Correlations between thermal properties and elastic wave velocities of volcanic rocks

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ABSTRACT: Thermal properties such as thermal conductivity are necessary to understand the subsurface thermal structure. It remains difficult to obtain such thermal properties without laboratory measurement on rock core samples, while such core samples are usually difficult to obtain especially at great depths. This research seeks to derive an empirical equation between thermal properties and elastic wave velocities by analysing laboratory measurement data on volcanic rock core samples. Measurements of thermal properties and elastic wave velocity have been conducted on volcanic rock core samples collected from Aso volcanic region, Japan. And correlations between measured physical properties have been discussed. Both thermal conductivity and P-wave velocity were found to decrease with increasing porosity. And thermal conductivity presented a tendency to increase as P-wave velocity increased, while an acceptable empirical equation failed to be obtained which indicated the need for further research.

Keywords: Thermal properties, elastic wave velocity, volcanic rocks, Aso volcanic area.

1 INTRODUCTION

A better understanding of underground phenomena associated with temperature, such as the frictional heat of faults during earthquakes, requires the study of subsurface thermal structure. Computing the thermal structure profile requires the thermal properties of rocks underground. Since it is still challenging to measure the thermal properties of rocks remotely from the ground with high operability and low cost, the predominant method of obtaining such data is laboratory measurement using rock samples. While laboratory measurement requires a certain size of samples, which are usually difficult to be retrieved at great depth and under the sea floor. On the other hand, well logging and geophysical exploration were well established and allowed the in situ physical properties underground like elastic wave velocity and resistivity obtained remotely. Therefore, correlations between these physical properties and thermal properties are of increasing interest. Thermal properties, especially thermal conductivity, are highly dependent on porosity, saturation, and mineral composition, and so does the elastic wave velocity of rocks. Based on this similarity, there is a possibility to obtain the thermal properties of rocks through elastic wave velocity data using the relationship between them.

Our final goal is to derive an acceptable empirical correlation between thermal conductivity and elastic wave velocity for estimating thermal conductivity from the velocity. As the first stage, this paper shows relationships between the thermal conductivity and P-wave velocity by analysing laboratory measured data from rocks collected in the Aso volcanic region of Southwestern Japan, where faulting and magmatic activity are vigorous (Kamata & Kodama, 1999; Mahony et al. 2011). Rock core samples were collected from boreholes drilled through the Futagawa fault, which is the source of the Mw 7.0mainshock of the 2016 Kumamoto earthquake.

2 ROCK CORE SAMPLES

To obtain fresh fault rock samples from the Futagawa fault zone, the Futagawa Fault Drilling Project (FFDP) was conducted in 2017-2018 by Kyoto University (2018). FFDP site is located in Mashiki town, west-southwest of Aso Volcano ~10 km away from the edge of the caldera (Shibutani et al. 2022). Rock core samples in this research were collected depth range from 354 m to 514 m of borehole FDB (including FDB-1 and its branch FDB-1R), drilled in FFDP. Rocks in this depth range were known as Pre-Aso volcanic rocks, which were deposited before the Aso caldera-forming stage (Watanabe & Ono 1969). These volcanic rocks can be subdivided into four different lava groups, namely, autobrecciated lava, massive lava, sheet lava with clinker, and autobrecciated sheet lava (Shibutani et al. 2022). Figure 1 illustrated the structural zonation of blocky magma flow. As magma flows, cooling is first concentrated along the flow edges. The centre part can be deformed in a ductile manner. While the outer shell of the rim is composed of torn clinkers and fractured blocks and rubbles. The advancing flow produces continuous milling and further fracturing, and the high shear rate of the basement and the 'conveyor belt' style advance of the fronts generates a similar layer of breccia on the flow base (Suh et al. 2011). Those containing only the centre part with a certain thickness will form dense massive lava, while the surface broken parts will form autobrecciated lava. And those mixing both the centre part and surface breccia and clinkers were named after sheet lava with clinker and autobrecciated sheet lava.

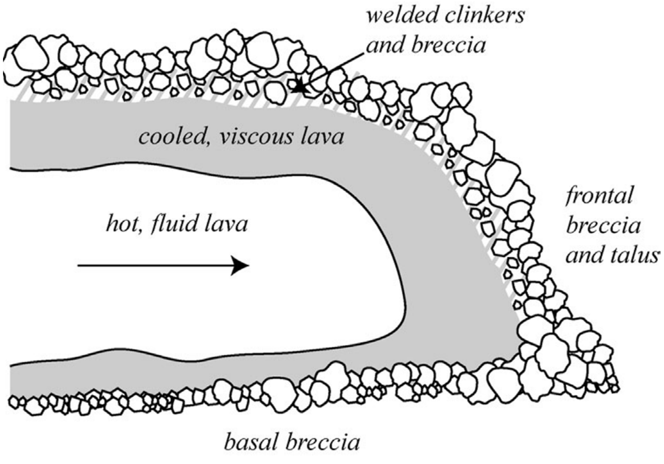


Figure 1. Structural zonation in blocky magma flow (Suh et al. 2011).

A total number of 48 rock core samples were collected from this depth interval of about 160 m. Of which, 8 are extremely brittle autobrecciated lava, exhibiting yellow-white to red-purple in colour due to strong alteration. And 17 are autobrecciated sheet lava, 5 are sheet lava with clinker, which also experienced alteration, and the clinkers generally alternate with lavas (Shibutani et al., 2022). 18 are massive lava, presenting grey to bluish grey in colour for most fresh parts and red-purple for altered parts (Shibutani et al. 2022).

3 MEASUREMENT METHODS

Original rock samples were collected from the relatively complete parts with a length of about 20 to 25 cm from cores excavated. These original samples need to be processed for the following measurements. Firstly, each original sample was cut into 3 or 4 sub-samples with an approximate length of 3 cm for each. The cut surfaces were then hand-sanded with sandpaper to make them flat. Samples should be fully saturated and totally dried before measurement. The saturated condition is to simulate the natural state of rocks under the groundwater level and the dried condition to study the effects of water in the pores of porous rocks. To fully saturated samples, they were immersed in pure water in a vacuum condition created by a vacuum chamber for more than 48 hours. And samples were put into an oven with a temperature of 105°C for more than 48 hours to get them fully dried, and then put into a vacuum chamber for 6 hours to cool to room temperature before measurement.

3.1 Buoyancy method

Porosity is one of the most fundamental physical properties of porous rocks, which describes the potential storage volume of fluid (water, gas, and oil) and influences most physical rock properties, for example, elastic wave velocity, electrical resistivity, and density (Schön 2015). Porosity mentioned in this research refers to the effective porosity, which is available to contribute to fluid flow through the rock. The buoyancy method (Franklin 1979) was adapted to measure porosity, wet bulk density and grain density. The main idea is to determine the volume of the specimen through the difference of masses of the saturated specimen measured in water and in air based on Archimedes' principle.

3.2 Hot disk method

The commercial thermal constants analyser TPS 1500 (Hot Disk, Gothenburg, Sweden) were adapted for the measurement of thermal conductivity, thermal diffusivity and specific heat capacity based on the transient plane heat source (hot disk) method (Gustafsson 1991; ISO 2008). During the measurement, a hot disk probe was sandwiched in a pair of samples, one above it and one beneath it, and a weight was placed on top to ensure good contact between samples and probe. The hot disk probe can operate as a heating source, which produces a heat pulse by an electrical current through it to generate a dynamic temperature field within the measured samples. And the probe can also serve as a dynamic thermometer to record the temperature increase of the probe as a function of time (Gustafsson 1991; ISO 2008). The change in temperature recorded by the probe itself over time is known to depend on values of both thermal conductivity and thermal diffusivity of surrounding samples. Such values can be determined by fitting the increasing temperature curve using least-squares analysis (Lin et al. 2014; ISO 2008). Finally, specific heat capacity can be calculated via known thermal conductivity and thermal diffusivity using the correlation between them.

3.3 Ultrasonic pulse transmission method

P-wave velocity and S-wave velocity of samples were measured using the ultrasonic pulse transmission method. An ultrasonic pulse from the transmitter passes through the sample and the receiver transforms the arriving elastic wave into an electrical signal. An oscilloscope visualizes the received signal and the travel time can be picked. During the measurement, a weight of 2.5 kg was put on the top of the transmitter (or receiver) to ensure good contact between the transmitter, specimen, and receiver, and smear a small amount of grease to the receiver and transmitter so that they adhere well with the specimen. The transmitting and receiving positions are swapped in two ways for the same specimen: forward and reverse. If the measured values of the two differ by more than 10%, the measurement should be repeated.

4 RESULTS AND DISCUSSIONS

4.1 Results

Measured results were shown in Table 1 in the mean ± standard deviation format, sorted by rock types. It can be noted that the porosity of autobrecciated lava and autobrecciated sheet lava are significantly higher than those of massive lava and sheet lava with clinker in terms of mean value and are more widely distributed (with more significant standard deviations). While the wet bulk density of massive lava and sheet lava with clinker is more significant than that of autobrecciated lava and autobrecciated sheet lava, and exhibits a more concentrated distribution. Thermal conductivity and P-wave velocity presented in Table 1 were measured under the saturated condition. Massive lava showed a much higher value in thermal conductivity than other lava groups.

Table 1. Measurement results of porosity, wet bulk density, thermal conductivity (saturated), and P-wave velocity (saturated).

Rock type	Sample number	Porosity (%)	Wet bulk density (g/cm^3)	Thermal conductivity (Wm^{-1}K^{-1})	P-wave velocity (km/s)
Autobrecciated lava	8	16.80 ± 9.01	2.47 ± 0.12	1.40 ± 0.12	3.79 ± 0.76
Autobrecciated sheet lava	17	13.88 ± 8.83	2.50 ± 0.13	1.38 ± 0.12	3.91 ± 0.94
Massive lava	18	8.57 ± 3.36	2.63 ± 0.06	1.74 ± 0.11	4.25 ± 0.44
Sheet lava with clinker	5	6.04 ± 3.24	2.64 ± 0.05	1.42 ± 0.13	4.45 ± 0.57

4.2 Discussions

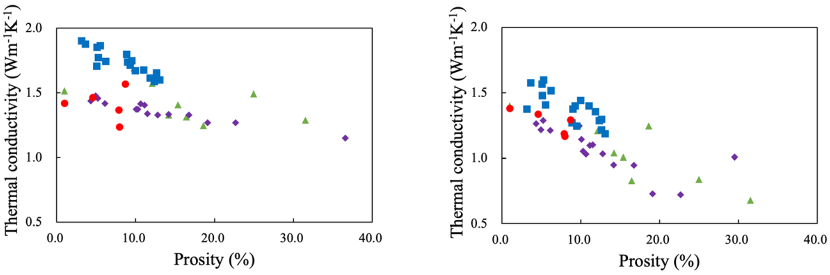
Relationships among thermal conductivity, P-wave velocity and porosity under both saturated and dry states were presented in Figure 2. As can be seen both thermal conductivity and P-wave velocity decrease with increasing porosity under both saturated and dry conditions. At the same time, thermal conductivity shows a general tendency to increase as P-wave velocity increases.

For thermal conductivity, as porosity increases, it decreases faster in the dry state than in the statured state (Figure 2 (a) & (b)). This is considered to be related to the fact that in the dry state, pores are filled with air, and the difference between the thermal conductivity of the air and the thermal conductivity of the rock skeleton is greater than the difference between the thermal conductivity of the water in pores and rock skeleton in the saturated state, which makes the thermal conductivity of rocks in the dry state more sensitive to changes in porosity.

Another thing to notice is that thermal conductivity obtained in the saturated state is more scattered, with the massive lava group exhibiting larger thermal conductivity compared with other groups with similar porosity. Results of XRD analyses and thin section observation carried out on selected samples turned out that there is no great variation in the types nor the relative contents of major rock-forming minerals between different lava groups, and no clay minerals, which are generally considered to be the product of thermal alteration (Shirozu 1985), were found. This is then considered to be due to the fact that massive lava contains less isolated pores than other lava groups, and these differences are detected by the buoyancy method. This results in the solid matrix of massive lava being surplus to the other lava groups for the same measured porosity, resulting in a larger thermal conductivity. This conjecture can also be corroborated by the higher bulk density of massive lava.

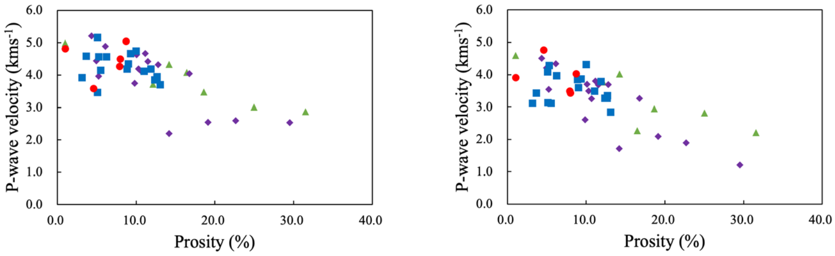
The difference in P-wave velocity measured under both saturated and dry conditions is smaller, compared to that of thermal conductivity. And P-wave velocity presented a tendency to decrease as porosity increased (Figure 2 (c) and (d)), and the rates of decrease in the e4two measurement conditions did not show a significant difference as thermal conductivity shown in Figure 2 (a) and (b). And here massive lave group didn't show a significant difference from other lava groups as it does in thermal conductivity. These differences were considered to be related to the fact that in elastic wave measurement, only the pulse that first reaches the receiver is considered, which means that only the rock "path" that can transmit the pulse fastest is of interest. Whereas, in thermal property measurement, all the rock particle within the probing depth is taken into account.

Thermal conductivity showed a general increasing trend with increasing P-wave velocity in both saturated and dry states, but highly scattered as shown in Figure 2 (e) & (f). The correlation coefficient between thermal conductivity and P-wave velocity is 0.25 in the saturated state and 0.63 in the dry state, nether showed a strong correlation. And it is also difficult to derive well-fitting equations from these plotted data for the relationship between the two. The reason is thought to be due to the inadequate sample size and the relatively narrow distribution of the measured data, especially the thermal conductivity. Also, the data of the massive lava group in Figure 2 (e) & (f) are above other groups, which makes the data more scattered and therefore does not allow for a relation equation. In the future, consideration will be given to increasing the sample size, and taking into account the specificity of massive lava to continue to investigate the relationship between thermal conductivity and P-wave velocity.



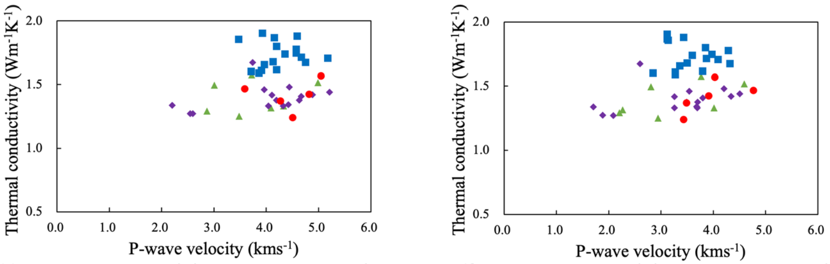
(a) Thermal conductivity (Saturated) vs. Porosity

(b) Thermal conductivity (Dry) vs. Porosity



(c) P-wave velocity (Saturated) vs. Porosity

(d) P-wave velocity (Dry) vs. Porosity



(e) Thermal conductivity vs. P-wave velocity (Saturated)

(f) Thermal conductivity vs. P-wave velocity (dry)

Figure 2. Relationships among thermal conductivity, P-wave velocity, and porosity.

5 CONCLUSION

Measurements of porosity, density, thermal properties, and elastic wave velocity have been conducted on 48 samples of andesite collected from the Aso volcanic region, Japan, and relationships among them have been discussed. Both thermal conductivity and P-wave velocity were found to decrease with increasing porosity. And massive lava exhibited higher thermal conductivity than other lava groups with similar porosity, which is considered to be due to the difference in the contents of isolated pores between these lava groups. As for thermal conductivity and elastic wave velocity, though general trends have been found that thermal conductivity tends to increase with increasing P-wave velocity in both saturated and dry states. However, the current data cannot allow us to derive well-fitting equations between them. The main reason is thought to be the sample size. More research needs to be done in future to study the correlation between thermal properties and elastic wave velocity.

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