Rheology of Coal. IV. Strength and Fracture of Coal

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Introduction

As well demonstrated by such example as that tar, which is usually accepted as a "ductile" material, is "brittle" under impact, or that rubber, which is typically "elastic" at ordinary conditions, becomes "brittle" at liquid air temperatures, the mechanical properties of solids are functions of, at least, time and temperature.

Coal is not, of course, a simple solid, but is of extreme complexity and variety. One of the present authors (K. I.) has tried experiments on the Young's modulus(1) and internal viscosity(2)(3) of coal, which might be able to propose an aspect on the structure and properties of coal from the rheological standpoints, in order to give more straightforward interpretations of the complex properties of coal. As one of the important rheological characteristics of coal, brittleness or strength for rupture is considered in this paper in the light of the facts disclosed in these preceding studies.

The strength of coal is a very important property in various fields of industry concerning coal. First, the mechanical strength is a leading factor for the efficient coal mining, whether the coal is mined by machines or by hands. The fracture of coal during the transportation or coal cleaning is a factor to determine the saleable output rate for definite purposes. The furnace or oven in which the coal is burned or carbonized desires stable

(1) K. Inouye, *J. Colloid Sci.*, **6**, 190, (1951).
(2) K. Inouye, *This Bulletin*, **26** 84 (1953).
(3) K. Inouye, *This Bulletin*, **26**, 157 (1953).

mechanical property of the coal used. There is no doubt of the importance of the strength when the coal is treated in a powdered form, as in floatation, briquetting etc.

In these cases, the coal is subjected to various kinds of stresses, especially varying duration of load. As described above, the coal strength is a function of time, so that the phenomena concerning the strength or fracture should be considered from the standpoint that one cannot speak of a definite characteristic strength of the solid, although some influences of inner flaws and chemical environments in the coal should not be neglected.

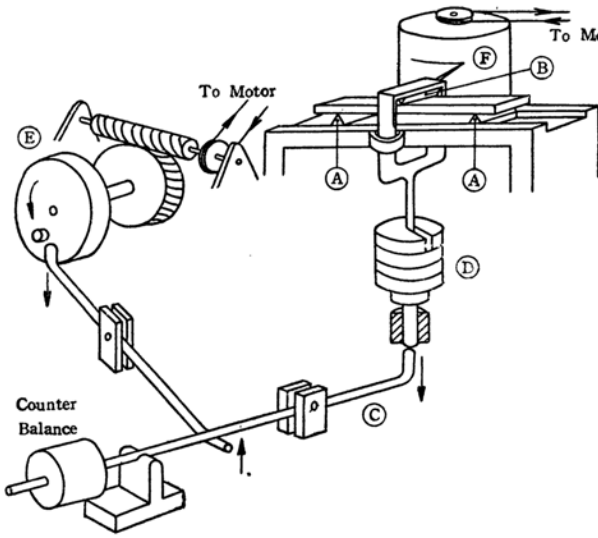

Fig. 1.—Experimental Apparatus

F. W. Preston and others[4] have shown, in their experiments on the fatigue of glass that the strength of glass is a simple function of time under a constant load,

$$\log t = -a/m + 1/fm \qquad (1)$$

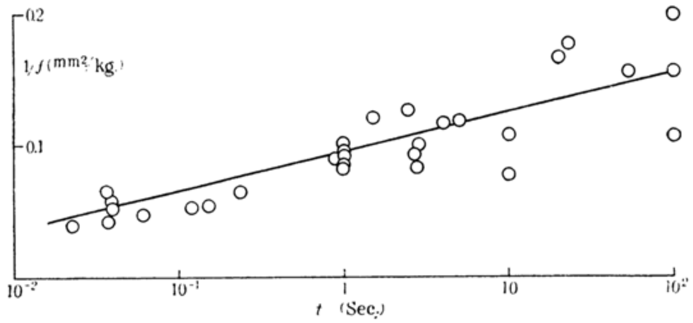

Fig. 2.—$1/f$ versus t for window glass

where, f is the stress required to break a solid, t its duration of application, and a and m are constants. Each sample is thus defined by the inclination factor m (termed fatigue modulus) and by the point t_0, where the line intersects the time axis.

N. W. Taylor[5] has proposed a theory which connects f with t. The slow process preceding fracture is shown to be the orientation of the atomic network contained in an elementary prism of length $r = \lambda_0 E/f$, where E is Young's modulus and λ_0 is the critical elongation required for fracture. The rate-controlling factor is the activation energy, $E\alpha/f$, for the orientation or rearrangement of the atomic network under the stress. The theory has lead to the equations,

$$t = (1/k_0)e^{E\alpha/fKT} \qquad (2)$$

and

$$\log t = -\log k_0 + (E\alpha/2.3\,KT)/f \qquad (3)$$

where K is the Boltzmann constant, T the absolute temperature and α and k_0 are constants. It is noteworthy that the logarithmic expression has the same form as the empirical relation by Preston et al.

The present authors have constructed an apparatus to measure the breaking stress at varying durations of load and, after some preliminary tests with glass in order to check the above-mentioned logarithmic relation between stress and time by their own apparatus, the breaking experiments were carried out on coal to interpret the fracture.

Apparatus and Experimental Procedures

Fig. 1 shows the apparatus schematically. The specimen, cut in a rectangular bar with the accuracy of 1% in each dimension and parallel to the bedding plane, is set on two wedge-shaped metals (A). The stress is applied by another wedge-shaped metal (B) just touched to the centre line in the upper surface of the specimen, when

(4) J. L. Glathart and F. W. Preston, *J. Appl. Phys.*, **17**, 189, (1946).
T. C. Baker and F. W. Preston, *J. Appl. Phys.*, **17**, 170, (1946).
(5) N. W. Taylor, *J. Appl. Phys.*, **18**, 943, (1947).

the shaft (C) is removed from the position of supporting the weight (D). The short duration of application can be changed by a gear and cam mechanism (E) driven by motor, covering the range of 1 sec. to 0.01 sec. The actual time of applied stress was measured by the recording dram method (F), a longer period than 1 second by the stopwatch.

The experimental procedure begins with a measurement to try to break the specimen at a certain time of load, t_1, with continuously changing weight, w, and if the specimen does not fracture at w_m but does at w_n, the breaking strength at t_1, f, is calculated from the equation,

$$f=\frac{3w_n l}{2b\tau^2} \tag{4}$$

where, l is the span length, b the breadth and τ the thickness of the specimen, assuming that the coal fractures is a dynamic solid.

The possible maximum error of the experiment is considered as follows: errors in dimensions of the specimen are ±3%, errors in measuring the weight ±6%, and errors in measuring the time, which however vary with the time range, are ±5% at maximum cases. The total error is, therefore, ±14% at its maximum.

All specimens were examined after being set

Table 1
Fracture Experiments of Coal Samples

Sample	Block No.	Average ash %, dry basis, in vol. (ϕ)	Ash % of specimen (dry basis)		$1/f$ (mm²/kg)	t (sec)
			in weight	in volume (ϕ)		
American	I	13.0	13.08	8.19	1.28	3×10^{-2}
(Bituminous,			19.00	12.34	1.48	1.5
strongly-caking)			19.56	12.73	1.54	3.2×10^{-2}
	II	65.0	67.93	55.97	1.18	2×10^{-2}
			69.50	58.57	1.62	1.5
			80.05	70.65	1.52	0.5
			80.07	70.38	1.78	3.5
	III	86.0	90.64	85.32	0.68	300
			91.15	86.07	0.58	4×10^{-2}
			91.37	86.40	0.66	50
			91.56	86.84	0.64	2.5×10^{-1}
Takashima	I	1.4	2.32	1.41	2.86	2×10^{-2}
(Bituminous, caking)			2.33	1.41	3.24	30
			2.37	1.44	2.32	4×10^{-2}
			2.91	1.77	3.90	300
	II	3.0	4.48	2.74	2.24	300
			4.75	2.89	2.00	0.1
			5.03	3.07	1.84	100
			5.49	3.37	2.18	2×10^{-2}
	III	10.0	12.13	7.65	0.84	1.3×10^{-1}
			17.80	11.50	0.64	4.6×10^{-1}
			22.07	14.52	0.98	5
Yubetsu	—	—	22.99	16.61	0.38	1
(Producer gas coal)			27.33	18.41	0.51	4
			28.69	19.42	0.38	4×10^{-2}
			29.43	20.00	0.46	0.5
			29.92	20.39	0.44	10
			31.38	21.53	0.44	3×10^{-2}
			40.63	29.11	0.62	24
			53.15	40.50	0.37	0.2
			55.10	42.41	0.50	3
			57.16	44.46	0.37	5×10^{-2}
			57.83	45.14	0.73	70
Shosaku	—	3.6	5.64	3.46	1.18	2
(Anthracite)			5.72	3.51	1.06	3×10^{-2}
			5.78	3.55	1.12	0.1
			5.83	3.59	1.36	2
			7.21	4.45	1.12	0.1
			7.24	4.47	1.18	2×10^{-2}

into the dess'cator of 76% relative humidity for about one month to avoid the influence of the moisture.

Tests on Glass

Approximately 30 specimens were prepared from a piece of window glass and tested by the apparatus. The time for fracture covered the ranges from 5×10^{-2} to 10^3 second. The values of $1/f$, or brittleness index, are plotted against $\log t$ in Fig. 2.

It would appear that the $1/f$ values are more dispersed in the range of longer duration than the shorter. It was, however, assumed that the linear relationship between $1/f$ and $\log t$ is valid in this case. The fatigue modulus, m, obta'ned using the statistical method is 2.90×10^{-2} mm^2./kg. This value is quite reasonable in comparison with those given by Preston et al.

Brittleness Data of Coals

The coals examined were selected from the same species whose structures were previously discussed in the preceding articles of this study. (For the descriptions of samples, see the reference 2 or 3.)

The brittleness data are given in Table 1 with ash concentrations. The ash contents are recalculated in volume percentages, ϕ, because its significant meaning to the properties has been proposed in the author's preceding reports. Several blocks were chosen for each sample and the specimens were made from each block. After the fracture measurements, the actual ash concentrations were obtained for each specimens, which showed, of course, some deviations; the table also gives the mean values, which were obtained by analyses of mixed powdered samples.

Fatigue Modulus and Activation Energy

The $1/f$ values were plotted against $\log t$ for each block and, assuming the linear relationship between $1/f$ and $\log t$, the fatigue modulus, m, they were obtained from the lines on the graph. The validity of the linear reltionship was better for the anthracite and also the producer gas coal; both showed higher strength and slight deviation in strength with the change of ash concentration than the bituminous coals did. The statistical considerations of the dependence of strength on various factors will be described further in the next paper of this study. Fig. 3 shows the $1/f$ versus $\log t$ relationship for Yubetsu coal. Two values with larger deviation at the durations longer than 10 sec. were omitted from the linear relation.

From Equations (1) and (3),

$$m = 2.3\,KT/E\alpha \tag{5}$$

and,

on the other hand, the molal activation energy for fracture is,

$$U = NE\alpha/f \tag{6}$$

where, N= Avogadro's number and hence $NK = R = 2$ cal./mol. Therefore, from (5) and (6), U can be calculated from the experimentally known data of m. U values in Table 2 were calculated at first in functions of $1/f$, and then for breaking time of 10^{-2} sec. and 10^2 sec., where T was taken as 288°K (15°C.), the mean room temperature during the experiments.

Table 2

Activation Energy for Fracture

Sample	$m\times10^2$ (mm^2/kg)	$t=10^{-2}$ sec f (kg/mm^2)	$t=10^{-2}$ sec U (Kcal/mol)	$t=10^2$ sec f (kg/mm^2)	$t=10^2$ sec U (Kcal/mol)
American					
I	18.9	0.82	8.52	0.53	13.2
II	22.0	0.88	6.88	0.49	12.3
III	2.30	1.71	33.8	1.49	38.7
Takashima					
I	31.8	0.42	10.0	0.28	15.2
II	5.52	0.50	48.0	0.45	53.4
III	11.0	1.52	7.94	0.99	12.2
Yubetsu	2.72	2.69	18.2	2.13	22.5
Shosaku	12.2	1.02	10.7	0.64	16.9

The values of f and U express the strength of coal in absolute units at different ranges of duration of load. It is noteworthy that in each cases the rupture can occur less easily with short time of application of stress than with longer deformation. In other words, the coal can be broken with less force when it is applied a for longer time than at short application. The total molal energy required to

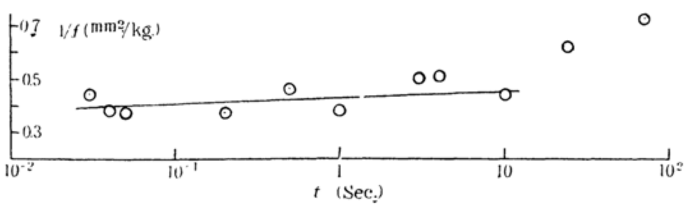

Fig. 3.—$1/f$ versus $\log t$ for Yubetsu producer gas coal.

"activate" the fracture is, however, larger when the deformation is applied for longer duration.

The stress for fracture, f, is larger for the specimen with higher ash concentration (Refer the variations between each result of American coal and of Takashima coal). A remarkable maximum in U values for Takashima coal seems to be difficult to be interpreted; it may be connected with the fact that the Young's modulus of this sample shows a minimum at $\phi=2$ and a maximum at $\phi=8$. (This fact will be reported in detail in Rheology of Coal VI by the present authors.)

The comparison of the strength and the activation energy between species of coals is rather of indefinite conclusion, because of the unequality of analytical composition, although some absolute expressions of industrially empirical strength can be shown.

The comparison of results for Takashima II ($\phi=3.0$) and Shosaku anthracite ($\phi=3.6$) may be interesting; these differences indicate that the bituminous coal is more "brittle" than the anthracite, when applied with stress of short duration, because the ratio of f between the samples is 2.04 at $t=10^{-2}$ sec.; while the difference in strength is slight under long duration of stress, because the ratio is 1.47 at $t=10^2$ sec. The comparison of American I ($\phi=13.0$) and Takashima III ($\phi=10.0$) may suggest the fact that the American bituminous coal is of lower strength than the Japanese bituminous coal. These considerations are readily understood if one refers to the results on the Young's modulus and internal viscosity for these coals.(1) (2) The detailed discussions with further experimental results will be reported in the next paper.

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