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ORIGINAL ARTICLE

Porosity and wave velocity evolution of granite after high-temperature treatment: a review

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Abstract

The evolution of porosity and changes in wave velocity in granite after high-temperature treatment has been experimentally investigated in different studies. Statistical analysis of the test results shows that there is a temperature threshold value that leads to variations in porosity and wave velocity. At a temperature that is less than 200 °C, the porosity of granite slowly increases with increases in temperature, while the wave velocity decreases. When the temperature is greater than 200 °C (especially between 400 and 600 °C), the porosity quickly increases, while the wave velocity substantially decreases. The temperature ranges of room temperature to 200 and 200–400 °C correspond to the undamaged state and the micro-damage state, respectively. The results confirm that there is an important link between the variations of physical and mechanical properties in response to thermal treatment. By studying the relationships among rock porosity, wave velocity and temperature, this provides the basis for solving multi-variable coupling problems under high temperatures for the thermal exploitation of petroleum and safe disposal of nuclear waste.

Keywords Thermal damage · Porosity · Wave velocity · Micro-mechanism · Damage coefficient · Critical threshold

Introduction

The variation in the physical and mechanical properties of rocks after high-temperature treatment or under high-temperature conditions is an important topic of study in rock engineering, such as for the purpose of rock drilling (Nasseri et al. 2007, 2009), petroleum and other deep boring (Gao 2004; Dutton and Loucks 2010), underground oil gasification (Chen and Wang 1980; Roddy and Younger 2010), geological carbon dioxide (CO_2) storage (Rutqvist et al. 2002), extraction of geothermal energy (Zhao 2000), nuclear waste storage (Sundberg et al. 2009), protecting rock buildings or stone artifacts that are considered to be cultural relics (Hajpál 2002), and stabilizing engineering constructions in rocks after the occurrence of a fire (Zhan and Cai 2007). High temperatures cause the development of new micro-cracks in rock and pre-existing cracks propagate further or widen (Dwivedi et al. 2008). In the process of heating, various physical and mineralogical changes take place and eventually lead to thermal damage. However, after cooling down, the thermal-induced changes can be reversed to some extent (Tian et al. 2012).

In most rocks subjected to geological hazards (such as earthquakes, landslides, rock collapse and fire hazards) and engineering projects, cracks (or porosity) have an important role in the variation of the rock properties, and relevant information on the structure of cracks (or porosity) in the rock mass could be reflected through wave velocity. Velocity fluctuations of the elastic waves have been considered to be potential precursory evidence of seismic activity and in response, testing methods that examine the generated acoustic waves have been developed to evaluate the deformation and fracture properties of rocks (e.g. Somerton and Boozer 1961; Blake 1982; Hovem 1996; Jones et al. 1997; Geerits and Kelder 1998; Darot and Reuschle 2000; Sun and Zhu

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2014). For example, fire hazards at buildings may go up to high temperature. Building fire is a common hazard in our life environment. In the initial stage of fire, the surface of building material may suffer to high temperature. As time goes on, the interior of material must go up to high temperature. This is dangerous to structural stability. Many researches demonstrated that wave velocity and compressive strength have a good linear relationship. So, the study of wave velocity may reveal the compressive strength of building materials.

Granite is a common igneous rock with broad applications in geotechnical engineering. Therefore, research on the thermal damage of granite based on the evolution of its porosity and the changes in wave velocities is extremely helpful for a wide range of geo-mechanical projects. Many laboratory experiments have already been conducted under different conditions to establish the correlations between thermal damage and changes in porosity or wave velocities, and a large amount of test data are also available from different literatures worldwide (e.g. Kou 1987; Lokajícek et al. 2012; Inserra et al. 2013). Numerous tests have been carried out on rock porosity and wave velocity for different purposes in previous studies. In these literatures, they all demonstrated temperature increases porosity and decreases wave velocity. Besides, pressure is another influencing factor on the properties of granite such as the decrease in permeability and the increase in wave velocity (Nasseri et al. 2009) due to its compaction effect in elastic phase. But with the crack generation or rock failure, a drastic increase in permeability and a quick decrease in wave velocity can be observed.

In this paper, the changes in porosity and wave velocities of granite after high-temperature treatment were investigated, based on which the mechanism of thermal damage on granite and its potential application are discussed.

The remainder of this paper is organized as follows. In "Porosity and wave velocity: experimental process", experimental data from different studies and its processing method are presented. The relationship between wave velocity and porosity during heating is analyzed and discussed in "Analysis and discussion". "Conclusion" contains the conclusions.

Numerous tests have already been carried out on rock porosity and wave velocity for different purposes (e.g. Kou 1987; Zhu et al. 2006; Lokajícek et al. 2012; Sun et al. 2015). In these literatures, they all demonstrated temperature increases porosity and decreases wave velocity. Besides, pressure is another influencing factor on the properties of granite such as the decrease in permeability and the increase in wave velocity (Nasseri et al. 2009) due to its compaction effect in elastic phase. But with the crack generation or rock failure, a drastic increase in permeability and a quick decrease in wave velocity can be observed. Each study typically has its own conclusions about the heating treatment processes. However, because each study has limited experimental data obtained from a small number of rock specimens, some researchers may pay too much attention to subtle differences in a specific rock type while ignoring important common characteristics. In view of this, we have attempted to take a new perspective by integrating the data from different resources and reconsider some previously overlooked conclusions.

The aim of this paper is to supply a more general perspective to researchers and engineers involved in analytical and numerical modeling of thermo-mechanical processes of pore and wave velocity in granite, such as underground mining, tunnel fire and nuclear waste storage.

Porosity and wave velocity: experimental process

The data used in this paper were carefully selected from a number of literatures which were original measurement data for granitic rocks without smoothing or any other processing and contained four or more measuring points from a sufficiently wide range of temperature. Table 1 lists the detailed data information including rock types, literature sources, sampling locations, main minerals or chemical compositions, test methods, grain size, density, sample size and heating process. Tables 2 and 3 list the pore characteristics including porosity, crack porosity and crack width, and the original wave velocity of granites from literatures in a large temperature range of 20–850 °C, respectively.

It is important to keep in mind that there is a great venture to compare results from various sources obtained by quite different measuring methods and often of unknown accuracy (Seipold 1998). One of the purposes of this paper is to find the temperature dependence on pore and wave velocity. To decrease data errors in different literatures resulting from materials, experiment and so on, the parameters of R_p, R_cp R_cw and R_w were defined.

R_p is used to describe the change of porosity. It can be defined as the ratio of the porosity at any temperature to the porosity at room temperature. R_cp is used to describe the change of crack porosity. It can be defined as the ratio of the crack porosity at any temperature to the crack porosity at room temperature, and can be calculated on the basis of scanning electron microscopy (SEM) test results and the elliptic crack model. The formula is shown in Eq. (1) (Etienne and Poupert 1989). R_cw is used to describe the change of crack width. It can be defined as the ratio of the crack width at any temperature to the crack width at room temperature. And R_w is used to describe the change of wave velocity. It can be defined as the ratio of the wave velocity at any temperature to the wave velocity at room temperature:

$$R_\mathrm{cp} = \frac{\pi}{4A} \sum a_j b_j, \quad (1)$$

Table 1 Properties of granite in selected previous studies

Type	Rock type	References	Site	Main mineral	Grain size	Density (g/cm^3)	Sample size	Test method/instrument	Heating process
Wave velocity (P)	Granite	Zhu et al. (2006)	Yuanjiang	–	–	2.628	Φ50 mm × 100 mm	U-sonic Ultrasonic tester	(a) 30 °C/min (b) 800 °C (c) 4 h (d) Natural cooling in oven
Wave velocity (P/S)	Granite	Kou (1987)	Stripa	Quartz, feldspar	Fine granular	–	Φ42 mm × 250 mm	Piezoelectric ceramic sound wave receiver	(b) 600 °C (c) 3 h (d) Natural cooling in oven
Wave velocity (P)	Granite	Nasseri et al. (2007)	Westerly	Quartz, microcline Plagioclase, phyllosilicates	Mean grain size is 0.75 mm	–	Brazilian disk specimens (75–30 mm thick)	–	(a) 1–2 °C/min (b) 850 °C (d) 1–2 °C/min
Wave velocity (P)	Granulite	Lokajícek et al. (2012)	India	Quartz, feldspar, hypersthene, biotite	Fine grained	2.6	Φ50 mm	–	(a) Complete temperature rise within 2 h (b) 600 °C (c) 2 h (d) Naturally
Wave velocity (P/S)	Granite	Xi (1999)	Xijiang	Quartz, feldspar, mica	–	–	Φ25 mm × 50–64 mm Cuboid 3 × 8 × 100 (mm)	SYC-2B	(a) Variable rate 3 °C/min (b) 610 °C
Wave velocity (P)	Granite	Wang and Shi (2017)	–	Microcline, plagioclase, quartz, biotite	–	2.62	Φ50 mm × 25 mm	The contact transmission technique	(a) 10 °C/3 min (b) 900 °C (c) 4 h (d) Cool to room temperature within 10 h
Wave velocity (P)	Granite	Sun et al. (2015)	Liyin	Quartz, feldspar, mica	–	2.76	Φ50 mm × 5100 mm	TICO	(a) 30 °C/min (b) 800 °C (c) 2 h (d) Naturally
Wave velocity (P)	Granite	Yin (2012)	Laurentian	Quartz, feldspar, mica	–	2.64	Φ100 mm × 150 mm	–	(a) 10 °C/3 min (b) 300 °C (c) 2 h (d) Naturally
Wave velocity (P/S)	Westerly granite	Inserra et al. (2013)	–	Quartz, feldspar, mica, accessories	–	–	Φ20 mm × 0 mm	Tektronix TDS340AP	(a) 50 °C/h (b) 500 °C (c) 30 min (d) Naturally

Table 1 (continued)

Type	Rock type	References	Site	Main mineral	Grain size	Density (g/cm^3)	Sample size	Test method/instrument	Heating process
Cracks density	Granite	Kou (1987)	Stripa	Quartz, feldspar	Fine granular	–	Φ42 mm × 250 mm	Displacement sensor (LV D T)	(b) 600 °C (c) 3 h (d) Natural cooling in oven
–	Granite	Chen et al. (2012)	Ningbo	Quartz, K-feldspar, plagioclase, mica	–	2.62	Φ40 mm × 80 mm	–	(a) 10 °C/min (b) 1000 °C (c) 6/h (d) Natural cooling in oven
Cracks density	Granite	Etienne and Poupert (1989)	Remiremont	Quartz, K-feldspar Plagioclase, biotite	Fine	–	Φ50 mm × 100 mm	SEM 250	(a) 1 °C/min (b) 800 °C (c) 1 h (d) 1 °C/min
Cracks density	Granite	Etienne and Poupert (1989)	Senones	Quartz, K-feldspar Plagioclase, biotite	Porphyritic texture	–	Φ50 mm × 100 mm	SEM 250	(a) 50 °C/h and 100 °C/h; 20–600 °C (c) 5 h (d) Naturally
Crack density	Westerly granite	Inserra et al. (2013)	–	Quartz, feldspar, mica	–	–	Φ20 mm × 40 mm	Fluorescent approach	(a) 50 °C/h (b) 500 °C (c) 30 min (d) Naturally
Porosity	Granite	Chaki et al. (2008)	Granulometry	Feldspars, mica K-feldspar Plagioclase, quartz	0.5–3 mm	2.687	Φ40 mm × 60 mm	Quantified by permeability	(a) 1 °C/min (b) 600 °C (c) 2 h (d) 1 °C /min

(a) Heating rate, (b) max temperature, (c) keep time and (d) cooling style

Table 2 Pore characteristic of the reviewed granites

Temp. (°C)	Porosity (%)						Crack porosity (%)		Crack width (μm)	
25	0.67	0.23	0.23	0.2	–	0.88	1.00	1.00	0.07	0.12
50	–	–	–	–	–	0.75	–	–	–	–
100	–	–	–	–	–	0.74	–	–	–	–
105	–	–	–	–	0.68	–	–	–	–	–
200	–	–	–	–	0.71	1.01	1.24	2.12	0.14	0.23
250	0.76	0.44	0.33	0.21	–		–	–	–	–
300	–	–	–	–	0.81	1.17	–	–	–	–
400	–	–	–	–	0.91	–	2.30	6.20	0.21	0.65
450	0.95	0.59	0.47	0.61	–	–	–	–	–	–
500	–	–	–	–	1.1	1.56	4.96	10.80	0.44	1.23
600	–	–	–	–	2.85	–	13.6	35.23	1.78	3.07
650	2.33	2.04	1.62	1.59	–	–	–	–	–	–
800	–	–	–	–	–	2.57	–	–	–	–
850	3.76	5.11	4.04	3.64	–	–	–		–	–
	Westerly granite (Φ, Sample)	Westerly granite (η_c, IG + GB, both cylindrical model)	Westerly granite (η_e, IG + GB, both elliptical model)	Westerly granite (η_M, IG (Elliptical model) + GB (cylindrical model))	Westerly granite	Jining granite	Remiremont granite	Senones granite	Remiremont granite	Senones granite
	Nasseri et al. (2007)				Chaki et al. (2008)	Sun et al. (2015)	Etienne and Poupert (1989)			

Table 3 Wave velocity of the reviewed granites

Temp. (°C)	Wave velocity (m/s)											
20	4755.56	4488	–	–	6575	5423.91	3262.72	5100	–	–	3442.54	2264.49
25	–	–	6988.05	–	–	–	–	–	–	–	–	–
50	–	–	–	–	6628	–	–	–	–	–	–	–
100	–	–	6885.67	4295.85	–	5463.83	3210.68	–	4064.52	2451.61	3011.38	2188.81
105	–	–	–	–	–	–	–	–	–	–	–	–
150	–	–	–	–	6171	5276.07	3207.1	–	–	–	2983.65	2227.73
200	4477.78	–	–	3721.69	5649	5180.26	3111.02	4864.29	3677.42	2279.57	2933.95	2155.82
250	–	3725	5580.2	–	–	–	–	–	–	–	2595.17	2039.22
300	–	–	–	–	5297	4850.71	2965.65	4371.43	3247.31	2129.03	2522.75	1989.27
350	–	–	–	–	–	–	–	–	–	–	2383.93	1961.54
400	3366.67	–	–	2624.67	4823	–	–	4071.43	2731.18	1827.96	2044.9	1622.75
450	–	3040	4274.74	–	–	3690	2356.39	–	–	–	2016.91	1461.46
500	–	–	–	1696.6	3764	–	–	3471.43	2193.55	1483.87	1856.13	1344.61
550	–	–	–	–	–	–	–	–	–	–	1695.09	1272.94
600	1755.56	–	2406.14	1499.39	3355	2023.26	1333.61	1800	–	–	1178.81	778.38
650	–	1650	–	–	–	–	–	–	–	–	–	–
800	1088.89	–	–	760.03	–	–	–	–	–	–	–	–
850	–	985	1382.25	–	–	–	–	–	–	–	–	–
	Yuanjiang granite (Vp)	Westerly granite (Vp)	Laurentian granite (Vp)	Jining granite (Vp)	India granite (under confining pressure of 0.1 MPa) (Vp)	Stripa granite (Vp)	Stripa granite (Vs)	Westerly granite (Vp)	Westerly granite (Vp)	Westerly granite (Vs)	Xinjiang granite (Vp)	Xinjiang granite (Vs)
	Zhu et al. (2006)	Nasseri et al. (2007)	Yin (2012)	Sun et al. (2015)	Lokajícek et al. (2012)	Kou (1987)		Chaki et al. (2008)	Inserra et al. (2013)		Xi (1999)	

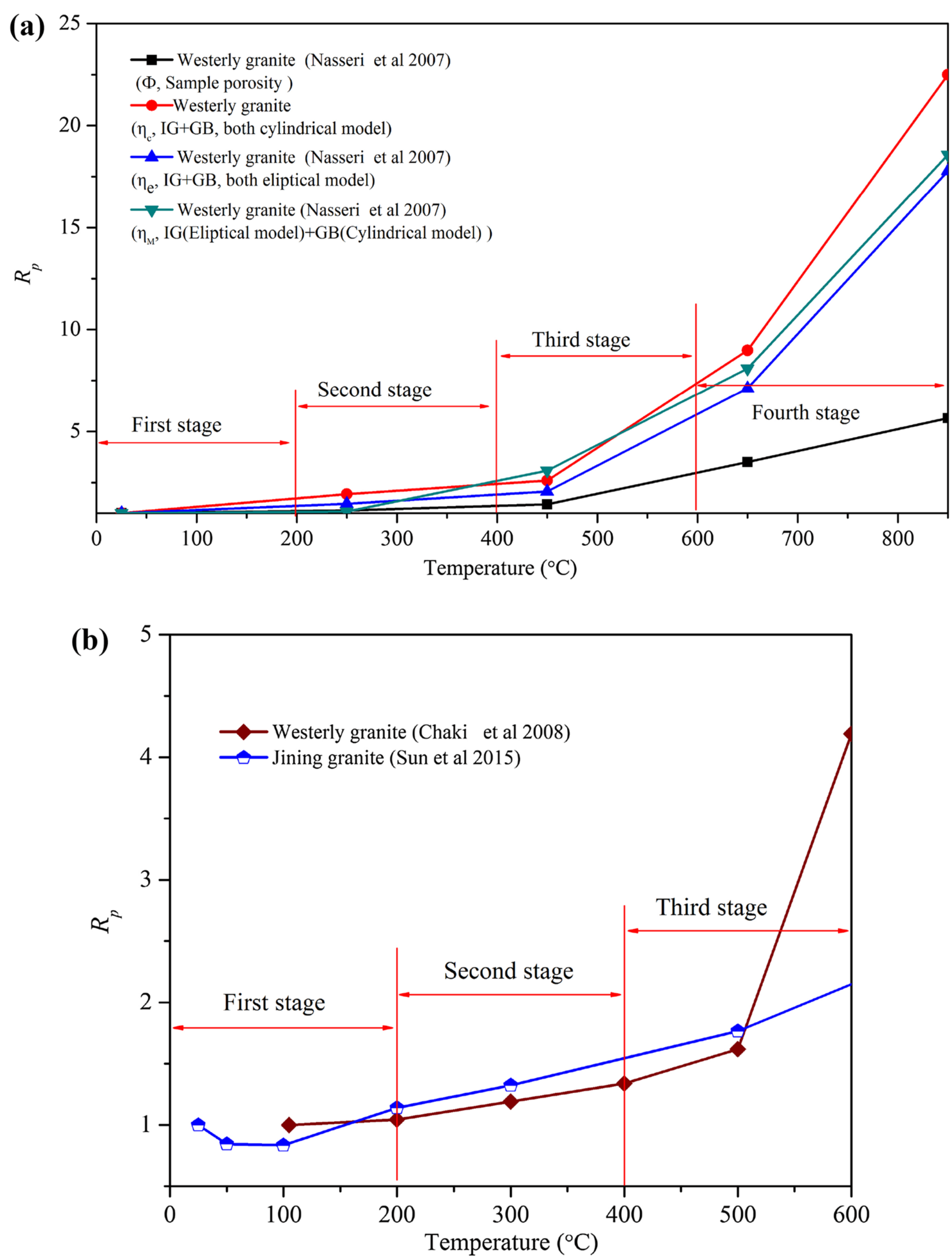
where A is the total area, a_j is the length of the tube, and b_j the diameter of the tube.

By these data statistics methods, we propose a division on the figures in four stages in pore and wave properties.

Figures 1, 2 and 3 show that the general variation of porosity parameters for granite increases with the increase of the treatment temperature. Although the variation of porosity is different, it is found that, below 200 °C, the fracture parameters change very little with the increase of the treatment temperature. When the temperature is more than 400 °C, the fracture parameters (crack width and crack porosity) quickly increase with additional increase in temperature.

It is generally accepted that the compressive wave velocities of rocks are reduced at increasing temperatures both under and after high-temperature treatment (Somerton 1992). The R_w after heating treatment at different temperatures tested on dry samples are plotted in Fig. 4. Although the level of variation in the wave velocities is different, almost all of the granite samples exhibit the same pattern of variation. The reduction in wave velocity is relatively minimal at a temperature that is less than 150 °C, but becomes significantly larger afterwards (especially when the treatment temperature is over 200 °C). At 200–600 °C, a trend of reduction in wave velocity is observed for all of the reviewed granite samples. When the treatment temperature

Fig. 1 Porosity variation with temperature



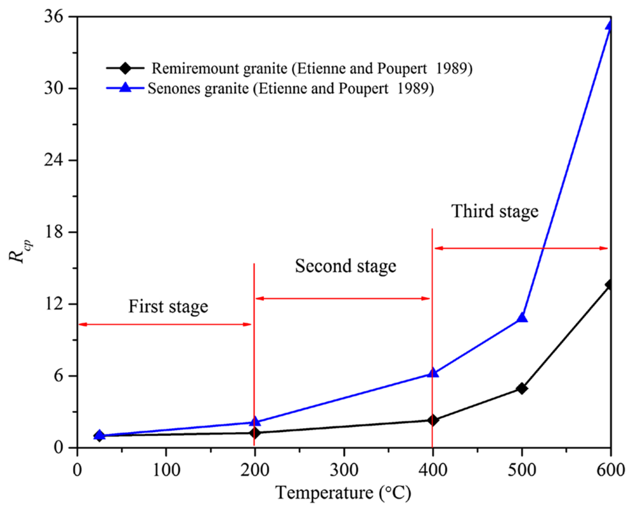


Fig. 2 Crack porosity variation with temperature

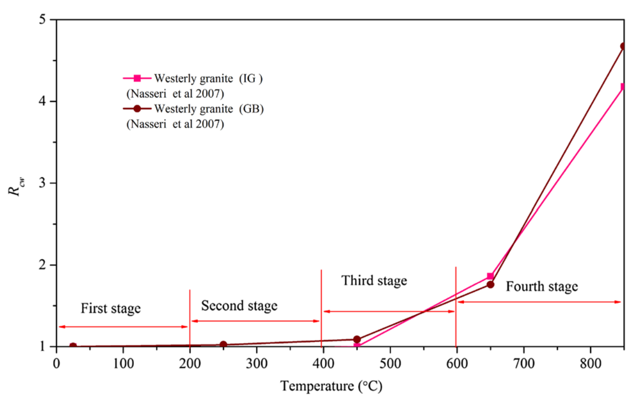


Fig. 3 Crack width with temperature

is over 600 °C, there are relatively little changes in the wave velocity.

Analysis and discussion

The reduction in the wave velocities and increase in the porosity of granite than underwent heat treatment are caused by variations in the internal structure induced by heat. Since granite is composed of mineral particles with different thermal expansion coefficients and thermo-elastic properties, high temperatures lead to inhomogeneous thermal expansion of the mineral particles or phase transition of some of the mineralogical components, thus production internal stress and microcracks in granite (Sun et al. 2015).

In the process of heating, the water inside granite changes form, i.e. absorbed, interlayer, and mineral water (e.g. crystal, structural, or zeolite water) would escape from granite under different temperatures. It is known that there is loss of absorbed water at around 100 °C; interlayer water between 100–300 °C; crystal water at less than 400 °C. There is also loss of structural water of the minerals at temperatures greater than 300 °C (Sun et al. 2013). The loss of crystal and structural water damages the mineral crystal lattice structure of the minerals, thus increasing the defects of granite. When the treatment temperature is over 400 °C, a series of physical actions and chemical reactions take place (Somerton and Selim 1961; Jana and Agnes 2012) (as shown in Fig. 5). Accordingly, the measured variations in porosity and wave velocity and temperature can be examined as four phases:

Phase 1 Room temperature to 200 °C. There is loss of absorbed water and expansion of the mineral grains of granite which correspond to the first peak value of the internal friction temperature in Fig. 6, so that there are slight changes in the porosity and wave velocity. It needs to be explained that the internal friction in this paper is the energy consumed by the physical changes in the rock (such as the development of cracks, phase transformation, and dehydration) under the effect of temperature (Xi 1999), and it was tested by the free vibration attenuation method and expressed as the attenuation of vibration amplitude (as shown the Q^{-1} on the longitudinal axis in Fig. 6).

Phase 2 200–400 °C: there is loss of crystal and structural water of the minerals (which corresponds to the second peak value in Fig. 6), so that there is significant increase in porosity and reduced wave velocities. Moreover, the testing in Zhang et al. (2007) showed fluctuations in the dissolution rates after the critical point of water, i.e., at a temperature that ranges from 300 to 400 °C. Variations in the water properties and kinetic behavior of water–rock interactions also affect other properties of the granite minerals, such as the release of silica and the fragmentation of the silicate framework of the minerals. The form of water at around the critical temperature (a lot of researches show that the critical temperature is around 374 °C, and when the temperature exceeds to the critical temperature and pressure arrives to a certain level, water will be in a supercritical state and has many special properties, such as strong oxidation and strong solubility) has a significant influence on the solubility, and physical and chemical properties of the granite minerals (Correa and Kruse 2018), and results in the collapse of the mineral skeleton and increase in defects. More defects initiate increases in porosity, but reduce the wave velocity.

Phase 3 400–600 °C. The physical and chemical properties of the granite minerals show obvious changes. Between 400 and 600 °C, especially at 500–600 °C, the minerals show chemical changes (Jana and Agnes 2012). At temperatures greater than 400 °C, some of the minerals are decomposed and volatilized (for example, the dehydroxylation of clay minerals, such as illite and kaolinite). During the loss of the structural water, there may be increases in porosity and fracturing. Oxidation/decomposition reactions (such as

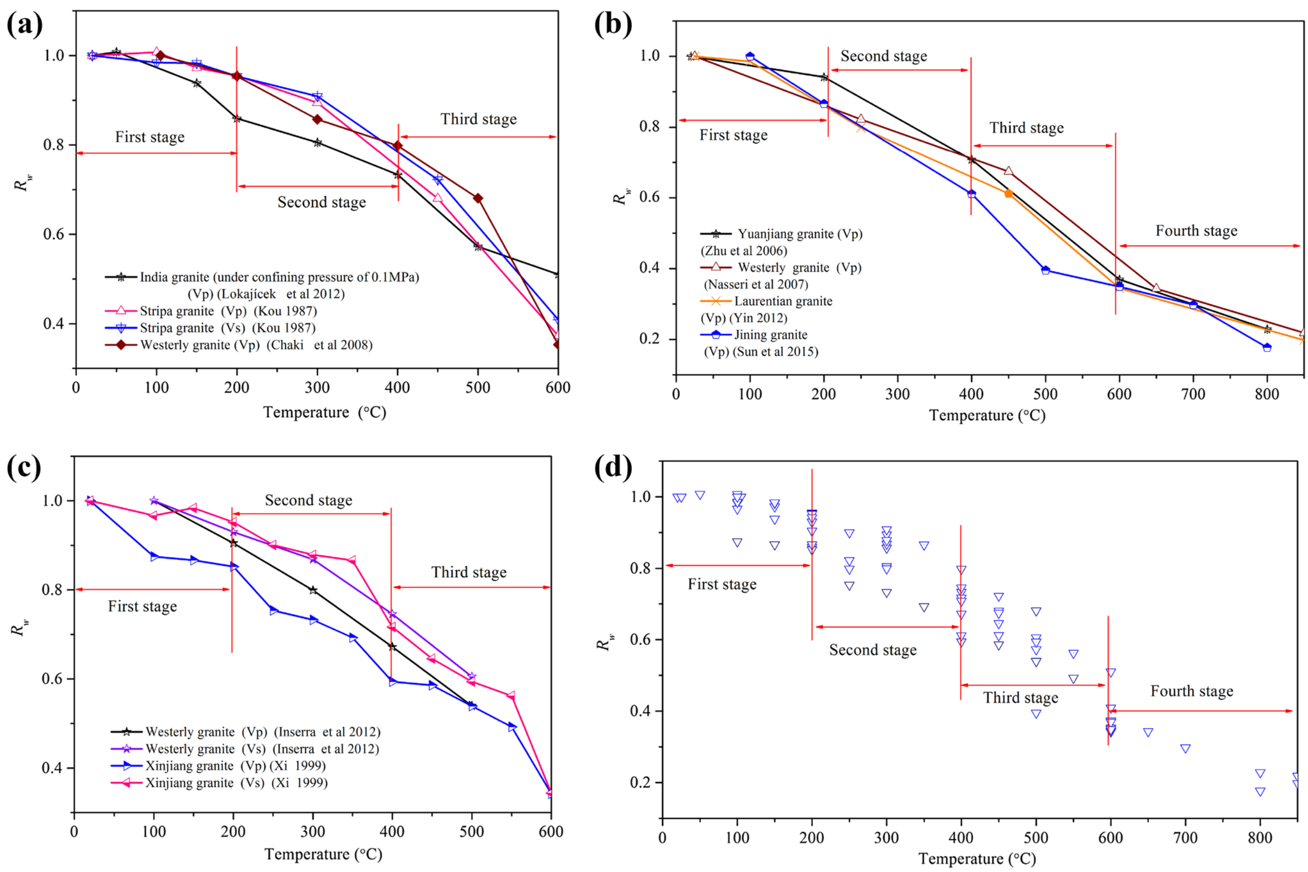
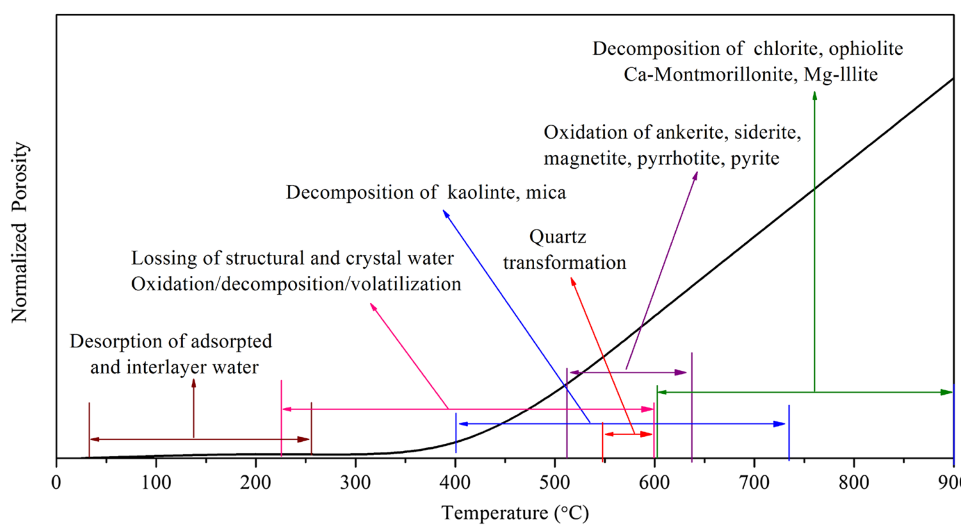


Fig. 4 Wave velocity changes with temperature. All the data from (**a**–**c**) was plotted in graph (**d**)

Fig. 5 The physical action and chemical reactions for granite heating progress. Results from Somerton and Selim (1961) and Jana and Agnes (2012)



that of ankerite, siderite, magnetite, and pyrite) are evidently observed in the range of 400–600 °C. At about 573 °C, the α-quartz is transformed into β-quartz (which corresponds to the third peak value in Fig. 6), thus causing noticeable changes in the porosity and wave velocity.

Phase 4 Over 600 °C. Some of the minerals begin to melt, which leads to greater defects. Moreover, some of the minerals decompose (such as chlorite, ophiolite, Ca–montmorillonite, and Mg–illite). Under the effects of solid mineral expansion and breaking of metallic bonds (such as Al–O,

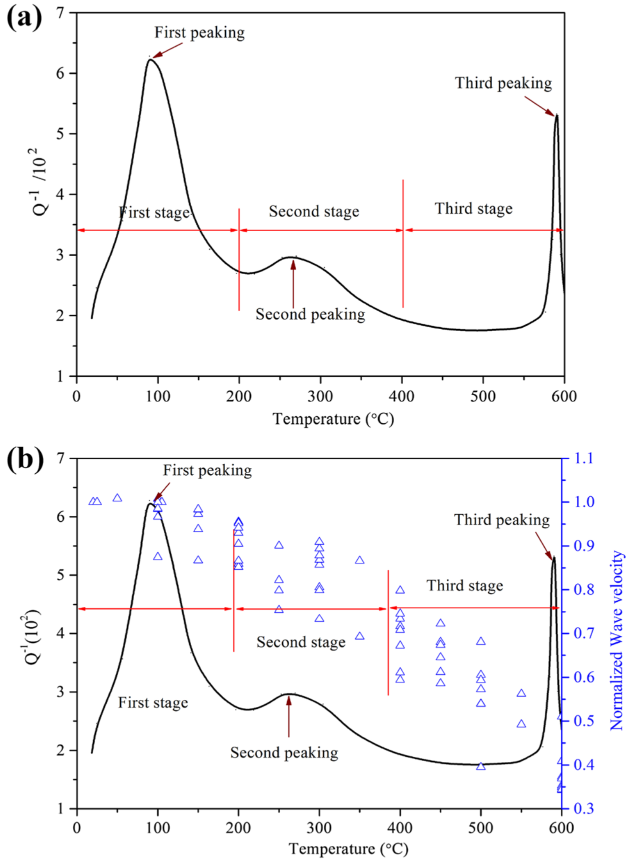


Fig. 6 Variations of internal friction and normalized wave velocity of granite with temperature. **a** Variation of internal friction (Xi 1999). **b** Variations of internal friction and normalized wave velocity

K–O, Na–O, and Ca–O), the wave velocities continue to reduce, while the porosity continues to increase.

Therefore, it can be said that the wave velocities decrease with increases in porosity. Hence, a damage model can be established based on the experimental data of the microstructure of granite and wave velocities, as shown in Eq. (2):

$$D = 1 - \left(\frac{V}{V_0}\right)^2, \quad (2)$$

where D is the damage coefficient, V is the wave velocity, and V_0 is the initial wave velocity.

This model uses the fissure coefficient of rock mass for reference because of the relevance of them. According to Eq. (2), the integrity of rock mass can be divided into complete, relative complete, broken, relative broken, extremely broken. And the thresholds in Table 4 were established by this. From Eq. (2), it is easy to see that the level of damage can be reflected in the changed values of the wave velocity. In this model, the level of damage of rock is evaluated in accordance with the limit values (as shown in Table 4) of the damage coefficients.

Table 4 Limit values of rock damage coefficients

Damage coefficient	Undamaged	Damage to microstructure	Secondary damage	Extensive damage	Completely damaged
D	0.0–0.25	0.25–0.45	0.45–0.65	0.65–0.85	>0.85

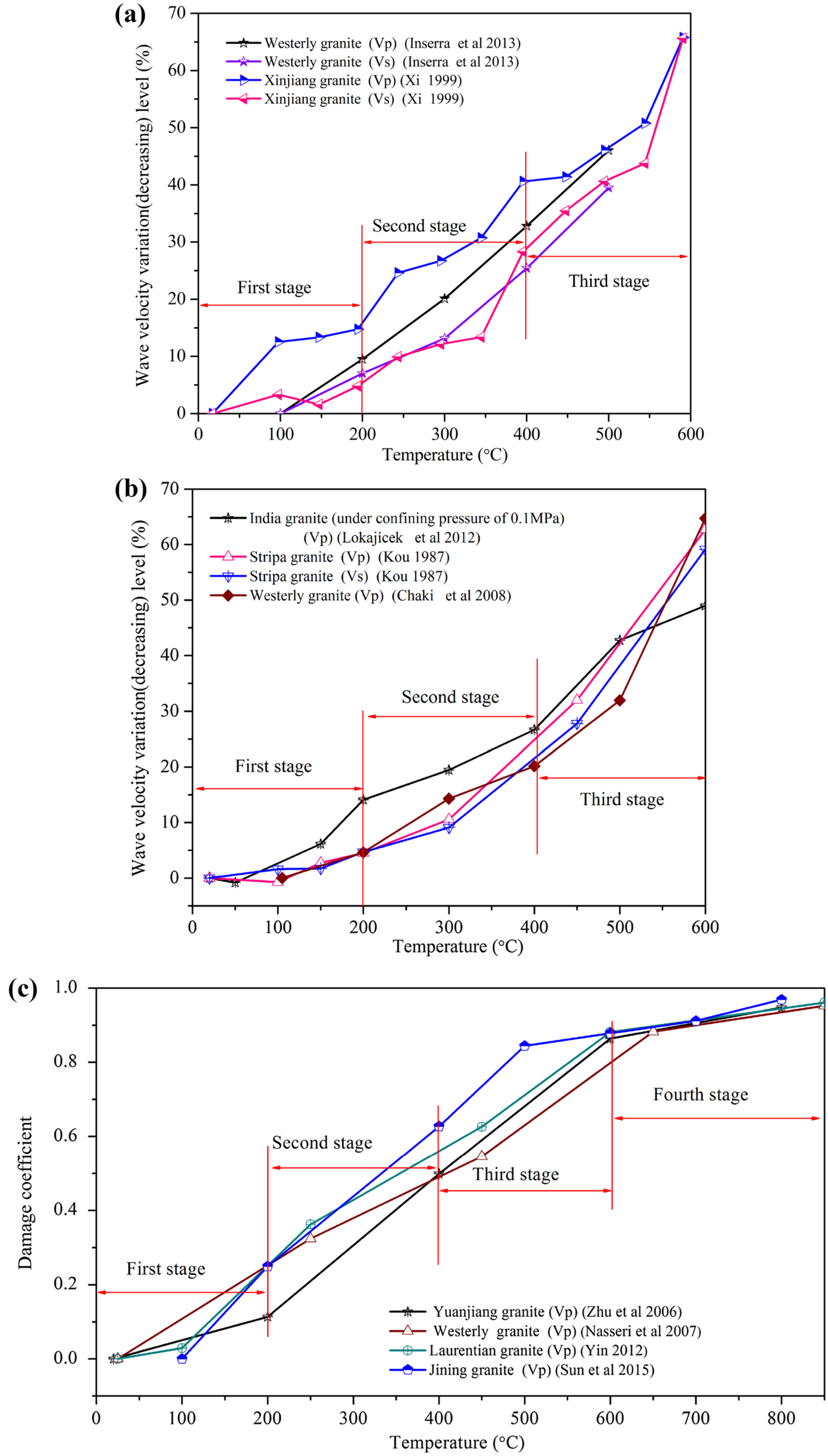
Table 4 and Figs. 7 and 8 show that: (1) at a temperature that is less than 200 °C, the granite is undamaged; (2) at temperatures between 200 and 400 °C, damage to the microstructure of granite begins; (3) at temperatures between 400 and 500 °C, there is secondary damage; and (4) at temperatures greater than 500 °C, the damage is extensive or the granite is completely damaged. The experimental results suggest that 400 °C is the critical threshold temperature for the thermal damage of granite. That is the reason why significant changes in the physical and mechanical properties of granite samples are observed in the temperature range of 300–600 °C, especially between 400 and 600 °C (Sun et al. 2015).

Conclusion

The data applied in this paper are taken from an extensive review of the extant literature. Based on the results and the data reported in previous studies on the evolution in porosity and changes in wave velocity after treatment at high temperatures, the process and critical threshold of the thermal damage of granite are discussed, and the following conclusions are drawn:

1. Increases in temperature during heat treatment leads the increased defects in rocks. With more defects, the porosity also increases, but the wave velocity is reduced. Initially, the wave velocity and porosity both slowly increase with increased temperature. However, after reaching 400 °C, the wave velocity and porosity change quickly, with increases in porosity and fracturing, and substantial decreases in the wave velocity. In tunnel and coal mine roadway fire, this drastic change may lead to water gushing. It contributes to gas transmission in underground coal gasification, while it has a detrimental effect on geological CO_2 storage.
2. Four phases are identified in the changes in wave velocity and evolution of porosity with temperature: from room temperature to 200, 200–400, 400–600 °C, and temperatures greater than 600 °C. At temperatures less than 400 °C, the loss of different forms of water has an obvious effect on the changes in wave velocity and evolution in porosity. Between 400 and 600 °C, especially from 500 to 600 °C, the minerals (such as anker-

Fig. 7 Damage coefficient with temperature



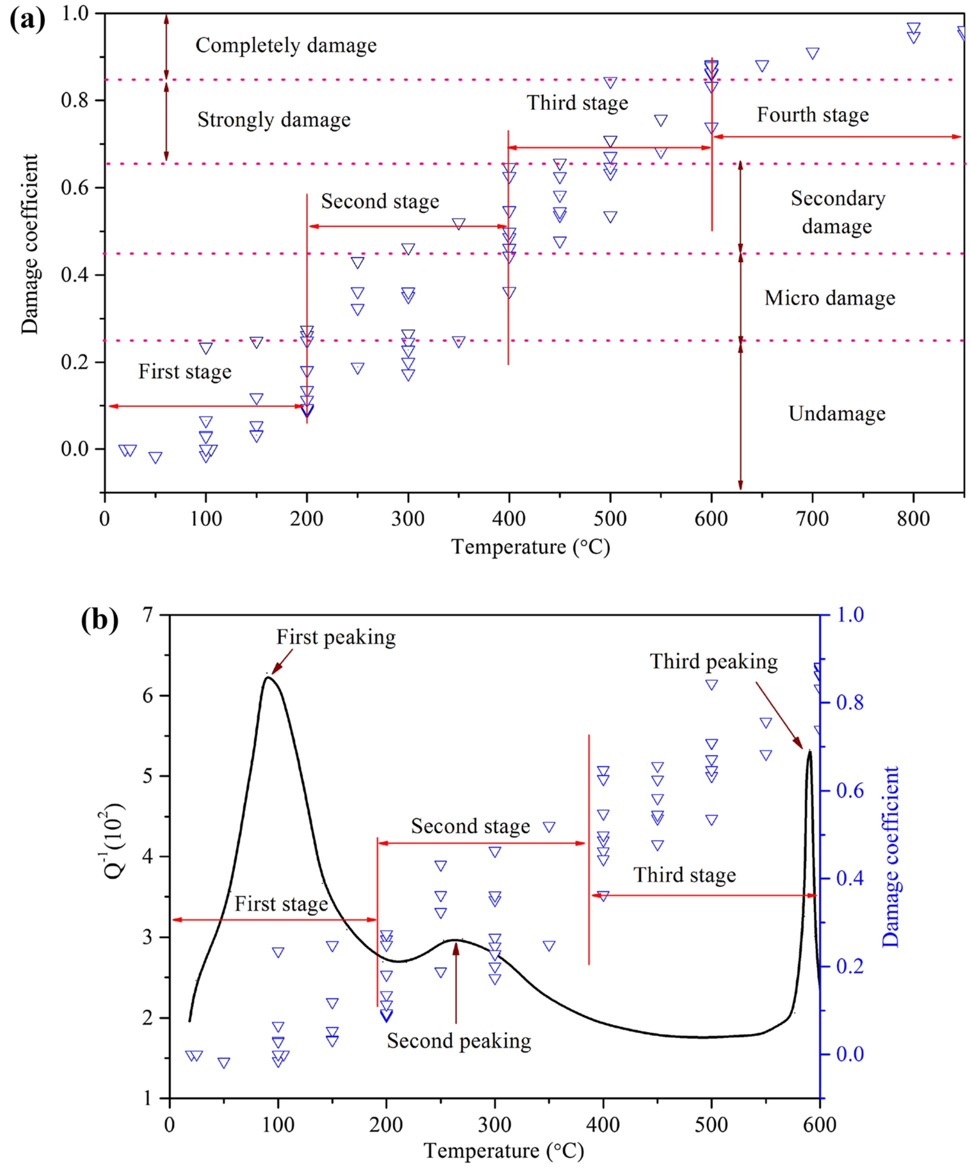


Fig. 8 Damage coefficient with temperature and variation of internal friction and damage coefficient

ite, siderite, magnetite, pyrrhotite, pyrite, illite and kaolinite) in granite undergo chemical changes, which are evidenced by the increased porosity and abrupt change of the wave velocities.

3. Generally, the temperature ranges of room temperature to 200, 200–400, 400–500 °C, and temperatures greater than 600 °C correspond to granite that is undamaged, beginning of damage to the microstructure of the granite, secondary damage, and extensive or complete damage, respectively. A temperature of 400 °C is, therefore, considered to be the critical threshold temperature for the thermal damage of granite.

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