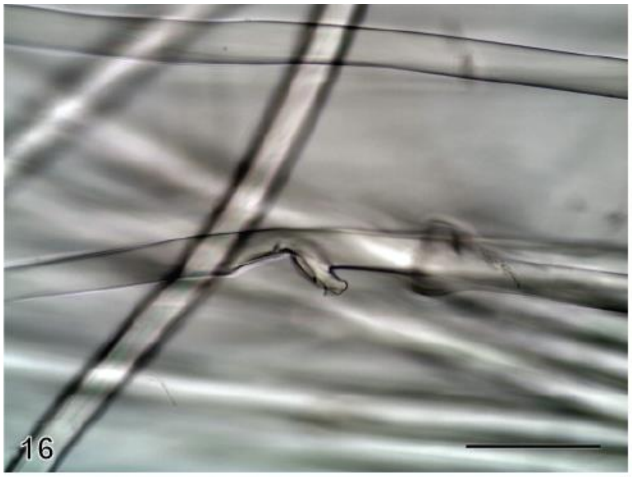
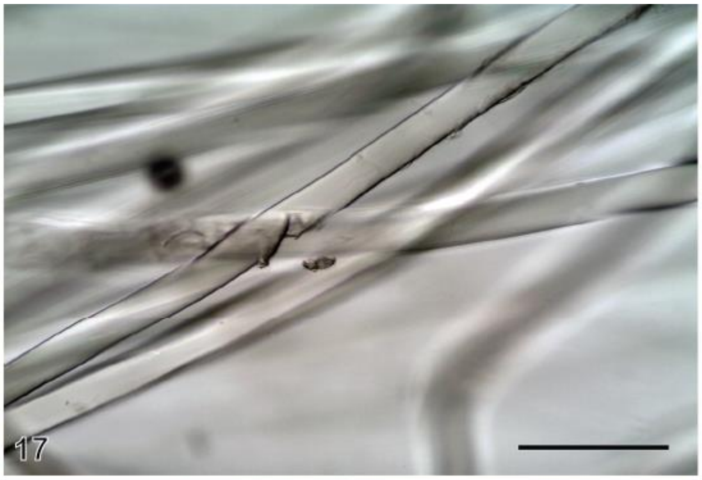
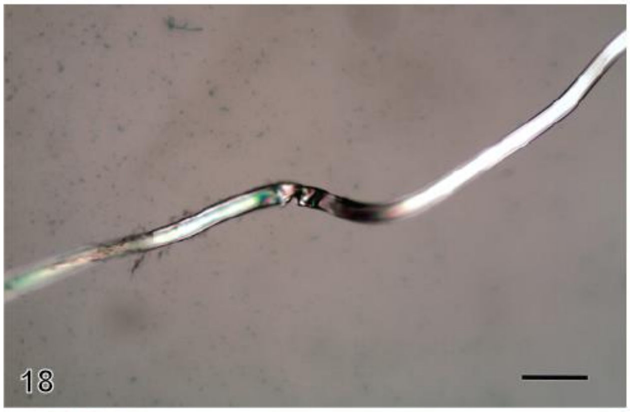
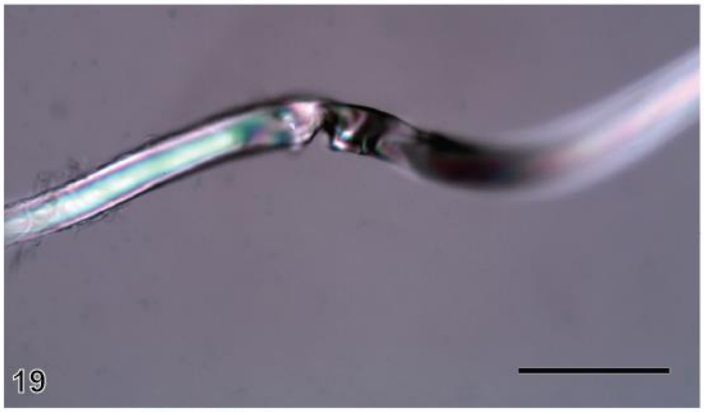


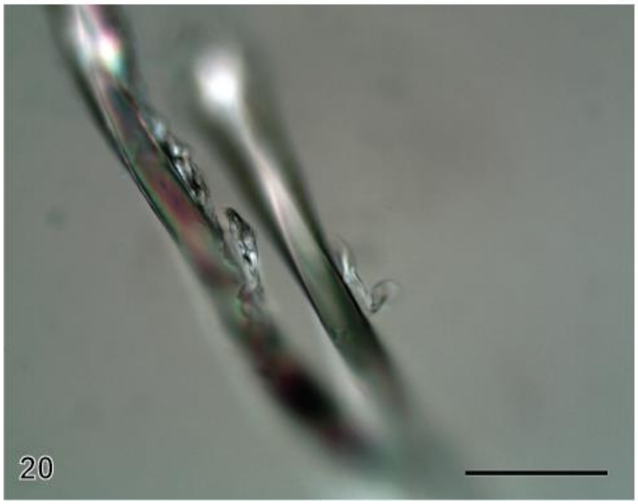
Figure 10: End of a nylon fiber from a 9 mm PMI accessory cord core viewed with a scanning electron microscope. **Figure 11:** Examination of nylon fibers from 7 mm accessory cord core break using brightfield microscopy (100X mag., scale bar = 100 µm). The broad jagged end with the deformed shape is the location of the break. The other end is where fibers were cut for slide preparation. **Figures 12-14**: Examination of nylon fibers from 11 mm Bluewater Assaultline core fibers after a break using a polarization filter (100X mag., scale bar = 100 µm). The variation in color of non-linear patterns shows where internal stresses exist in each fiber. **Figure 15**: Examination of multiple nylon fibers from 11 mm Bluewater Assaultline core fibers after a break using a polarization filter (100X mag., scale bar = 100 µm). The bottom portion of the figure is where the fibers have melted together. Each fiber extending from this break show deformation through the colorization the polarization filter provides.

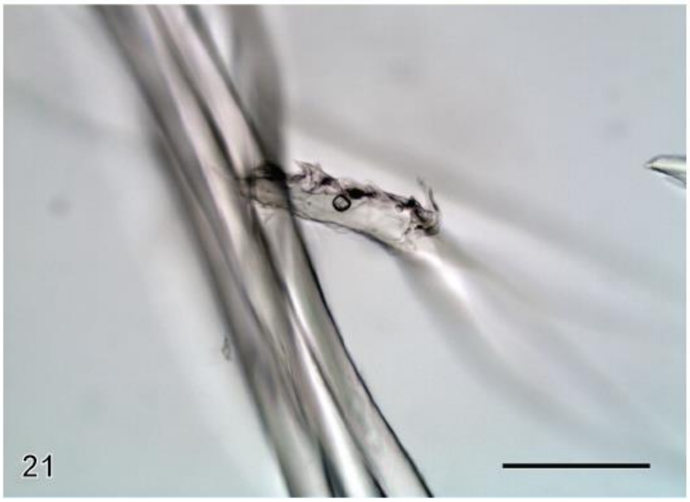












Figures 16 & 17: Brightfield images of ropes that were tumbled with sand prior to testing (100X mag., scale bar = 100 µm). Fibers are from the core of a 9 mm PMI accessory cord. **Figures 18 & 19**: Image of a fiber from the core of a 9 mm PMI accessory cord core tumbled with sand prior to testing and breaking (18: 100X mag., scale bar = 100 µm; 19: 200X mag., scale bar = 100 µm). The polarization filter shows where internal stresses have occurred in the fiber as a result of the contact with sand particles. **Figure 20**: Image of fibers tumbled with ½” limestone gravel prior to testing and viewed with a polarization filter (100X mag., scale bar = 100 µm). The fibers are from a 9 mm PMI accessory cord. The laminar separations are typical of the fibers tumbled with limestone. **Figure 21:** Image of fibers tumbled with ½” limestone gravel prior to testing and viewed with only brightfield microscopy (100X mag., scale bar = 100 µm). The fibers are from a 9 mm PMI accessory cord.