Thermal effect on compressional wave propagation across fluid-filled rock joints

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1. Introduction

In the Earth's crust, temperature increases by about 25 °C per kilometer of depth (Wolfson 2011). Significant influences of temperature on hydraulic, mechanical and wave characteristics of rock masses have been found by previous studies (Zhao and Brown 1992; Zhao 1994; Wang 2001). Understanding the thermal effect on wave behaviours through rock masses containing fluids is of great importance to academic developments and practical applications in fields of geophysics, geomechanics, geothermics and so on (Grab et al. 2017).

Over the past decades, the thermal effect on wave characteristics of subterranean fluids (e.g., groundwater and hydrocarbons) and saturated porous rocks have been extensively investigated (Spencer Jr and Nur 1976; Timur 1977; Jones and Nur 1983; Wang et al. 1990; Wang and Nur 1990; Batzle and Wang 1992; Jaya et al. 2010; Dashti and Riazi 2014; Maraghechi et al. 2016). For instance, Wang et al. (1990) measured P- and S-wave velocities in porous rocks saturated with air, water, light oil and heavy oil over the temperature range from 22 °C to 92 °C using the ultrasonic pulse-transmission technique. It was found that P-wave velocity decreases faster in the rock sample saturated with heavy oil than those with either air, water or light oil as temperature increases, whereas S-wave velocity is much less sensitive to the type of filling fluid. Wang and Nur (1991) reported that velocities of hydrocarbons approximately linearly decrease with increasing temperature based on the measurd wave velocities in pure hydrocarbons and their mixtures in the temperature range from -10 °C to 120 °C. More recently, Xi et al. (2007, 2011) investigated temperature-dependent wave attenuation in fluid-saturated rocks and found that attenuated peak shifts to higher frequency as temperature increases.

Numerous investigations have shown that the presence of fluids in sparsely large-scale rock joints strongly affects wave propagation and attenuation (Pyrak-Nolte et al. 1990; Li and Ma 2009; Li et al. 2010; Wu et al. 2014; Yang et al. 2019, 2020). Despite considerable efforts devoted to the temperature-dependent wave attributes of subterranean fluids and rocks with fluid-saturated micro-cracks/pores, the thermal effect on wave behaviours across sparsely large-scale fluid-filled rock joints has still been poorly understood. Pyrak-Nolte (1988) reported that heat appears to increase spectra amplitudes of transmitted waves across the fracture based on ultrasonic tests on single water-saturated fractures at room temperature and 100 °C respectively. Nevertheless, only two different temperature situations were examined, which is inadequate to fully understand the thermal effect on wave behaviours across individual fluid-filled rock joints. As indicated in that study, understanding the thermal effect on wave attributes of fluid-filled rock joints could play a crucial role in many practical applications, e.g., deep geological nuclear waste disposal and enhanced geothermal system. In view of this, it is of great academic and engineering significance to determine the thermal effect on wave responses to fluid-filled rock joint/fracture.

In this paper, ultrasonic pulse-transmission tests have been conducted on single rock joints filled with one liquid (water or light oil) over a typical range of temperature, aiming to systematically and quantitatively determine compressional wave behaviours across single fluid-filled rock joints under different thermal conditions. Different key wave attributes, including wave velocity, transmission coefficient and frequency spectra, were calculated and analysed based on the experimental data. The findings in this study provide more insights into the interaction between wave propagation and individual fluid-filled rock joints.

2. Methods

2.1 Sample preparation

A rock sample with single planar joint at its midplane was manufactured using black gabbro rock from Shanxi, China according to the method used by Yang et al. (2019, 2020). The length and diameter of the jointed rock sample were about 106 mm and 50mm, respectively. Besides, the joint aperture was around 6 mm. With the jointed rock sample, a series of fluid-filled joints were prepared by injecting different fluids into the open joint. Additionally, an intact rock sample with the same dimensions as the jointed sample was prepared using the same rock block to obtain reference data for further analysis of wave attributes of fluid-filled joints. The uniaxial compressive strength, Young's modulus, Poisson's ratio, bulk density and porosity of intact gabbro rock masses are 312.44 MPa, 100.36 GPa, 0.29, 2818.32 kg/m^3 and 0.23% respectively.

Table 1 summaries test conditions of fluid-filled rock joints under a typical range of laboratory temperature for this study. To be specific, water ranging from 10℃ to 80℃ at an interval of 10 ℃ was injected into the open joint respectively to prepare a series of water-filled joints. Similarly, the light oil, i.e., Shell Tellus S2 M68 (abbr. M68 in this paper), ranging from 10 ℃ to 60 ℃ at an interval of 10 ℃ was injected into the empty joint to produce different oil-filled joints. At room temperature (20 ℃), the density and bulk modulus of water are 998.2 kg/m3, 2.1 GPa respectively, while M68 has a density of 875.1 kg/m^3 and a bulk modulus of 1.7 GPa. Furthermore, according to the method suggested in ASTM Standard D445 (2006), the kinematic viscosities of water and M68 at different temperatures were measured using the Rheometer (model MCR 702) in the laboratory, which are tabulated in Table 2.

2.2 Apparatuses

The testing system is illustrated in Fig. 1. For each measurement, incident pulses with the dominant frequency of 100 kHz are generated and sent into the jointed rock sample by an Olympus P-wave transducer, i.e., emitter (model X1020). The emitter is excited by a 200-Voltage spike with duration of 10^{-5} s at a repetition rate of 100 Hz generated by an Olympus pulser/receiver (model 5077PR). The transmitted signals through the tested specimen are detected and captured by the other Olympus P-wave transducer, i.e., the receiver (model X1020) connected to the pulser/receiver, which could be digitized, displayed and recorded by a Tektronix digital oscilloscope (model DPO 2012B). Particularly, 64 digitized transmitted pulses are stacked to obtain the steadily received wave with duration of $1.2\text{x}10^{-4}$ s and a sampling interval of 10^{-9} s. To better couple the interfaces between the rock sample and transducers, the Vaseline is used to seal these interfaces. In addition, a constant external axial force (at about 100 N) is imposed to the assembly of the specimen and transducers to improve the coupling of their interfaces and enhance the stability of the test system. Five tests were performed for each case, and the mean results were considered in the analysis.

3. Results

3.1 Wave velocity

According to the method suggested in ASTM Standard D2845-08 (2008) and Fratta and Santamarina (2002), wave velocities of fluid-filled joints and corresponding jointed rock samples were calculated. Fig. 2 shows the wave velocities as a function of temperature. It is found from Fig. 2a that the increasing temperature (from 10 °C to 80 °C) could result in a nonlinear increase by about 3.34% in wave velocity of water-filled joint, thereby causing higher wave velocity in the corresponding jointed rock sample. Furthermore, the temperature dependence of wave velocity across water-filled rock joint is consistent with that of wave velocity in water (Wilson 1959). It implies that the thermal effect on wave velocity across the individual water-filled joint is highly affected by that on wave velocity through filling water component.

On the contrary, wave velocity of the individual M68-filled rock joint decreases by nearly 5.43% as temperature increases from 10 °C to 60 °C, as illustrated in Fig. 2b. More specifically, the decreasing rate of wave velocity becomes gradually slow with increasing temperature. The finding is approximately consistent with previous findings on temperature dependent wave velocity of the light oil (Wang and Nur 1991). It indicates that the thermal effect on wave velocity across single M68-filled rock joint is determined by temperature-dependent properties of the light oil M68.

3.2 Transmission coefficient

Transmission coefficient is defined as the ratio of the peak-to-peak amplitude of initial wave transmitted through the jointed rock sample to that of initial pulse transmitted across the intact rock specimen (Nagata et al. 2014; Yang et al. 2019, 2020). Fig. 3 illustrates transmission coefficients versus temperature. It is shown that transmission coefficient across the water-filled joint sharply increases by around 50% with the temperature from 10 °C to 20 °C, followed by an increase by about 14% as temperature further goes up to 80°C. It indicates that increasing temperature could lead to more wave energy transmission through the water-filled rock joint, particularly for the temperature range of 10 °C to 20 °C.

On the other hand, as temperature gradually increases from 10 °C to 60 °C, an approximately linear decrease in transmission coefficient for rock sample with single M68-filled joint is observed. It means that a higher temperature could result in less wave energy transmission across the M68-filled rock joint.

3.3 Frequency spectra

Frequency spectra of transmitted waves through jointed rock samples could provide insights into transmitted wave energy distribution over frequency range, which are generally obtained by conducting the fast Fourier transform on tapered initial pulses (Pyrak-Nolte et al. 1990; Zhao et al. 2006). Fig. 4 depicts the frequency spectra for fluid-filled rock joints under different temperatures. It is shown that, compared with the dominant frequency, the amplitude is more sensitive to the varying temperature.

For rock samples with the water-filled joint (see Fig. 4a), the spectral amplitude increases with the rising temperature. Particularly, the increase in amplitudes is more remarkable at lower temperatures. For instance, the peak amplitude increases by around 65.5% when the temperature changes from 10 °C to 20 °C, while it increases by about 13.8% when the temperature further climbs up to 80 °C. It means that, as temperature goes up, transmitted wave energy through the water-filled joint significantly increases at the low temperature range, followed by a continuously slow growth at higher temperatures. In addition, the dominant frequency slightly increases with the increase of temperature. It indicates that more high-frequency wave modes could transmit through the water-filled joint with increasing temperature.

By comparison, for rock samples with the M68-filled joint (see Fig. 4b), the maximum spectral amplitude slightly decreases by about 12% as the temperature increases over the tested temperature range (from 10 ℃ to 60 ℃). Additionally, the dominant frequency decreases slightly with increasing temperature, implying that less high-frequency wave modes can transmit across the M68-filled joint at higher temperature.

4. Discussion

The compressional wave velocity of rock joints filled with water increases with temperature, which agrees well with the thermal effect on wave speed in water (Wilson 1959). The thermal effect on wave velocity across single water-filled joints could be attributed to the temperature-dependent water properties. To be specific, with temperature increasing from 10℃ to 80℃, the water density slightly decreases, while the compressibility of water gradually decreases to the minimum at about 65 ℃ before increasing (Eisenberg et al. 2005). By contrast, for the filled fluid of light oil (M68 used in this study), an increase in temperature results in the reduction of wave speed across the joint, which is in accord with temperature dependent wave properties of liquid hydrocarbons (Wang and Nur 1991). It is likely because that the increase of temperature causes thermal expansion of M68, weakening intermolecular repulsive forces (Wang et al. 1990). Accordingly, compressibility of the light oil increases, thereby causing lower wave velocity. However, findings of wave velocity in this study are somewhat different from the results of rock masses containing fluid-saturated micro-cracks/pores (Wang and Nur 1990). For rock masses with water-saturated micro-cracks/pores, either the filled water or light oil may cause the deceased wave speed with increasing temperature, which is mainly because that the decreasing effective bulk moduli of the whole saturated rock dominates wave velocity in rock masses (Spencer Jr and Nur 1976).

Furthermore, the current study reveals that a higher temperature leads to more wave energy transmission through single water-filled joint. It is in accord with findings of water-saturated marine sediments reported by Carbo and Molero (2002). From the perspective of fluid mechanics, the thermal effect on wave transmission through individual water-filled rock joint could be attributed to viscous effects (Morse and Ingard 1986; Kinsler et al. 2000). To be specific, the increasing temperature results in the decrease of water viscosity (see Table 2), thereby reducing viscous loss of wave energy when waves propagate through water layer in the joint (Korson et al.1969; Vennard and Street 1975; Xu et al. 2003). Additionally, the increasing temperature leads to an increase in wave velocity but a sufficiently small decrease in density. As a result, acoustic impedance of water gradually increases within the temperature range of 10 °C to 80 °C; and hence more wave energy can transmit at the rock-water interface based on the layered medium theory (Zhu et al. 2011, 2012).

On the contrary, the increasing temperature results in less wave energy transmission across the light oil-filled rock joint, which is in partial agreement with the findings of oil sand (Eastwood 1993). This could be explained by the Darcian resistance mechanism that the oscillation of solid and fluid continua gradually becomes out of phase for relatively low fluid viscosity caused by higher temperature, thereby causing more wave energy loss (Eastwood, 1993). It may also because that the increase of temperature could reduce the density and wave velocity of M68, thereby lessening wave impedance of M68. Consequently, wave transmission at the M68-rock interface decreases according to the layer medium theory (Zhu et al. 2011). From the perspective of fluid acoustics, the finding could be explained by the temperature dependent properties of the light oil that the relaxation rather than viscosity of M68 may dominate wave attenuation in the M68 layer (Litovitz and Davis, 1965, Nur et al., 1984). Specifically, as temperature goes up, although the decreasing viscosity causes less wave dissipation (see Table 2), the relaxation in oil could lead to much more wave absorption, which results in the reduction of total transmitted wave energy across the M68-filled joint.

This study focuses on wave behaviours across water- and M68-filled rock joints over a typical temperature range (i.e., 10~80 °C) in the laboratory, and all tests were conducted under the atmospheric pressure so as to highlight the effect of temperature. Therefore, to provide valuable insights into wave behaviours across individual fluid-filled rock joints in the more complex and practical subsurface environment, additional future efforts are required by taking into consideration the combination of temperature, pressure and chemical factors.

5. Conclusions

The main conclusions are summarized as follows.

1) Wave velocity across the water-filled joint nonlinearly increases by around 3.34% as temperature increases from 10 °C to 80 °C, mainly attributed to the slight decrease in density and the decrease in compressibility of water. Wave velocity across the M68-filled joint approximately linearly decreases by about 5.43% with temperature increasing from 10 °C to 60 °C due to the increase in compressibility of the light oil;
2) A higher temperature results in more wave energy transmission through the water-filled rock joint because of less wave absorption induced by the decreasing water viscosity and more wave transmission at the rock-water interface due to the increasing wave impedance

of water. On the contrary, wave energy transmission across the M68-filled joint decreases with the temperature attributed to less wave transmission at the rock-oil interface resulted from decreasing wave impedance of oil and more wave absorption caused by the relaxation in oil produce.

3) The thermal effect on compressional wave attributes of fluid-filled rock joints is highly dependent on the type of fluid because of the differences in thermophysical properties.

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Conflict of Interest Statement

We declare that there is no conflict of interest in this paper.

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Table 1. Rock joints filled with fluid (water or M68) at different temperatures

Types of fluid-filled joints	Temperatures of filling fluids (°C)							
Water-filled joints	10	20	30	40	50	60	70	80
M68-filled joints	10	20	30	40	50	60	--	--

Table 2. Kinematic viscosities of water and M68 (light oil) at different temperatures

Temperature (℃)	Kinematic viscosity (mm^2/s)	
	Water	M68
10	1.31	364.53
20	1.00	203.78
30	0.80	124.11
40	0.66	83.89
50	0.55	60.16
60	0.47	47.65
70	0.41	--
80	0.36	--

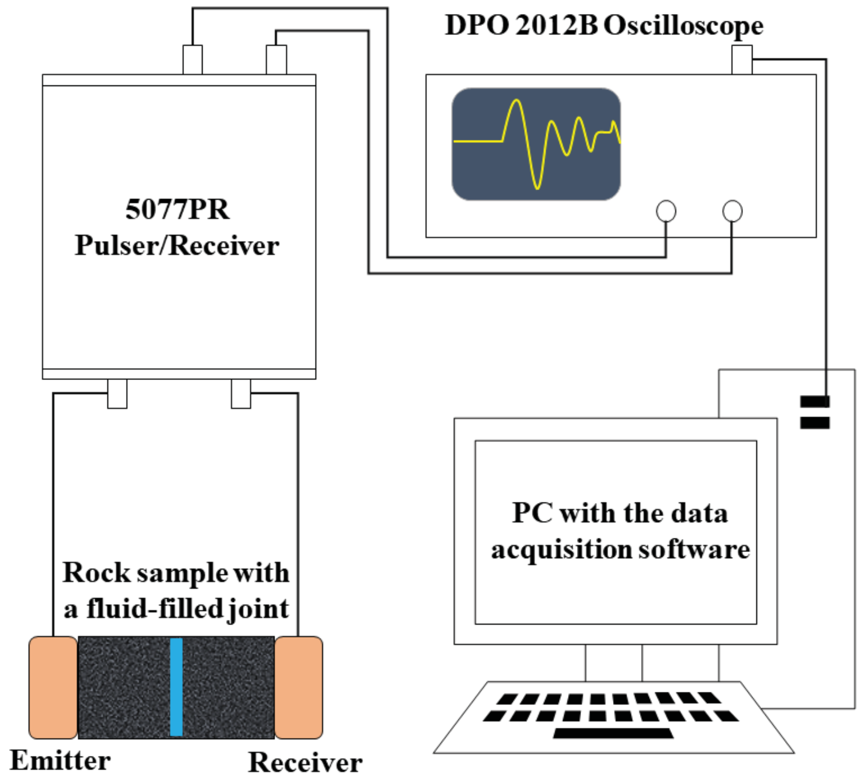

Fig. 1 The schematic of experimental system used in this study.

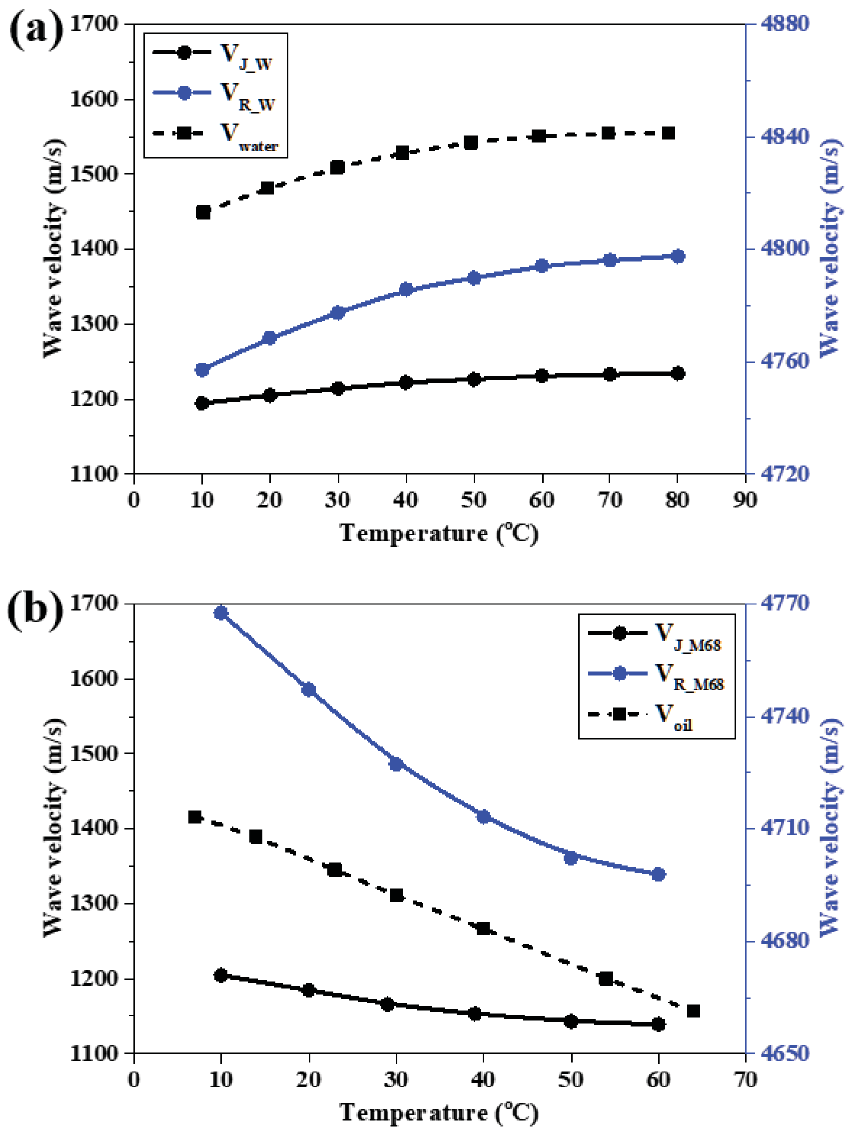

Fig. 2 Wave velocities versus temperature for: (a) water-filled joint and the corresponding jointed rock sample; and (b) M68-filled joint and the corresponding jointed rock sample. V_{R_W} and V_{R_M68} are wave velocities of rock samples with single water-filled and M68-filled joints, respectively. V_{J_W} and V_{J_M68} represent wave velocities in water- and M68-filled joints, respectively. Wave speed of water (V_{water}) measured by Wilson (1959) and wave speed of one kind of light oil (V_{oil}) measured by Wang and Nur (1991) are also presented in the figure.

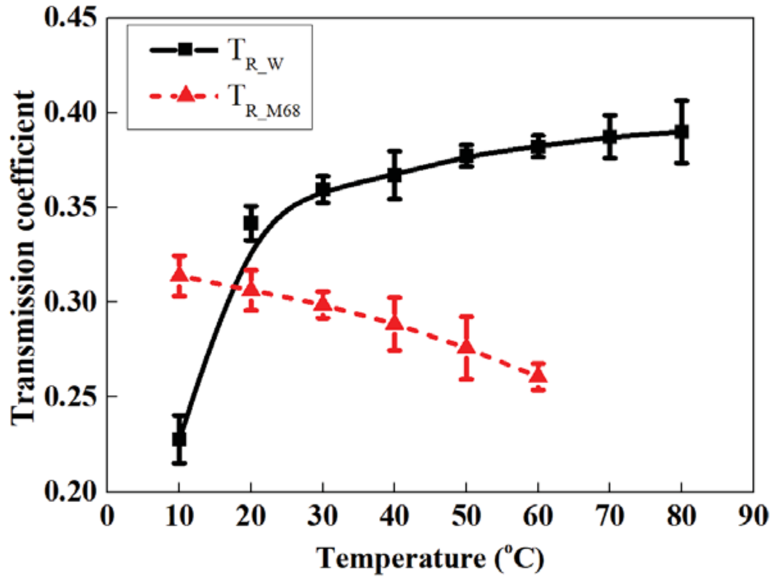

Fig. 3 Transmission coefficients versus temperature for rock samples with individual fluid-filled joints. T_{R_W} and T_{R_M68} represent transmission coefficients across rock samples with single water-filled and M68-filled joints, respectively.

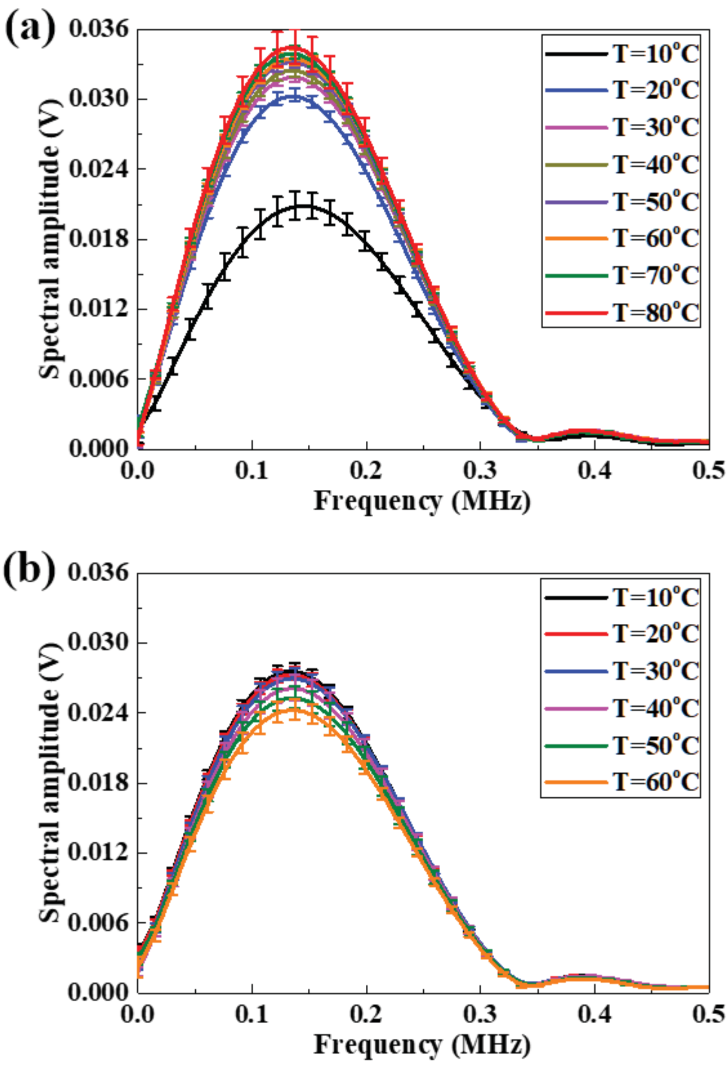

Fig. 4 Thermal effect on spectral contents of waves transmitted through jointed rock samples with: (a) single water-filled joints; and (b) single M68-filled joints.