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EFFECT OF AQUEOUS ENVIRONMENT AND VISCID DROPLET ON DEFORMATION OF SPIDER THREAD

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ABSTRACT

A s one of serial studies on the mechanical properties of spider threads, their amino acid compositions, the microstructure of dragline, the surface tension of the viscid droplet regularly spaced on capture thread and the effect of aqueous environment on the stress-strain curve were investigated. It was shown that (1) the dragline consisted of three layers at least, (2) the surface tension of the viscid droplet was about 65mN/m and (3) the shape of stress-strain curve was fairly affected by aqueous environment surrounding the thread.

KEYWORDS

Spider thread, Sticky droplet, Deformation, Rubber elasticity, Microstructure, Super contraction, Aqueous environment, Surface tension

1.INTRODUCTION

Some experiments on the structure and the strength of spider thread have been made on the analysis of amino acid composition, the crystalline structure, the microstructure, the mechanical properties, the effect of environment on the mechanical properties and so on using samples of spiders Nephila clavata and Argiope amoena [1,2,3,4,5,6,7].

It is interesting to note that the shape of stress-strain curve is very different between dragline and capture thread. The stress-strain curve of dragline shows a work hardening after steep yield point and breaks at small strain after elastic behavior. For capture thread, on the other hand, the curve which resembles that of rubber is upwardly concave (J-shaped) and the fracture strain, which amounts to 4 occasionally, is fairly large compared with that of dragline. The amino acid composition of capture thread without viscid droplets is nearly the same as that of dragline. Hence, the difference in the shape of the stress-strain curve between them may be attributed to the existence of viscid liquid attached to capture thread. In this paper, at first the fundamental properties of the droplet such as its shape and its surface tension are investigated, secondary the micro structure of dragline is observed using a urea super-contraction method developed by Vollrath et al. [8] and finally the effect of viscid droplet on the deformation behavior of the thread is shown.

2.EXPERIMENTAL

The spiders Nephila clavata and Argiope amoena who generally constructed orb webs were used for the test, since it was easy to collect threads from their living bodies and their webs.

Formation process of droplet
At first, how droplets were arranged at a regularly spaced row on capture thread was observed at an appropriate time interval. As soon as a spider constructed an orb web, a short part of the capture thread was cut out by means of a specially devised tool, and was subsequently set on an optical microscope. Furthermore, the shape of the droplets and their average spacing were measured for both spiders used here.
Surface tension
A collected quantity of viscid liquid is too small to measure the surface tension by a Du Nouy meter in which a large volume of test liquid was necessary. Therefore, a new machine was constructed as shown schematically in Fig.1. As illustrated in the enlarged view, the test liquid filled between the flat cylinders③ facing each other forms a symmetrical meniscus④. If the radii of meniscus curvatures are defined as r_1 and r_2, the surface tension T is calculated by Laplace equation

$$F = \pi r_1^{\ 2} p, \quad p = T\,(1/r_2 - 1/r_1)$$

$$T = F/[\pi r_1^{\ 2} p(1/r_2 - 1/r_1)] \qquad (1).$$

The shape of the meniscus and the applied force F was recorded by a video camera through an optical microscope. The values of r_1 and r_2 were measured by the radii at the necked region. The measurement was done at a humidity of about 60% and a temperature 20℃.
Microstructure
Since the diameter of dragline is 5 μ m at most even for an adult female of Nephila clavata, it is difficult to observe its cross section by an optical microscope. A swelling technique by urea was used to investigate the microstructure. In urea, the thread diameter becomes more than 10 times bolder than the original one. A mixed solution of different concentrations of $CO(NH)_2$; 6-12M, NaOH(pH8); 0.05-1M and NaCl; 50mM was used. When threads shorter than about 5mm are placed in a swelling agent on a glass slide, they begin to swell immediately at their both ends.
Furthermore, a recoil test developed by Allen [9] was used to facilitate the observation of the interior structure of the thread.
Tensile test
How to prepare tensile specimens using samples collected from both spiders was stated elsewhere. When the dragline is wetted by water, it contracts after sufficient time. This phenomenon was named super contraction (SC) by Work [10]. The tensile samples for SC draglines were made as shown in Fig.2. The paper flame with a tight dragline set previously at its rectangular window was folded at the central part so that its ambient length might be obtained. After submersion during sufficient period, the thread became tight and the tensile specimen with an ambient SC ratio (SCR) was made. The super contracted ratio SCR was defined as SCR = $(L_0\text{-Lc})/L_0$ where L_0 was the original length of the flame window and Lc was the shrinkage length after SC. Tensile tests were done for dry and wet draglines with ambient SCRs and capture threads.

3. EXPERIMENTAL RESULTS AND DISCUSSIONS
Formation process and geometry of viscid droplet
When a spider produced two core threads by a pair of flagelliform glands, viscid liquid produced by a pair of aggregate glands covered the core fibers simultaneously. Just after the capture threads were drawn out from the glands, the viscid liquid was still parallelepiped around the core threads. More than 10 minutes was necessary at least until some signs for the generation of regularly necked parts were recognized. After about 40minutes, a series of regularly spaced droplets formed completely along the core fibers.
The shape of the droplet is nearly the same for both spiders used as shown in Fig.3 where the dimensions are normalized by the maximum radius of the droplet. As shown by the solid curve in the figure, its shape is approximated well by a revolution ellipsoid.
Surface tension of sticky liquid
The load-time curves for the sticky liquid are shown in Fig.4. The liquid between the cylinders was pulled at a constant speed until their gap reached 0.25mm(point A), then the gap was kept constant for

a while (from A to C) and successively, it was pulled again at C. When stopping the machine, the meniscus is changing its curvatures very slowly due to its high viscosity and hence, the load drop occurs steeply. Using the curvatures at the stable period (B), the surface tension was estimated to be about 65±3 mN/m. This is nearly equal to that of water (73mN/m). This is plausibly due to the fact that the sticky liquid just after collected may contain a fairly large fraction of water.

Microstructure

As soon as urea liquid is dropped on the threads, swelling began at their both ends and moved to the central part. In the case where the concentrations of urea and NaCl are high, the interior substance becomes milky and flows out from the outer ring of the thread like a balloon. For the short thread, only the outer ring remains occasionally, the core material being solved out. This may indicate that the outer layer is stronger to swelling agents such as rain and fog than the core material. The observation of the short SC thread stained in a reagent of Coomassie Brilliant Blue shows that the thread consists of 3 layers, those are, the outer layer, the middle layer and the core.

The middle layer from which the outer layer is striped off at the recoil test can be seen in a fortunate case. This observation may show that the middle layer consists of numerous micro-fibrils parallel to the thread axis, which may be important for supporting the strength of dragline.

These features are illustrated schematically in Fig.5.

Tensile behavior Load(P)-draw ratio(λ) curves of dry and wet draglines with ambient SCRs are shown in Fig.6 (a) and (b). The value of P is calculated by (1-SCR) F where F is the actually recorded load, the cross sectional area being 1/(1-SCR) times larger than that of SCR=0. λ is defined as L/Lc where L is the length under deformation and $Lc=(1-SCR)L_0$ is the original length before deformation as defined above. P- λ curves in a dry state have a steep knee point denoting yield. The knee point tends to decrease with an increase in SCR. The P- λ curves after yielding are upwardly concave like rubber. But in a wet state, they are upwardly concave (J-shaped) without any distinct knee point. This may be similar to that of rubber.

Viscid droplets attached to capture threads were dissolved out into water. After the capture threads were soaked in water during 1 minute and more than 1 hours, they were sufficiently dried in air and were provided for tensile tests. If the capture thread was soaked in water during more than 1 hour, viscid droplets were completely removed from them and only the core threads remain. The dry core threads without any droplets were pulled. The P- λ curves for dry(②,③) and wet(①)capture threads are shown in Fig.7. The P- λ curves of wet capture threads has nearly the same shape as that of capture threads with viscid droplets. As the soaking time increases and the viscid droplets are much removed, the yield load increases. The P- λ curves of dry capture threads without any viscid droplet are very similar to those of dry draglines. This may be supposed by the fact that the amino acid compositions for both threads are nearly the same.

These behaviors may be explained well on the basis of a 3 elements model consisting of yield, rubber and spring elements as shown in Fig.8. The yield element does not move due to friction until the stress is lower than the yield stress Y. The rubber element shows rubber elasticity where the relationship between stress and λ is expressed by Langevin function. The spring element represents an elastic spring. If the applied stress exceeds Y, the behavior is governed by the rubber element. The yield stress Y is a function of SCR. In the case of wet thread, Y is chosen 0.

CONCLUSION

For the deformation behavior, it was shown that (1) the P- λ curve for capture thread without any viscid droplet was not different from that of dragline and (2) the capture thread with viscid liquid behaved like the dragline wetted and swollen by water sufficiently.

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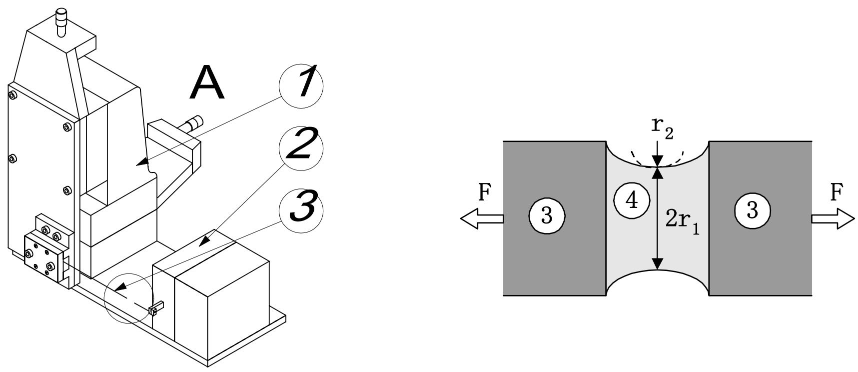


(a) (b)

Fig.1 Schematic illustration of a testing machine for measuring surface tension of viscid liquid.
①;cross table, ②;load cell, ③solid cylinders, ④;sticky liquid.

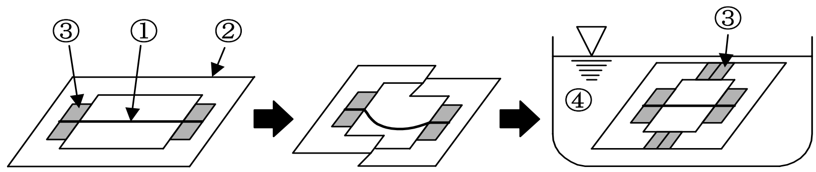
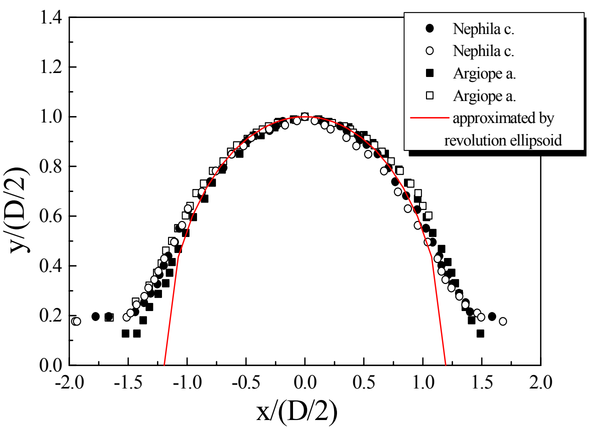


Fig.2 How to prepare tensile samples of dragline contracted by water.
①;dragline, ②;paper frame, ③;adhesive tape, ④;water.



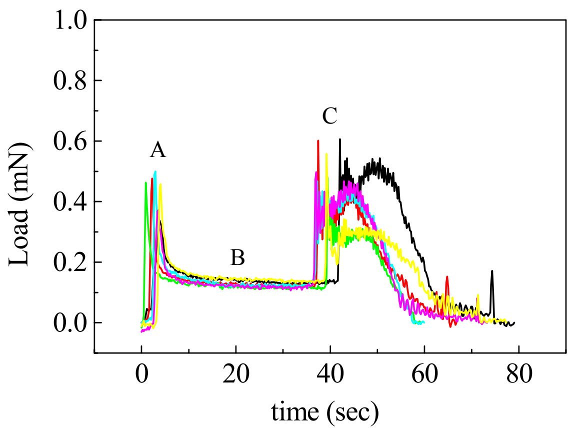


Fig.3 Shapes of viscid droplet for both spiders used in this experiment. The dimensions are referenced by the maximum radius of the droplet.

Fig.4 Load-time curves for spider viscid liquid tested using a home made surface tension meter.

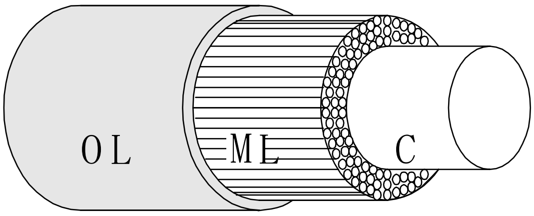
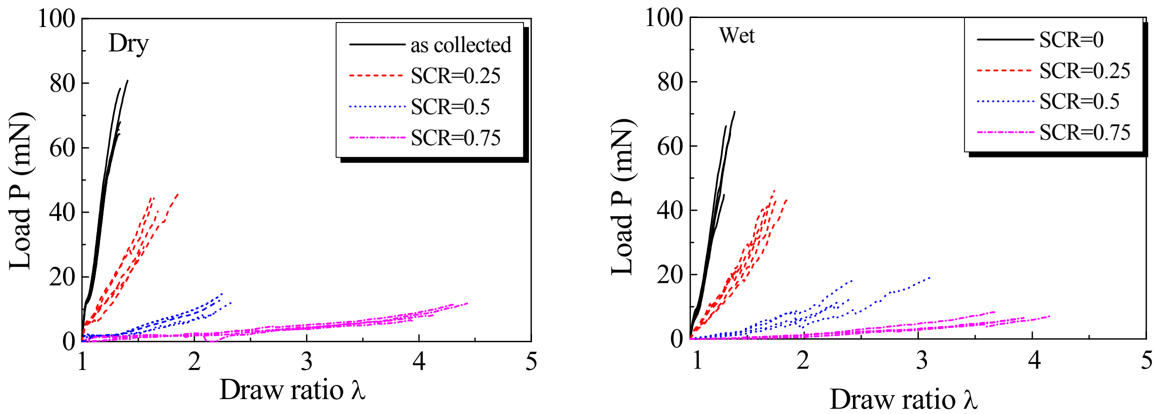
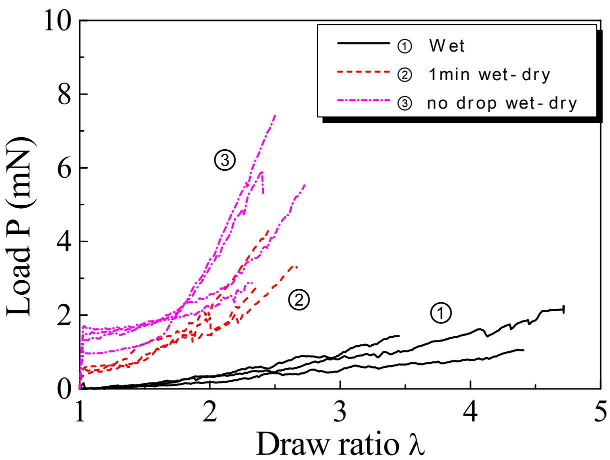


Fig.5 Schematic illustration of dragline microstructure.
OL; Outer layer insensitive to rain and fog, ML; Middle Layer with oriented micro-fibrils supporting strength, C; Core with amorphous substance.



(a) dry state (b) wet state

Fig.6 Load-draw ratio curves for draglines with different SCRs under (a) dry and wet states.



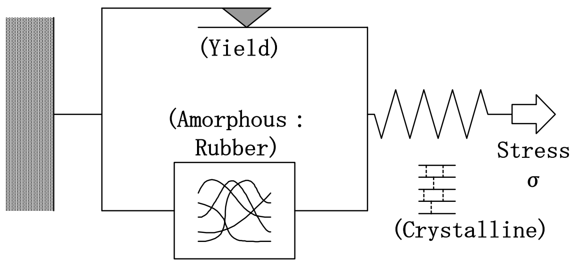


Fig.7 Load-draw ratio curves for capture thread under different conditions.

Fig.8 3-elements model for deformation of spider thread.