On the Rheology of Netting Twine-V

4 Element Model^{*1}Kazue TANIDA^{*2}

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E_1 Since the values of vinylon are considerably larger than those of other materials, an elongation for instantaneous load for vinylon is rather difficult to obtain. Also, as its average ratio of change is larger than that of other materials for the same number of single yarns n to E_1 , vinylon is considered to be most affected by the twist.

E_2 From the shape of the curves for E_2 and n for long-time loading, these materials can be divided into two groups namely, nylon, polyethylene and vinylon, polyester. Polyethylene is seen to be easily elongated to about 3-4 times more than nylon.

η_1 A decrease in the fluidity of the twine is caused with an increase in n , and this effect is the same for all 4 materials. The fluidity of polyethylene is 5-7 times greater than those of the other 3 materials.

η_2 From the relation between η_2 and n , two groups are seen to be formed. Namely, nylon, polyethylene and vinylon, polyester, as was in E_2 and these show the same behaviour pattern for n under long-time loading. The latter group is found to be affected to a greater extent than the former group by n , which in turn is affected by the twist. Polyethylene shows a fluidity that is 4 times greater than that for nylon in the same group. Considering these facts, nylon and polyethylene, amongst the 4 materials, are seen to show a rapid response, whereas the one with the slowest response is vinylon, for instantaneous tensile loading. In the creep behaviour tests, while under a long loading period polyethylene shows the most fluid elongation.

A general creep figure is obtained and represents figures of netting twines of 26 types of 4 materials, that is, nylon, vinylon, polyester and polyethylene to which a constant, static, tensile load has been attached; and this is shown in Fig. 1. From this curve it is obvious that the strain of netting twine consists of; 1) instantaneous elasticity, 2) retarded elasticity and 3) viscous flow. From this fact, it can be clearly stated that netting twine is a visco-elastic substance. It can also correspondingly be considered as a 4 element model as in Fig. 2. Results of the calculated values obtained from a series of observations and experiments, instantaneous Young's modulus E_1 , E_2 and normal viscosity η_1 , η_2 are shown in Table 5.

Methods and Materials

The schematic diagram of the experimental apparatus, further improved on than that used in the previous papers^{1,2)}, is shown in Fig. 3. Constant static tensile load is attached to the sample twine SAM, and the period taken for the load to act is almost instantaneous. Namely, the time

required was approx. 0.2 seconds. The Lissajous' figure for the relation between its elongation and loading time was recorded on an X-Y recorder. The length of dL_1 , dL_2 and dL_3 in Fig. 1 were measured by a vernier calliper having an accuracy of 1/20 mm. The stress per unit cross-sectional area of the sample twine employed in the previous report³⁾ is used and retardation times, τ , of the Voigt structure that were obtained in the previous paper⁴⁾ are also used. Sample twines to be utilized in this expt. Must first have their tensile strains adjusted so as to converge at a single point, as shown in the previous paper²⁾; and the length of the sample twine and the load are 125.0 cms and 4 kgf respectively. Elongations of 5 sample twines of the same type were measured. The 5 creep curves obtained were standardized geometrically and reduced to only a single curve for each type. This was then chosen as the subject for analysis.

The Lissajous' figure recorded on the X-Y recorder is terraced and not a smooth curve as described in the previous paper¹⁾. The terraced curve is then rounded off to form a smooth curve. This curve can be corresponded to the 4 element

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Fig. 1. A creep curve for netting twine showing the relation between tensile elongation dL and loading time t , under static tensile loading. dL_1 : OA, dL_2 : AB, dL_3 : BC, CG: parallel line to t -axis through G, BF: Line tangent to the creep curve at point G.

Fig. 2. 4 element model. E_1, E_2 : springs, η_1, η_2 : dashpots. E_1 and η_1 compose the Maxwell structure. E_2 and η_2 compose the Voigt structure.

Fig. 3. A schematic diagram of the experimental apparatus for measuring the elongation of netting twine under tensile loading.

ADJ: An adjuster for electric zero setting of the variable resistance. UCL: Upper clip of SAM. SAM: Sample twine. LCL: Lower clip of SAM. VR: A variable resistance ganging with the elongation of sample twine.

model as shown in Fig. 2. The relationship between strain dL/L and loading time t , when a sample twine L cms long was loaded with a tensile stress p kgf per cross-sectional area of the twine, can be expressed as follows;

$$\frac{dL}{L} = \frac{p}{E_1} + \frac{p}{E_2}(1 - e^{-(E_2/\eta_2) \cdot t}) + \frac{p}{\eta_1} \cdot t \quad (1)$$

where E_1 , E_2 , η_1 and η_2 are model constants as in Fig. 2. The first term on the r.h.s. of Eq. (1) expresses the strain with E_1 , the second term the strain with E_2 and η_2 and the third term the strain with η_1 , respectively.

Comparing Eq. (1) with the creep curve in Fig. 1, dL_1/L corresponds to p/E_1 , dL_2/L to p/E_2 and according to that $p/E_1 + p/E_2 + (p/\eta_1) \cdot t$ is found to be a single equation for t . Since the slope of the inclined dotted line BF corresponds to p/η_1 , Eq. (1) can be rewritten. Taking Napierian logarithms on both sides the following equation can be obtained.

$$\ln \left(\frac{p}{E_2} \right) - \frac{E_2}{\eta_2} \cdot t$$

$$= \ln \left(\frac{p}{E_1} + \frac{p}{E_2} + \frac{p}{\eta_1} \cdot t - \frac{dL}{L} \right) \quad (2)$$

On drawing the graph of Eq. (2) the slope of the line obtained, showing the relation between the r.h.s. of Eq. (2) and loading time t , is $-E_2/\eta_2$. Namely, retardation time τ is equivalent to $-E_2/\eta_2$ and hence η_2 can be obtained by measuring τ .

Results and Discussion

Results obtained for E_1 are shown as in Table 1, Fig. 4, for E_2 as in Table 2, Fig. 5, for η_1 as in Table 3, Fig. 6 and for η_2 as in Table 4, Fig. 7, respectively. Four elements are put together as in Table 5 for comparing the values of E_1 , E_2 , η_1 and η_2 .

E_1

Taking a look at Table 1, Fig. 4, showing the values of instantaneous E_1 , the mutual relation in materials are virtually the same as the relation in the previous paper³⁾. This is due to the loading

Table 1. Instantaneous Young's modulus E_1 in the Maxwell structure

	n	dL_1 (cm)	$(dL_1/L) \times 10^3$	$p \times 10^{-9}$ (dyne/cm ²)	$E_1 \times 10^{-9}$ (dyne/cm ²)
Nylon	9	10.705	85.64	1.1763	13.74
	12	9.040	72.32	0.9387	12.98
	15	7.860	62.88	0.7801	12.41
	18	6.810	54.48	0.6521	11.97
	21	6.015	48.12	0.5622	11.68
	24	5.320	42.56	0.4895	11.50
Vinylon	12	3.940	31.52	0.8205	26.03
	15	3.815	30.52	0.6920	22.67
	18	3.495	27.96	0.5721	20.46
	21	3.365	26.92	0.4983	18.51
	24	3.090	24.72	0.4292	17.36
	27	2.765	22.12	0.3651	16.51
Polyester	12	8.085	64.68	0.9732	15.05
	15	7.080	56.64	0.8211	14.50
	18	6.125	49.00	0.6766	13.81
	21	5.555	44.44	0.5889	13.25
	24	4.800	38.40	0.4957	12.91
	27	4.350	34.80	0.4415	12.69
Polyethylene	9	4.795	38.36	0.5565	14.51
	12	4.005	32.04	0.4142	12.93
	15	3.260	26.08	0.3237	12.41
	18	2.925	23.40	0.2675	11.43
	21	2.605	20.84	0.2296	11.02
	24	2.255	18.04	0.1816	10.07

n : Number of single yarns. dL_1 : Elongations of sample twines. dL_1/L : Strain of sample twines 125.0 cm in length. p : Instantaneous tensile stress per unit cross-sectional area of sample twines.

Fig. 4. Relation between instantaneous Young's modulus E_1 of the Maxwell structure and number of single yarns n .

time where the time required by the 4 kgf to act is extremely short; less than 0.2 seconds, as mentioned in the previous paper³¹. It is thus considered that the actions of the two dashpots are infinitesimal and the greater part of the elongation is due to the spring E_1 . Since the values of vinylon are considerably larger than those of the other materials, it is rather difficult to obtain an elongation for instantaneous load. Also, since the average ratio of change is larger than that of the other 3 materials for the same number of single yarns n to E_1 , vinylon is considered to be most affected by the twist.

E_2

According to Table 2, Fig. 5, the values of E_2 decrease with the increase of values of the number of single yarns n , which is the same as for E_1 . It shows that elongation of the material of a single yarn by itself or yarns together is affected by the twist and increases when the number of single yarns n also increases. From the shape of the curves two groups are seen to be formed. Namely, nylon and polyethylene constitute shapes that are linear having inclinations equivalent to each other.

Table 2. Instantaneous Young's modulus E_2 in the Voigt structure

	n	dL_2 (cm)	$(dL_2/L) \times 10^3$	$p \times 10^{-9}$ (dyne/cm ²)	$E_2 \times 10^{-9}$ (dyne/cm ²)
Nylon	9	3.145	25.16	1.1763	46.75
	12	2.560	20.48	0.9387	45.84
	15	2.180	17.44	0.7801	44.73
	18	1.830	14.64	0.6521	44.54
	21	1.595	12.76	0.5622	44.06
	24	1.405	11.24	0.4895	43.55
Vinylon	12	1.775	14.20	0.8205	57.78
	15	1.740	13.92	0.6920	49.71
	18	1.690	13.52	0.5721	42.32
	21	1.655	13.24	0.4983	37.64
	24	1.585	12.68	0.4292	33.85
	27	1.440	11.52	0.3651	31.69
Polyester	12	2.560	20.48	0.9732	47.52
	15	2.500	20.00	0.8211	41.06
	18	2.340	18.72	0.6766	36.14
	21	2.160	17.28	0.5889	34.08
	24	2.075	16.60	0.4957	29.86
	27	1.985	15.88	0.4415	27.80
Polyethylene	9	4.630	37.04	0.5565	15.02
	12	3.765	30.12	0.4142	13.75
	15	3.190	25.52	0.3237	12.68
	18	2.780	22.24	0.2675	12.03
	21	2.490	19.92	0.2296	11.53
	24	2.035	16.28	0.1816	11.16

n : Appeared in Table 1. dL_2 : Elongations with Voigt element E_2 . dL_2/L : Strain for sample twines 125.0 cm in length. p : Appeared in Table 1.

Fig. 5. Relation between instantaneous Young's modulus E_2 of the Voigt structure and number of single yarns n .

Fig. 6. Relation between coefficient of viscosity of the Maxwell structure and number of single yarns n .

Table 3. Coefficient of viscosity η_1 in the Maxwell structure

	n	dL_3 (cm)	$(dL_3/L) \times 10^3$	$p \times 10^{-9}$ (dyne/cm ²)	$t \times 10^{-2}$ (sec.)	$\eta_1 \times 10^{-14}$ (poise)
Nylon	9	2.905	23.24	1.1763	540	27.33
	12	1.815	14.52	0.9387	450	29.09
	15	1.910	15.28	0.7801	600	30.63
	18	1.230	9.84	0.6521	480	31.81
	21	1.240	9.92	0.5622	576	32.64
	24	0.795	6.36	0.4895	432	33.25
Vinylon	12	2.510	20.08	0.8205	612	25.01
	15	1.885	15.08	0.6920	585	26.85
	18	1.555	12.44	0.5721	600	27.59
	21	1.405	11.24	0.4983	636	28.20
	24	1.150	9.20	0.4292	621	28.97
	27	1.170	9.36	0.3651	750	29.26
Polyester	12	1.775	14.20	0.9732	504	34.54
	15	1.755	14.04	0.8211	609	35.62
	18	1.370	10.96	0.6766	594	36.67
	21	1.095	8.76	0.5889	558	37.51
	24	1.095	8.76	0.4957	672	38.03
	27	0.960	7.68	0.4415	672	38.63
Polyethylene	9	4.870	38.96	0.5565	414	5.91
	12	4.080	32.64	0.4142	558	7.08
	15	3.295	26.36	0.3237	672	8.25
	18	2.150	17.20	0.2675	600	9.33
	21	1.740	13.92	0.2296	621	10.24
	24	1.180	9.44	0.1816	573	11.02

n, p : Appeared in Table 1. dL_3 : Flowing elongations in the Maxwell structure. t : Loading time.

Table 4. Coefficient of viscosity η_2 in the Voigt structure

n		9	12	15	18	21	24	27
Nylon	$E_2 (\times 10^9 \text{ dyne/cm}^2)$	46.75	45.84	44.73	44.54	44.06	43.55	
	τ (sec)	519.7	507.5	492.0	481.8	468.0	461.8	
	$\eta_2 (\times 10^{12} \text{ poise})$	243.0	232.6	220.1	214.6	206.2	201.1	
Vinylon	$E_2 (\times 10^9 \text{ dyne/cm}^2)$		57.78	49.71	42.32	37.64	33.85	31.69
	τ (sec)		540.7	523.1	498.2	473.0	459.5	435.0
	$\eta_2 (\times 10^{12} \text{ poise})$		312.4	260.0	210.8	178.0	155.5	137.9
Polyester	$E_2 (\times 10^9 \text{ dyne/cm}^2)$		47.52	41.06	36.14	34.08	29.86	27.80
	τ (sec)		827.6	744.1	657.1	567.1	470.1	406.9
	$\eta_2 (\times 10^{12} \text{ poise})$		393.3	305.5	237.5	193.3	140.4	113.1
Polyethylene	$E_2 (\times 10^9 \text{ dyne/cm}^2)$	15.02	13.75	12.68	12.03	11.53	11.16	
	τ (sec)	457.6	436.7	417.6	402.6	373.3	353.7	
	$\eta_2 (\times 10^{12} \text{ poise})$	68.7	60.1	53.0	48.4	43.0	39.5	

E_2 : Appeared in Table 2. τ : Retardation time Tau appeared in the previous paper⁴.

Fig. 7. Relation between coefficient of viscosity of the Voigt structure and number of single yarns n .

On the other hand, vinylon and polyester constitute shapes that are curved having virtually the same inclination. This suggests that the spring of the Voigt structure shows similar dynamic action for identical groups except for a difference in the values, polyethylene can be seen to be easily elongated to about 3–4 times more than nylon, and this is due to the dashpot affixed in parallel by the spring. The elongation is suppressed in a little while but the change due to elongation over a period of time is greater than when compared to the other materials. Owing to the values of the dashpot, as shown in Table 3, Table 4, Fig. 6 and Fig. 7, which are considerably smaller than those

of the other materials, it can be considered that the sample twine is rather fluid on the whole.

η_1

According to Table 3, Fig. 6, the relationship between the number of single yarns n and η_1 is positive whereby in the case of E_1 and E_2 , this relationship was negative. This shows that an increase in the number of single yarns causes a decrease in the fluidity of the twine and this effect is the same in all the 4 materials. It is worthy to note that the fluidity of polyethylene is 5–7 times greater than that in the other 3 materials.

η_2

The relationship between η_2 and n , as in Table 4, Fig. 7 is negative for all the 4 materials, as was the case with ' n ' w.r.t. E_1 , E_2 , and suggests increasing fluidity w.r.t. the number of single yarns. These 4 materials can be divided into 2 groups nylon, polyethylene and vinylon, polyester according to their coefficients and the numeric value of polyethylene is several times smaller than that of the other 3 materials. It can therefore be concluded that polyethylene is the most fluid of the 4 materials.

Relation between Netting Twine and Model Elements

From the Maxwell structure in Fig. 2, if the values of E_1 for instantaneous loading are small the twine is found to elongate easily, and this shows it having a superior shock absorbing effect. If the values of η_1 for long time loading are small, the twine shows a fluid elongation rather easily. From the Voigt structure, the elongation for E_2 is damped by η_2 w.r.t. time and it is difficult to obtain an elongation for instantaneous loading.

Table 5. All-inclusive table of E_1 , E_2 , η_1 and η_2

	n	E_1	E_2	η_1	η_2
Nylon	9	13.74	46.75	27.33	24.30
	12	12.98	45.84	29.09	23.26
	15	12.41	44.73	30.63	22.01
	18	11.97	44.54	31.81	21.46
	21	11.68	44.06	32.64	20.62
	24	11.50	43.55	33.25	20.11
Vinylon	12	26.03	57.78	25.01	31.24
	15	22.67	49.71	26.85	26.00
	18	20.46	42.32	27.59	21.08
	21	18.51	37.64	28.20	17.80
	24	17.36	33.85	28.97	15.55
	27	16.51	31.69	29.26	13.79
Polyester	12	15.05	47.52	34.54	39.33
	15	14.50	41.06	35.62	30.55
	18	13.81	36.14	36.67	23.75
	21	13.25	34.08	37.51	19.33
	24	12.91	29.86	38.03	14.04
	27	12.69	27.80	38.63	11.31
Polyethylene	9	14.51	15.02	5.91	6.87
	12	12.93	13.75	7.08	6.01
	15	12.41	12.68	8.25	5.30
	18	11.43	12.03	9.33	4.84
	21	11.02	11.53	10.24	4.30
	24	10.07	11.16	11.02	3.95

Unit and order: E_1 ($\times 10^9$ dyne/cm²), E_2 ($\times 10^9$ dyne/cm²), η_1 ($\times 10^{14}$ poise), η_2 ($\times 10^{13}$ poise).

The elongation is seen to be gradual and fluid to the maximum elongation point for E_2 , with the lapse of time. Considering these facts, and looking through Table 5, nylon and polyethylene amongst the 4 materials are seen to have a rapid response,

while the one with the slowest response is vinylon, for instantaneous loading. In the creep behaviour tests while under a long loading period, the values of E_2 , η_1 and η_2 for polyethylene are somewhat smaller than those of the other 3 materials and hence it is considered to have the most fluid elongation. In light of the preceding discussion, the most suitable materials for respective fishing methods should be chosen in fishing gear. Since netting twines and ropes possessing 4 elements are more suited for fishing gear, grasping the dominating cause of these elements for the purpose of developing these materials is required. In this series of experiments the loading weight of 4 kg is constant for any of the samples. The correction with simulation or, in addition to this series, other experiments with even load per cross-sectional area of the twine are considered to be necessary.

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