

EFFECT OF GEOLOGICAL COMPACTION ON THE DEFORMATION OF SEDIMENTARY ROCKS



Effet de la compaction géologique sur la déformation des roches sédimentaires

Die Wirkung der geologischen Verdichtung auf der Verformung der Sedimentgesteine

Hitoshi KOIDE, Kazuo HOSHINO

Geological Survey of Japan, Tokyo, Japan

Gensuke ENDO, Munehiro KITAOKA

Waseda University, Tokyo, Japan

SUMMARY:

The characteristics of deformation of clastic sedimentary rocks are closely related to the porosity which is reduced during the process of geological compaction. Various kinds of Tertiary sedimentary rocks in Japan have been deformed experimentally under confining pressures. Porous sedimentary rocks show the transition from brittle behavior to ductile behavior at low confining pressures. The critical pressure for transition from normal ductile behavior to visco-ductile behavior is related to the effective pressure which the rock suffered during geological compaction. Natural and artificial over-pressure may cause flow-like deformation of soft sedimentary rocks.

RESUME:

Les caractéristiques de la déformation des roches sédimentaires clastiques sont en relation avec la porosité qui se diminue dans le processus de la compaction géologique. Des diverses roches sédimentaires tertiaires au Japon ont été déformées en expérimentations triaxiales. Les roches sédimentaires poreuses font la transition de la condition fragile à la déformation ductile à la basse pression laterale. La pression critique pour la transition de la condition ductile normale à la condition visco-ductile est en relation avec la pression efficace que la roche a souffert dans le processus de la compaction géologique. La surpression naturelle et artificielle peut causer la déformation fluide des roches sédimentaires tendres.

ZUSAMMENFASSUNG:

Die Verformungseigenschaften der sedimentären Trümmergesteine bezieht sich auf die Porosität, die sich unter dem geologischen Verdichtungsprozess vermindern. Die Verformung der verschiedenen Arten von tertiären Sedimentgesteinen wurde unter triaxialem Druck untersucht. Poröse Sedimentgesteine zeigen die Umwandlung vom fragilen bis zum dehnbaren Verhalten unter niedrigem Seitendruck. Der kritische Druck für die Umwandlung vom normalen dehnbaren bis zum viskidehnbaren Verhalten bezieht sich auf den wirksamen Druck, den die Gesteine während der geologischen Verdichtung erfahren haben. Es wird angenommen, dass durch natürlicher und künstlicher Überdruck die flüssigen Verformung der weichen Sedimentgesteine verursacht wird.

1. INTRODUCTION

A great variety of mechanical properties of clastic sedimentary rocks multiply the difficulty of estimation of mechanical stability of rock mass. Often, it is impossible to test every variety of rocks which participate in deformation. During the process of compaction, sedimentary rocks continuously transform from unconsolidated sediments into hard rocks.

The overburden pressure and tectonic stress gradually reduce the porosity of sedimentary rocks. One of the authors reported the relation between porosity and strength of clastic sedimentary rocks (Hoshino, 1974). The chemical composition, mineral assembly and texture of rocks also change during the process of compaction. In case of porous sedimentary rocks, the porosity is the most important factor which indicates the degree of compaction and which controls the characteristics of deformation.

In this paper, characteristics of deformation of sedimentary rocks under confining pressure are discussed in terms of geological compaction. The apparatus and method of experiments have been described in

Hoshino et al. (1972).

2. POROSITY EFFECT

The porosity of rock is gradually reduced by compaction. The older rock is generally less porous than younger rocks under similar sedimentary and tectonic environments.

In case of Tertiary sedimentary rocks in Japan which have been tested, the relation between absolute age (α) and porosity (ρ) is roughly (Fig. 1):

$$\log_{10} \rho (\%) = 1.62 - 0.03\alpha (\text{million years})$$

The modulus of deformation clearly increases with the reduction of porosity (Fig. 2). The compaction hardens sedimentary rocks. For example, relation between porosity and modulus of deformation (E) at the confining pressure of 100MPa is:

$$\log_{10} \rho (\%) = 1.54 - 0.03E (\text{GPa})$$

3. BRITTLE-DUCTILE TRANSITION

The behavior of deformation of rocks is classified based on the stress-strain

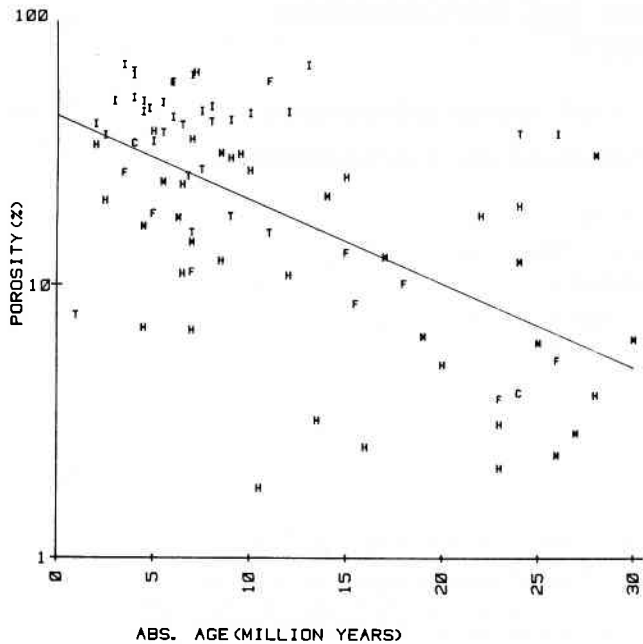


Fig. 1 Porosity(%) versus absolute age (million years) of sedimentary rocks in Japan. The tested rocks include 25 claystones(H), 21 siltstones(I), 24 sandstones(F, M, C.) and 11 tuffs(T).

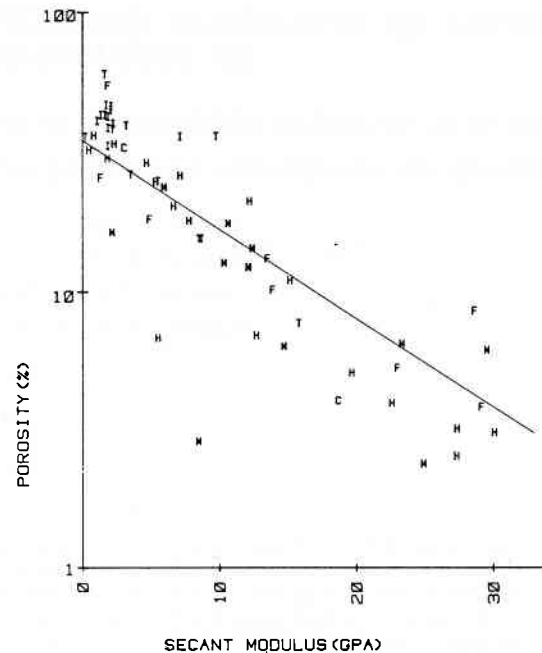


Fig. 2 Porosity(%) versus secant modulus of deformation(GPa; secant modulus at 1% strain) of sedimentary rocks at the confining pressure of 100MPa.

relation as in Fig. 3. The brittle behavior shows abrupt fracturing with no or very slight inelastic deformation. The ductile behavior is characterized by large inelastic deformation over the yield point without fracturing. Rocks often show work hardening at the ductile condition. The transitional behavior shows inelastic deformation but is accompanied with partial stress drop by faulting.

The behavior of deformation of rock is transformed from brittle failure through transitional mode into ductile flow with the increase of confining pressure. Soft sedimentary rocks are transformed into ductile state at very low pressure. However, the transition of behavior of soft rocks follows similar simple law as the one for hard rocks which was found by Mogi(1966) and Byerlee(1968). The fields of brittle failure and of transitional and ductile deformation are divided by a boundary line (R) in the confining pressure-strength diagram(Fig.4).

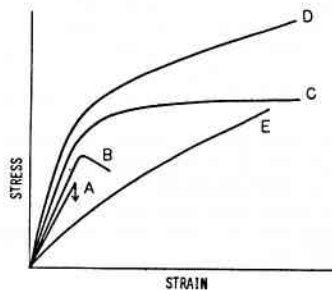


Fig. 3 Schematic stress-strain curves showing behaviors of deformation.

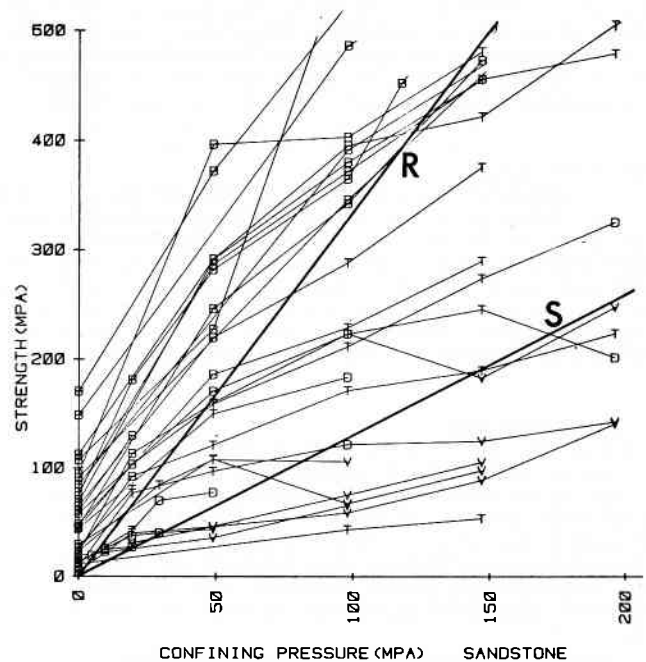


Fig. 4 Ultimate strength(MPa) versus confining pressure of sandstone showing behaviors of deformation. B: brittle, T:transitional, D: ductile and V:visco-ductile behaviors. The lines R and S are boundaries of transition of behavior. The stress at 5% strain is indicated instead of ultimate strength in case of ductile and visco-ductile behaviors.

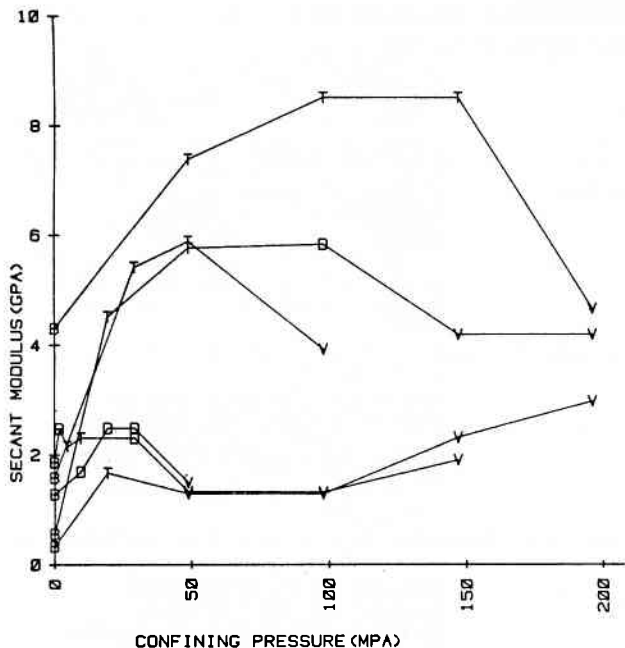


Fig. 5 Change of modulus of deformation (GPa; secant modulus at 1% strain) with the confining pressure (MPa).

4. Visco-ductile flow

A phase of extremely ductile flow has been found by deformation experiments of soft sedimentary rocks under confining pressures (Koide et al., 1971, Hoshino et al., 1972). This flow phase was temporarily named as visco-ductile behavior.

The visco-ductile behavior is characterized by a monotonical gentle slope of stress-strain curve (E in the Fig. 3).

Usually, modulus of deformation becomes higher with the increase of confining pressure. However, the modulus of deformation of porous sedimentary rocks drops sharply due to the transition into visco-ductile flow over a certain value of confining pressure (Fig. 5).

Test data of core samples indicate that the critical confining pressure for transition into visco-ductile flow becomes higher with increase of sampled depth. The critical pressure is almost appropriate to the overburden pressure (Fig. 6).

The transition into visco-ductile flow is a kind of thixotropic weakening. A structural framework of porous sedimentary rock is broken by higher confining pressure than the effective precompaction pressure. Porous sedimentary rocks are liquefied by high effective confining pressure. The transition into visco-ductile flow from normal ductile deformation occurs along the boundary line (S) in the Fig. 4.

The equivalent viscosity after the definition by Griggs (1939) is very low for porous sedimentary rocks (Fig. 7). The low equivalent viscosity indicates the viscous liquid-like behavior of porous sedimentary rocks.

The effective precompaction pressures in several sedimentary basins in Japan are estimated based on the transition pressure into visco-ductile flow (Fig. 8). The rate of increase of precompaction pressure reflects the difference of sedimentary and tectonic environment among sedimentary basins.

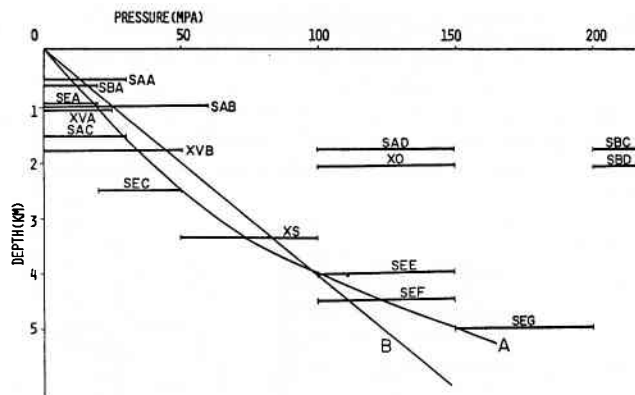


Fig. 6 Sampled depth of core versus pressure (MPa) for transition into visco-ductile flow. Length of line indicates range of uncertainty. The line B denotes the overburden pressure where density of rock is 2500 kg/m^3 .

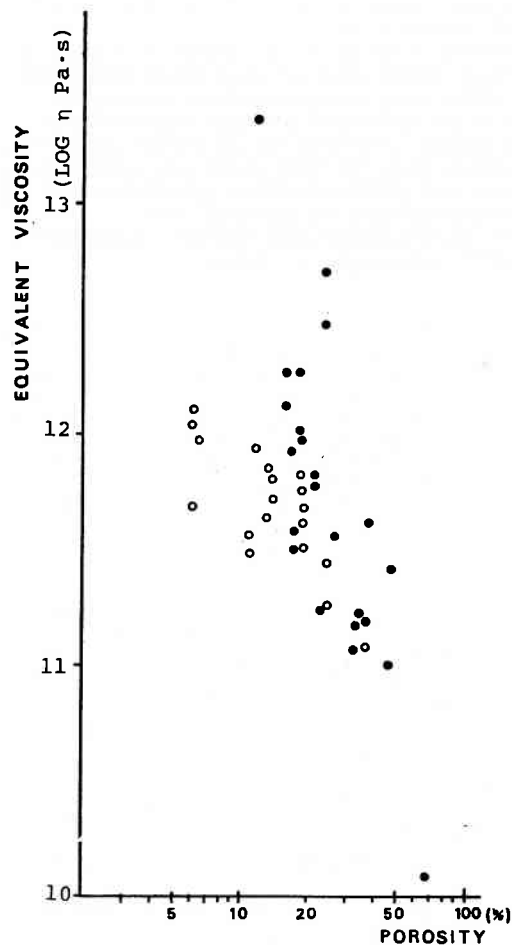
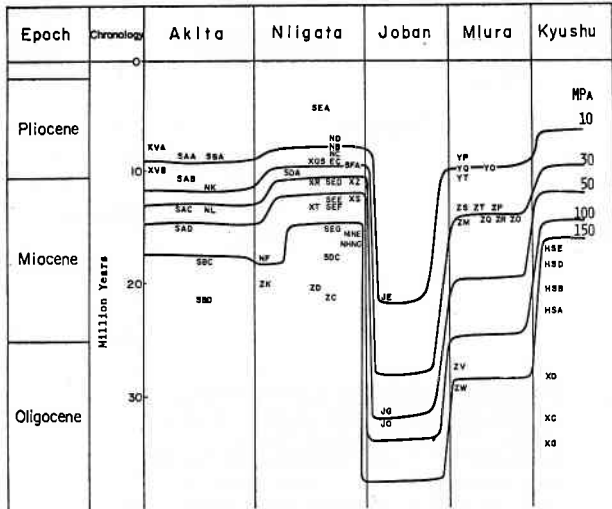


Fig. 7 Equivalent viscosity (Pa·s) versus porosity (%) of sedimentary rocks. Open circles are for sandstones and solid circles for claystones.

Fig. 8 Effective precompaction pressure estimated from transition pressure into visco-ductile flow in several Tertiary sedimentary basins in Japan.



5. CONCLUSION

The experimental deformation of various sedimentary rocks in Japan indicates that sediments are hardened and solidified by geological compaction.

Thixotropic weakening causes visco-ductile flow under higher confining pressure than the effective precompaction pressure which the rock suffered in the sedimentary basin. A rapid increase of pressure causes visco-ductile flow if the pressure uprises higher than the precompaction pressure.

An overpressure by natural and artificial disturbance may induce liquefaction of soft sedimentary rocks.

REFERENCES

- Byerlee, J.D. Brittle-ductile transition in rocks, Jour. Geophysic. Res., Vol. 73, 1968, pp. 4741-4750.
- Griggs, D. T. Creep of rocks, Jour. Geol., Vol. 47, 1939, pp.225-251.
- Hoshino, K. Effect of porosity on the strength of the clastic sedimentary rocks, Advances in Rock Mechanics, Proceedings Third Intern. Soc. Rock Mech. Congr., II-A, 1974, pp. 511-516.
- Hoshino, K., Koide, H., Inami, K., Iwamura, S. and Mitsui, S., Mechanical properties of Japanese Tertiary sedimentary rocks under high confining pressures, Geological Survey of Japan, Report No. 244, 1972, 200p.
- Koide, H., Hoshino, K., Inami, K., Iwamura, S. and Mitsui, S., Variation of mechanical properties of Tertiary sedimentary rocks in Japan, Jour. Geolog. Soc. Japan, Vol.77,1971, pp.327-334.
- Mogi, K. Pressure dependence of rock strength and transition from brittle failure to ductile flow, Bull. Earthquake Res. Inst., Vol. 24, 1966, pp.215-232.
- H. Koide, K. Hoshino- Geological Survey of Japan, 8 Kawada-cho, Shinjuku, Tokyo 162, (Japan)
- G. Endo, M. Kitaoka - Waseda University, 4-170 Nishi-Okubo, Shinjuku, Tokyo 160 (Japan)