Relationship between thermal conductivity and porosity in sedimentary soft rocks by an experimental approach

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ABSTRACT: Relationship between thermal conductivity and porosity in sedimentary rocks are required for understanding the fundamental characteristics of rock thermal property in geoscience and geoengineering areas. To examine the relationship by laboratory experiments, we used core samples collected from a deep ocean drilling program called Nankai Trough Seismogenic Zone Experiment by Integrated Ocean Drilling Program. The thermal conductivity of the core samples was measured at high pressure to simulate subduction by reducing the sample porosity. The experimental results revealed a clear inverse relationship between thermal conductivity and porosity of the sedimentary rocks.

Keywords: Sedimentary soft rock, Thermal conductivity, Porosity, High pressure, Laboratory experiment.

1 INTRODUCTION

Thermal conductivity of rocks is required for understanding heat transmission and thermal structure in geoscience and geoengineering areas. Thermal conductivity of a water-saturated rock is dependent on mineral composition of the rock and thermal conductivities of the minerals, as well as porosity and thermal conductivity of the pore water. Therefore, a quantitative relation between thermal conductivities of a given rock type with certain lithology and its porosity might be useful to approximately estimate the rock's thermal conductivity based on its porosity. We have experimentally examined the relationship between thermal conductivity and porosity in sedimentary soft rocks using core samples retrieved from the drilling site C0012 of the ocean drilling program Nankai Trough Seismogenic Zone Experiment (NanTroSEIZE) by the International Ocean Discovery Program (IODP), and estimated the thermal conductivity depth profile at site C0002 in the Nankai accretionary prism (Lin et al., 2020). Here, we report the laboratory experiments and results of the thermal conductivity measurements of three representative samples with initial porosity of approximate 34–61% under high confining and pore pressures.

2 SEDIMENTARY SOFT ROCK SAMPLES

We collected six siltstone core samples with initial porosities ranged from 34% to 61% from the drilling site C0012 by the IODP in the Nankai Trough subduction zone, southwest Japan (Lin et al., 2020). To show the results more clearly, we only report the measurement data of three samples in this conference extended abstract. The core samples were retrieved during IODP expeditions Exp 222 and Exp 333 at the location (32°44.9′N, 136°55.0′E) with a water depth ~3500 m (Expedition 322 Scientists, 2010). This drilling site C0012 is located at the Philippine Sea Plate just before subducting below the Eurasian Plate at the Nankai trough.

Table 1 shows sample IDs, their depth in meters below seafloor (mbsf), lithological unit, lithology, geological age, and basic physical properties (wet bulk density, grain density, porosity and thermal conductivity) (Lin et al., 2020). These three core samples covered a very wide porosity range from ~61% to ~34%. For an example, the core sample name C0012A32R3 shown in Table 1 denotes that it was retrieved from the site C0012, borehole A, 32nd rotary-drilled core (R), 3rd core section. In addition, "H" of C0012D05H3 means hydraulic piston coring system (HPCS). Thermal conductivity shown in the table was measured in this study under atmospheric pressure and room temperature conditions. Density and porosity under atmospheric pressure were determined by the buoyancy method. Lithology and age are after Expedition 322 Scientists (2010).

Table 1. Sample ID, depth (meters below seafloor: mbsf), lithological unit, lithology, geological age, and basic physical properties (modified from Lin et al., 2020).

Sample ID	Depth (mbsf)	Lithological Unit, Lithology and Age	Wet bulk density kg/m^3	Grain density kg/m^3	Initial Porosity %	Thermal conductivity $Wm^{-1}K^{-1}$
C0012D05H3	~144	Unit IC, Hemipelagic mud, late Miocene	1710	2790	60.6	1.34±0.02
C0012A32R3	~341	Unit IV, Hemipelagic mudstone, middle Miocene	1940	2790	47.2	1.52±0.03
C0012G01R4	~518	Unit VI, Calcareous pelagic claystone, early Miocene	2230	2860	33.8	1.80±0.07

3 THERMAL CONDUCTIVITY MEASUREMENT METHOD

We measured thermal conductivities of the sedimentary soft rock specimens under high confining and high pore fluid pressures and room temperature. A measurement system of thermal conductivity under high confining and high pore fluid pressures was used for the experiments (Figure 1). It was first established by Lin et al. (2011) and reconstructed by Lin et al. (2018). This system consists of a commercial thermal conductivity meter (Kyoto Electronics Manufacturing, QTM-500), a high-pressure vessel in which the rock specimen, sensors of thermal conductivity measurements were installed and two high resolution syringe pumps (Teledyne Isco, 260D and 65D). One of the syringe pumps is for controlling confining pressure (65D, maximum up to ~138 MPa); and the other is for pore pressure (260D, maximum up to ~52 MPa). The pore pressure pump allows us to monitor drainage volume of pore fluid from the specimen and to derive porosity change of the specimen during the experiment. We measured the thermal conductivity at each step after porosity of the rock specimens was reduced under high pressures up to a maximum effective pressure of approximate 50 MPa. Consequently, an empirical equation, i.e., an experimental quantitative relationship between thermal conductivity and porosity in the sedimentary soft rocks was obtained.

To change the porosities in the sedimentary soft rock specimens, we increased the confining pressure stepwise to 60 MPa while holding the pore pressure constant at 10 MPa. We then measured the thermal conductivity at each confining pressure. We define the effective pressure P_{eff} as the difference of confining pressure P_c and pore pressure P_p, i.e., $P_{eff} = P_c - P_p$. We set the effective

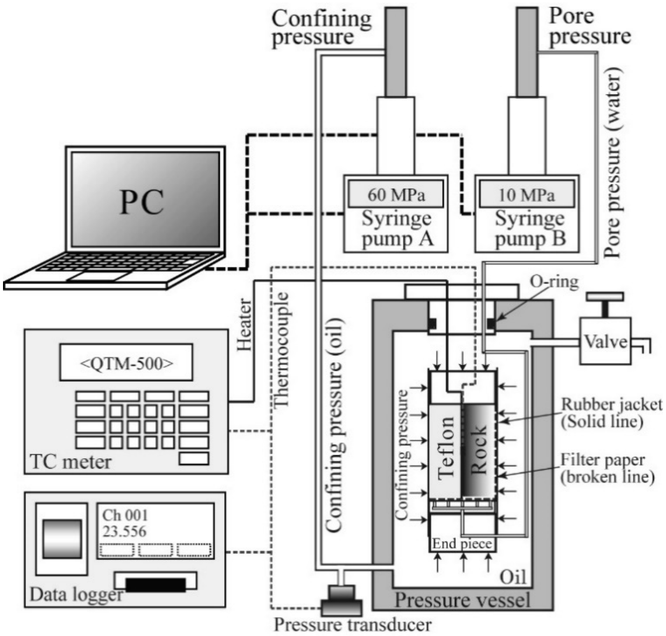

Figure 1. Schematic diagram of the apparatus used in this study for thermal conductivity measurements under high confining pressure and high pore pressure conditions. It is the same system used in Lin et al. (2020).

pressures of the thermal conductivity measurements to 1, 5, 10, 20, 30, 40, and 50 MPa (Figure 2). Because all the sedimentary soft rock specimens used in this study were retrieved from relatively shallow depths (<518 mbsf), effective pressures greater than 5 MPa exceed the maximum pressure that the rock of the rock specimens had experienced. Therefore, the high pressures caused larger porosity changes (deformation), and this process is called normal consolidation. This enabled us to get a thermal conductivity change pattern in a wide porosity range.

4 RESULTS

Figure 2 shows thermal conductivity values measured at various effective pressure conditions for all the three sedimentary soft rock specimens. Thermal conductivity was also measured under atmospheric pressure condition prior to increasing the confining and pore pressure. The results show that thermal conductivity under atmospheric pressure generally increased with depth (Table 1) but appears to depend on the lithology of rock and detailed mineral composition. Overall, the thermal conductivity of wet rock specimens (sea water saturated) increased with increasing effective pressure (Figure 2). As mentioned above, consolidation process of the specimens continued a long time and caused large porosity decreasing under a higher effective pressure than the experienced maximum pressure of the rock. Thus, thermal conductivity was measured several times in this process at the same effective pressure condition. As a result, thermal conductivity increased even under the same effective pressure conditions (Figure 2).

In the light of the observation that the thermal conductivity of a sedimentary soft rock specimen is more directly and strongly dependent on porosity than effective pressure conditions, we show the relationship between measured thermal conductivity and porosity estimated from the initial porosities and the drained water volume of the three specimens in Figure 3. A clear trend was observed for all of the specimens in which the thermal conductivity increased with decreasing porosity. Although the detailed curves differed between the specimens owing to differences in lithology and mineral compositions, the relationship between thermal conductivity and porosity of the three specimens were essentially the same.

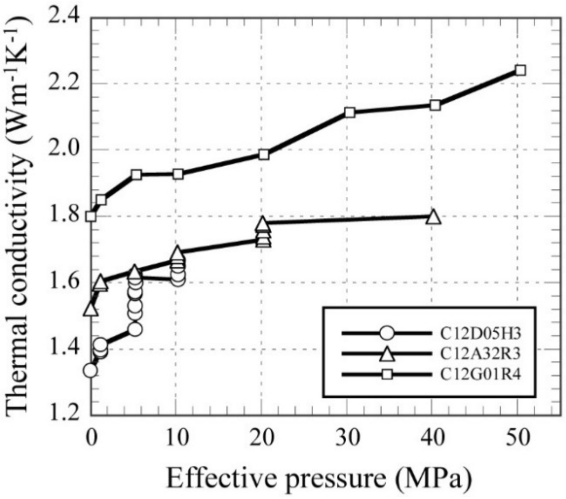

Figure 2. Relationships between measured thermal conductivity and effective pressure of the three rock specimens. Thermal conductivities were measured six or seven times for each test. Then, the data of each plot represents the mean value of the six or seven measured values.

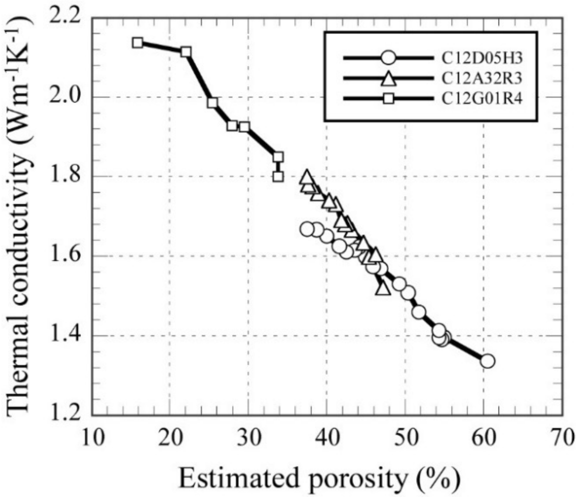

Figure 3. Relationships between measured thermal conductivity and estimated porosity of the three specimens. Same as in Figure 2, each plot shows the mean value of the six or seven measured thermal conductivities. Both Figures 2 and 3 were modified from Lin et al. (2020).

5 SUMMARY

Knowledge of rock thermal conductivity is necessary for various geoscience and geoengineering problems, for an example, for understanding the thermal structure of active seismogenic zones, such as the Nankai Trough subduction zone, SW Japan. To obtain a quantitative relationship between thermal conductivity of sedimentary soft rocks and their porosity, we measured the thermal conductivity of six rock specimens from a depth range of ~144 to ~518 mbsf at site C0012 (Lin et al., 2020); but showed our measurement method and typical results of three specimens only in this conference extended abstract simply. To change the porosity of the specimens, the thermal conductivity measurements were carried out under high-pressure conditions to a maximum effective pressure of ~50 MPa corresponding to a depth of more than ~4 km below seafloor. An experimental relationship (an empirical equation) between thermal conductivity and porosity for sedimentary soft rocks with a wide porosity range from approximately 60% to 30% was obtained (Lin et al., 2020). We expect that this relationship is useful for predictions of thermal conductivity from porosity in sedimentary formations because the porosity is more easily and more popularly measured than thermal conductivity.

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