6. *Elastic and Viscous Properties of Volcanic Rocks at Elevated Temperatures. Part 2.*

By Shūzō SAKUMA,

Earthquake Research Institute.

(Read Dec. 16, 1952.—Received Dec. 20. 1952.)

1. Introduction.

In the previous report[1], the writer described the mechanical properties of lava-specimens from the Oo-sima volcano. The newly ejected tholeiitic basalt showed quite extraordinary behaviours when its temperature was changed within the range of 20°–1100°C. Young's modulus for it increased at first at low temperature, then it showed a rapid decrease at 700–800°C and viscous flow could be seen beyond that temperature. Elasticity and viscosity were influenced by the time spent in heating as well as the frequency of heat-treatments in the laboratory. The properties were so extraordinary that the writer failed to explain them on the basis of our knowledges concerning metals, artificial glass and other materials. Subsequently, the writer thought it more appropriate at present to study other rocks of simpler structures. From the standpoint just mentioned, the following experiments on vitreous silica, obsidian and Sanukite were carried out.

2. Method.

The same method of bending and sagging thin plates of specimens (ca. 8 cm × 1 cm × 0.3 cm) was adopted as in the previous studies. The specimens acted more or less visco-elastically at high temperatures without exception. Fig. 1 shows the trend of deformation when constant load is applied and then removed. The method of analysis for such visco-elastic bodies, which was adopted in the previous report, was revised a little as follows. By assuming the condition of constant stress,

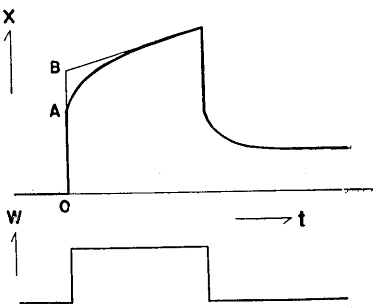


Fig. 1. Deformation (x) of a visco-elastic body under constant load (W).

---

[1] S. SAKUMA, *Bull. Earthq. Res. Inst.*, **30** (1952), 269.

$$\frac{P_{xx}}{\tau}=E(\dot{e}_{xx}+\tau'\ddot{e}_{xx})\ , \tag{1}$$

where E is Young's modulus, and τ and τ' are relaxation times. Then by integration,

$$e_{xx}=\frac{P_{xx}}{E\tau}t+\left(C_1-\frac{P_{xx}}{E\tau}\right)\tau'+C_2e^{-\frac{t}{\tau'}}\ . \tag{2}$$

Put $e_{xx}=\dfrac{P_{xx}}{E}$ at $t=0$, we obtain

$$e_{xx}=\frac{P_{xx}}{E}+\frac{P_{xx}}{E\tau}t-C_2\left(1-e^{-\frac{t}{\tau'}}\right)\ . \tag{3}$$

In the previous paper[2], the whole recoverable part (OB in Fig. 1), including the delayed elastic deformation (AB in Fig. 1, elastic fore-effect or fore-creep in other words), was regarded as the elastic deformation, and Young's modulus was calculated on the basis of the deformation OB. In the present analysis Young's modulus E corresponds to the instantaneous deformation (OA), and the delayed elastic effect can be discussed separately.

At any rate, the amount (x) of deformation actually observed through the apparatus is connected with the coefficients of elasticity E and viscosity η by the following formulae[2].

$$\left\{\begin{aligned}
&x=\left(\frac{Wl^3g}{48I}+\frac{5wl^4g}{384I}\right)\left\{\frac{1}{E}\left(1+\frac{t}{\tau}\right)+C\left(1-e^{-\frac{t}{\tau'}}\right)\right\} && (4)\\
&\text{where } I=\frac{1}{12}bd^3\ .\\
&\eta\doteqdot\frac{\tau E}{3}\ . && (5)
\end{aligned}\right.$$

3. Specimens.

(1) Obsidian. It is a typical natural glass, collected by Dr. Y. Kawano from Wadatōge, Nagano Pref. The rock[3] is of blackish colour. Phenocrysts of plagioclase, biotite and augite are scattered sparsely in the groundmass of colourless glass, and microlites as well as crystallites are lacking.

(2) Sanukite. Collected by Dr. R. Morimoto from Kasuga-yama,

---

[2] S. SAKUMA, *loc. cit.*, 1).

[3] Y. KAWANO, Report No. 134, *Geol. Surv. Japan.* (in Japanese)

Nijō-san, Osaka Pref. The aphanitic andesite[4] contains phenocrysts of plagioclase and hypersthene sparsely in the glassy groundmass. The compact and uniform groundmass consists of glass and equigranular minute crystals of plagioclase, hypersthene, magnetite and of biotite. The rock is hard and of blackish colour as a whole.

(3) Vitreous silica. Specimens of vitreous silica were furnished by the Nihon Quartz Co. Though it was annealed at about 1500°C, a slight heterogeneity was seen even with naked eye.

Dr. Y. Kawano and Dr. R. Morimoto kindly placed at the writer's disposal their rock specimens. To them the writer's cordial thanks are due. The results of chemical analysis are also cited in Table 1.

Table I. Chemical Composition of Specimens.

	Obsidian[3]	Sanukite[4]
SiO_2	76.24	61.72
Al_2O_3	12.56	19.18
Fe_2O_3	0.68	0.53
FeO	0.58	4.11
MgO	0.23	2.12
CaO	0.96	5.59
Na_2O	2.84	2.65
K_2O	4.20	1.99
H_2O_+	0.69	0.45
H_2O_-	0.17	0.23
TiO_2	0.38	0.62
MnO	0.05	0.10
P_2O_5	0.25	0.18
Total	99.83	99.47
Analyst	Y. Kawano	T. Kushida
Location	Wadatōge	Kasugayama

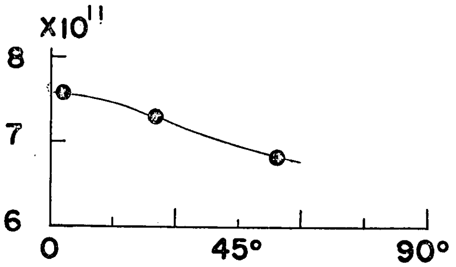


Fig. 2. Young's modulus of obsidian at room temperature (in dyne/cm²) versus the angle of stress to the direction of flow structure in the specimen.

4. Results.

(1) The obsidian. The absolute value of Young's modulus is affected slightly by the flow structure in the rock. It varies according to the angle between the principal stress and the direction of flow structure in the specimen, as is shown in Fig. 2.

The general trend of variation of elasticity versus temperature is quite similar among three examined obsidian specimens. Young's modulus hardly decreases with the rise of temperature until above 600°C, where the rapid augmentation of delayed elastic effect and decrease of elasticity take place. (Figs. 3 & 4). Viscous flow also develops so much

---

4) R. Morimoto, unpublished data, oral communications.

within the range from 650° to 760°C that the present method of experiment failed beyond that temperature. (Fig. 7)

Repeated heating and cooling resulted in a slight decrease of elasticity as well as viscosity.

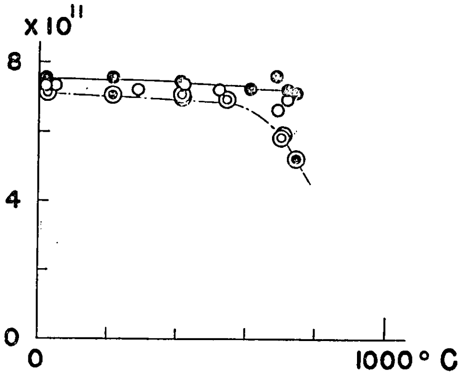


Fig. 3. Variation of Young's modulus of obsidian specimen No. 4 with temperature.
single circles: 1st run;
double circles: 2nd run;
filled circles: heating.

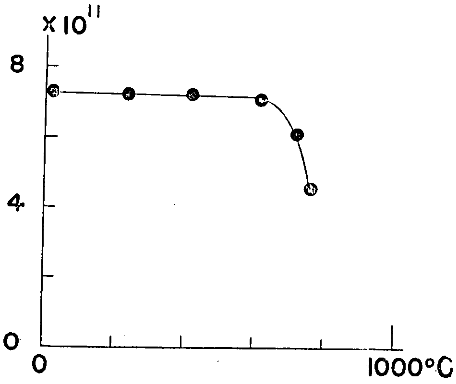


Fig. 4. Variation of Young's modulus of obsidian specimen No. 3 with rise of temperature.

(2) The Sanukite. Only one specimen was examined to this date. With the rise of temperature, elasticity shows no remarkable change till above 650°C, then both the delayed elasticity and viscous flow become noticeable. However, the rate of decrease of viscosity with rising temperature around 700°–800°C is far less than that of the obsidian, and the rate comes to increase remarkably again at above 1000°C. (Figs. 7(a) & 7(b)). Young's modulus for the instantaneous part of deformation also decreases greatly at high temperature as will be seen in Fig. 5. In detail, however, we can notice that the delayed elastic deformation does not change in accordance with the variation of Young's modulus with temperature. Really, Young's modulus begins to decrease significantly from above 800°C, about 150°C higher than the temperature (650°C) at which anelasticity becomes measurable. As a result, the ratio of the delayed elastic part to the instantaneous part of deformation does not change monotonously with temperature. (Fig. 8)

Young's modulus in the cooling process is same as in the heating stage. Lower viscosity in cooling is also worthy of notice.

(3) Vitreous silica. Two specimens were tested up to 1100°C. As

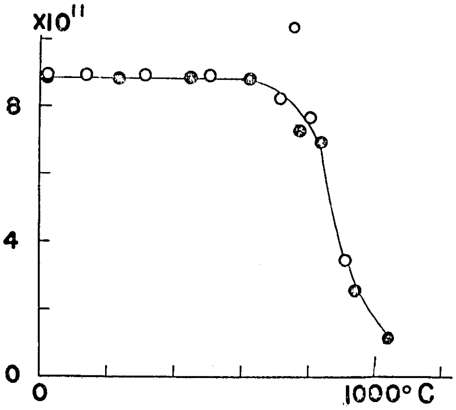


Fig. 5. Variation of Young's modulus of Sanukite.
filled circles: heating;
open circles: cooling.

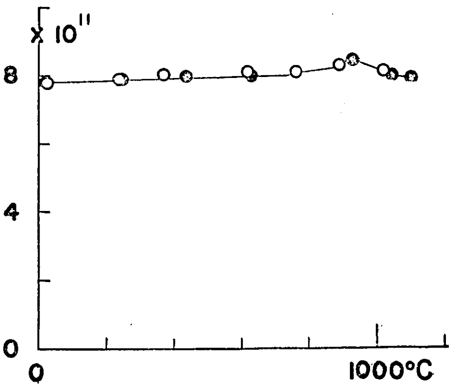


Fig. 6. Variation of Young's modulus of vitreous silica with temperature.
filled circles: heating;
open circles: cooling.

will be seen in Fig. 6, Young's modulus increases slightly with the rise of temperature and tends to decrease at about 1000°C. Only a small amount of viscous flow and delayed elasticity appears beyond 900°C. The whole trend of variation of Young's modulus is nearly reversible in the cooling stage. The increase of elasticity up to 1000°C, amounting to several per cents, was already revealed[5] by many authors in the experiments concerning rigidity of silica. The tendency of increasing elasticity with temperature is somewhat similar to that observed in the case of the Oo-sima lava, although to larger extent in the latter case. It seems not improbable that the growth of microcrystals, if any in super-cooled vitreous materials, would cause an anomalous increase of elasticity.

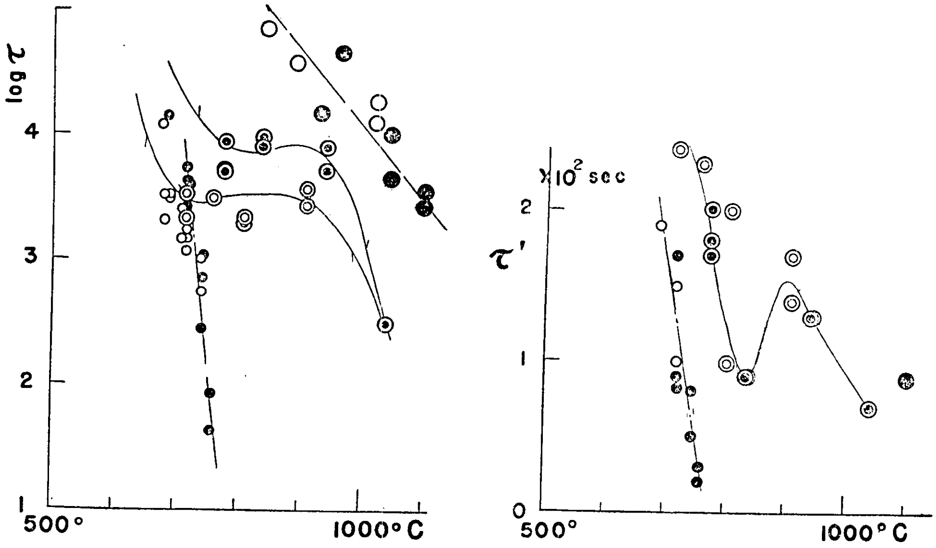
It is a particular feature of the vitreous silica that, when compared with the obsidian and the Sanukite, no anelasticity can be observed at such temperature as 650°-800°C.

5. Discussion.

When the behaviours of the three typical specimens are compared with one another, they can be distinguished unmistakably. The variations of Young's moduli of the obsidian and the Sanukite are rather ordinary and resemble that of artificial glass. In contrast to them, that

---

[5] R. SOSMAN, "The Properties of Silica," U.S.A. (1927).
K. IIDA. *Bull. Earthq. Res. Inst.*, **13** (1935), 665.



(a) τ versus temperature. (b) τ' versus temperature.

Fig. 7. Variation of relaxation times with temperature.
larger circles: vitreous silica; smaller circles: obsidian;
double circles: Sanukite; filled circles: heating; open circles: cooling.

of vitreous silica is extraordinary. Distinct difference may be noticed also in their softening temperatures. The obsidian can be regarded as vitreous, because very sparse phenocrysts only can be found in the glassy base by microscopic studies. The differences in elasticity as well as in anelasticity existing between the two vitreous materials must be ascribed to the difference in their chemical compositions. Consequently, we are inclined to conclude that the interstitial glass itself does influence very much the dynamical properties of glassy rocks at least at elevated temperatures. It is not unreasonable to imagine that the conclusion may hold even in the case of volcanic rocks of higher crystallinity.

The aphanitic andesite (Sanukite), with minute minerals scattered in hard glass, softens at only a little higher temperature than the obsidian, but its viscosity does not decrease so rapidly as the latter. We cannot tell at present whether it is due to their differences in the chemical composition in their glassy parts, or to the existence of the microlites in the glassy base of the Sanukite.

Quantities concerning the delayed elasticity are also illustrated in Figs. 7(b) & 8. There also will be seen obvious differences between the two kinds of glass, and somewhat intermediate characteristics of the Sanukite.

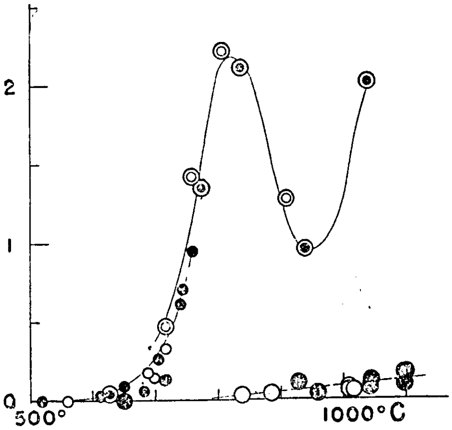


Fig. 8. Ratio of delayed elastic part (AB) to instantaneous part (OA) of deformation under constant load.
larger circles: vitreous silica;
smaller circles: obsidian;
double circles: Sanukite;
filled circles: heating;
open circles: cooling.

Some more words have to be added here about the coefficients E, τ, τ' and the constant C in the equation (4). In the previous paper, the coefficients were regarded simply to be concerned with the rock specimen as a whole. However, what part of the rock deforms instantaneously and what part behaves anelastically in process of time? This problem is too much complicated to be solved at once. When we attempt to summarize the results with the aid of the rheological methods, a puzzling fact turns up. Various rheological models can yield quite the same curve of deformation versus time under constant load. It is highly confusing that not one but several models behave in a similar way. Two of them are illustrated in Fig. 9. One of them (A), i. e. Burger's model, which is the Maxwell body coupled with the Kelvin body in series, is frequently used in chemistry. The equation (1) was derived from the model after some procedures of approximations[6]. Our coefficients E, τ, τ' correspond to E_1, τ_1, τ_2 respectively in this Burger's model. The other model (B) of pararell Maxwell bodies is adopted widely in the research field of artifical glass[7], in which our E corresponds to E_1+E_2 and other coefficients can be replaced by functions of E_1, E_2, τ_1 and τ_2. Both of the models give solutions of the same form under the condition of constant load. Accordingly, it is not easy at present to build up a single definite rheological model for the observed

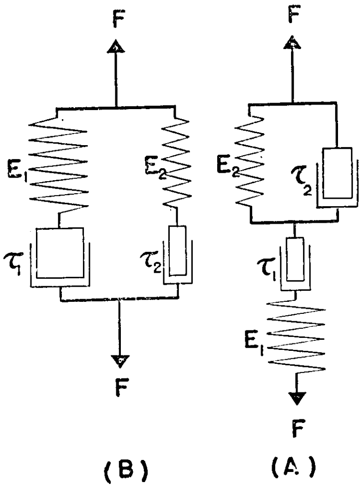


Fig. 9. Rheological models for the behaviours of rocks at high temperature.

---

6) M. REINER, "Deformation and Flow," *London* (1949). p. 279.

7) T. SATÔ. read at the annual meeting of Physical Society of Japan, 1951.

visco-elastic deformation of the rocks, much less to correlate the obtained coefficients directly and duly with the actual petrographical constituents in the rock specimens.

In spite of the restrictions just mentioned, however, the present method of experiment has proved itself useful and reliable enough for the investigations of dynamical properties of rocks. The writer believes that more systematic studies are desirable concerning the rocks of various kinds of interstitial glass as well as those of various mode of aggregation of minerals.

In concluding, the writer wishes to express his hearty thanks to Dr. T. Minakami, Dr. R. Morimoto and Mr. J. Ossaka for their advices and criticisms given from the volcanological and petrological viewpoints.

---

6. 高温に於ける火山岩の粘性及び弾性

第2報

地震研究所　佐久間修三

第1報と同じ撓み法によって，和田峠産の黒曜岩，二上火山の讃岐岩，人工熔融石英の三者について，その粘弾性的性質を室温から1100°Cまでの範囲で測定した．前に報告した大島熔岩に比して，これらの物質はより簡単な変化形式をもっていることが判った．即ち，天然ガラスである黒曜石では，650°C附近から急に粘性が減り，ヤング率も亦減少する．これに対して，同じくガラス状物質であり乍ら熔融石英では，粘性は前者よりはるかに大きく，その減少の割合も小さい上に，弾性率は1000°C附近までは温度と共にむしろ増加する．一方，ガラス質の石基中に微細な結晶を均一にまじえた讃岐岩では，温度上昇に伴う粘性の減り方は前2者の中間的な性質を示し，弾性率の変化はむしろ黒曜岩のそれに類似している．

これらの粘弾性現象を，微視的な過程に直ちにむすびつけて説明することはむづかしいが，岩石の粘性のみならず弾性も或せまい温度領域で急減することは著しい事実であって，これらは結晶粒間を埋めるガラス質部分の性質に多く関係していると思われる．