Environ Earth Sci (2015) 74:2341–2349
DOI 10.1007/s12665-015-4234-9

ORIGINAL ARTICLE

Thermal damage pattern and thresholds of granite

Qiang Sun · Weiqiang Zhang · Lei Xue · Zhizhen Zhang · Tianming Su

Received: 11 April 2014 / Accepted: 25 February 2015 / Published online: 6 March 2015

Abstract High temperature may lead to the development of new microcracks or growth of pre-existing microcracks within granite, varying its physical and mechanical properties. Experiments were conducted to study the evolution of the physical and mechanical properties of granite specimens from room temperature to 800 °C. The specimens were heated in heating furnace and uniaxial compression tests were done using MTS servo-controlled testing machine. The results indicate five phases in the variation of physical and mechanical properties with temperature: from room temperature to 100, 100–300, 300–400, 400–600, and 600–800 °C. The first phase corresponds to the vaporization-escaping interval of adhered water, bound water, and structural water. Larger changes of physical and mechanical parameters in the temperature range of 300–600 °C, mostly 400–600 °C, are probably caused by the transition from the brittle state to plasticity (or ductility) of granite, and 400 °C may be a critical threshold of its thermal damage. These results confirm the important link among physical and mechanical properties in response to thermal treatment.

Keywords Thermal damage · Physical and mechanical properties · Micro-mechanism · Phase transformation · Critical threshold

Q. Sun (✉) · W. Zhang · Z. Zhang
School of Resources and Geosciences, China University of Mining and Technology, Xuzhou, Jiangsu Province 221116, People's Republic of China
e-mail: sunqiang04@126.com

L. Xue
Key Laboratory of Engineering Geomechanics, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, People's Republic of China

T. Su
Research Institute of Highway Ministry of Transport, Beijing 100088, People's Republic of China

Introduction

Thermally induced microcracks can significantly change the physical and mechanical properties of rock. Knowledge of the variation of these mechanical and physical properties with temperature is important to understand and model many processes in engineering projects, geological disasters, and geological structure formation, such as rock drilling (Nasseri et al. 2007, 2009), rock fragmentation, ore crushing, underground oil or gasification (Chen and Wang 1980; Chen et al. 1999; Liu et al. 2005), extraction of geothermal energy, deep petroleum boring, underground repositories of nuclear wastes (Zhang et al. 2001, 2008), protection of rock building or rocky cultural relics (Hajpal 2002), earthquake (Foulger 1995; Yang et al. 1997; Ramdani 1998), folding (Shimamoto and Hara 1976; Parish et al. 1976; Anderson and Bridwell 1980), geothermal activity (Mereer 1973), magmatic intrusions (Koide and Bhattacharji 1975; Knapp and Norton 1981), and plate tectonics (Pracht 1971; Heuze 1983; Björnsson 2008; Albaric et al. 2009; Craig et al. 2012).

Information about the evolution of physical and mechanical properties with temperature may be also used to analyze the thermal damage and identify the critical thresholds of rocks. Numerous studies have shown that some properties of granite are correlated to thermal damage, such as mechanical strength (e.g., compressive and tensile strength), Poisson's ratio, elastic modulus, porosity, acoustic velocities, permeability, wave velocity, fracture toughness, and fracture roughness (Bauer and

Johnson 1979; Chen and Wang 1980; Géraud et al. 1992; Jones et al. 1997; Yang et al. 1997; Xu and Liu 2000; Liu et al. 2005; Dwivedi et al. 2008; Nasseri et al. 2009; Xu et al. 2010; Xi et al. 2011; Lokajícek et al. 2012; Zhi et al. 2012; Chen et al. 2012; Yin 2012). Furthermore, exposure of fault planes to increased temperature has been found to reduce the friction coefficient (Stesky 1978; Lockner et al. 1986; Blanpied et al. 1998). Hence, the growth of cracks with temperature may lead to different level of thermal damage.

The important preoccupation of our study is to know the pattern of variation of physical or mechanical parameters with temperature in thermally cracked granites, and understand the underlying mechanism. In this paper, uniaxial compression tests were conducted on granites mined from Jining, Shandong, China. Before the tests, the granite specimens were heated to typical temperatures and then cooled, and then their stress–strain curves and peak stress under uniaxial compression, porosity, and P-wave velocity were measured and analyzed.

Experimental tests and results

Granite samples with average density of 2.76 g/cm^3 at room temperature were cut into φ 50 × 100 mm cylinders, which were then heated up to designated temperatures (25, 50, 100, 200, 300, 400, 500, 600, 700, and 800 °C) in a high temperature furnace (type MTS652.02). The heating rate was 30 °C/min, and each designated temperature was kept constant for about 2 h. The power was cut off and the specimen was allowed to cool naturally with the temperature of the furnace.

The mass, volume, porosity, and P-wave velocity of these specimens were tested before and after heating. The porosity was measured by a Microporous structure analyzer apparatus (type 9310) produced by Micromerities equipment Co., Ltd., and P-wave velocity was collected by TICO test machine, at the same time with this action.

Uniaxial compression tests of these specimens were carried out on an electro-hydraulic servo-controlled testing machine (MTS815). These tests were strain controlled at the rate of 0.0015 mm/s.

X-ray diffraction (XRD) (type D/Max-3B) analysis showed that feldspar, illite, and pyroxene are the main components (Fig. 1), accompanied by a small amount of other minerals. However, the experimental results of Zhang et al. (2010) showed that the Luhui granite (mined from Linyi, Shandong, China) contains feldspar, quartz, illite, calcite, and siderite.

The porosity and stress–strain curves of granite specimens heated up to different temperatures are shown in Table 1, Figs. 2 and 3. With the increase of temperature, especially above 400 °C, the mass loss continues to increase, as shown in Fig. 4.

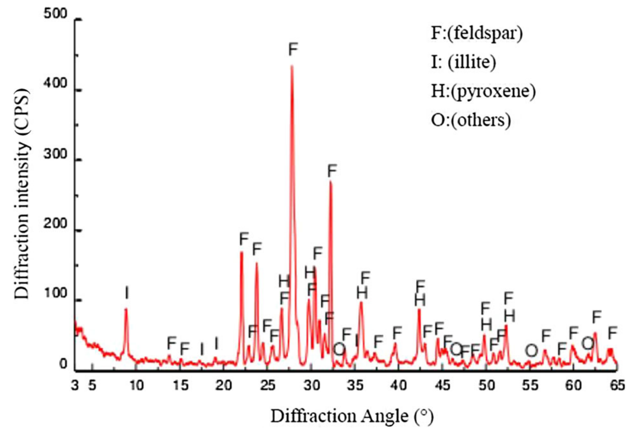

Fig. 1 XRD spectrum of granite sample (under 25°)

Table 1 Porosity under different temperature

Temperature °C	Porosity/%			
	Sample 1	Sample 2	Sample 3	Average value
25	0.97	0.96	0.72	0.88
50	0.73	0.81	0.70	0.75
100	0.87	0.68	0.66	0.74
200	0.91	1.06	1.05	1.01
300	1.04	1.11	1.37	1.17
500	1.49	1.37	1.82	1.56
800	2.62	2.42	2.68	2.57

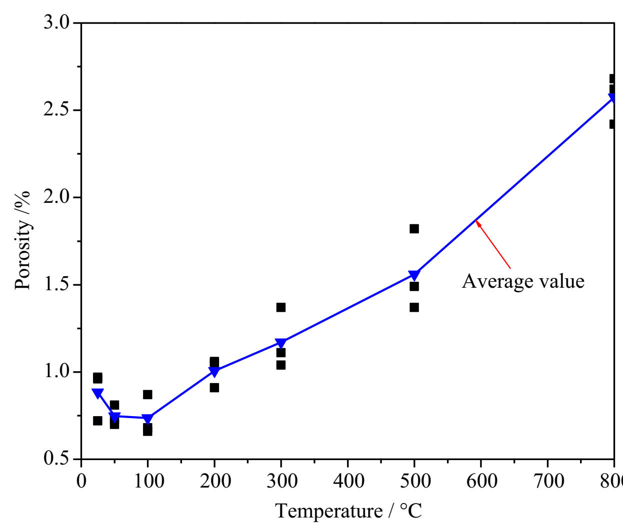

Fig. 2 Porosity of stress–strain of granite samples after different temperature

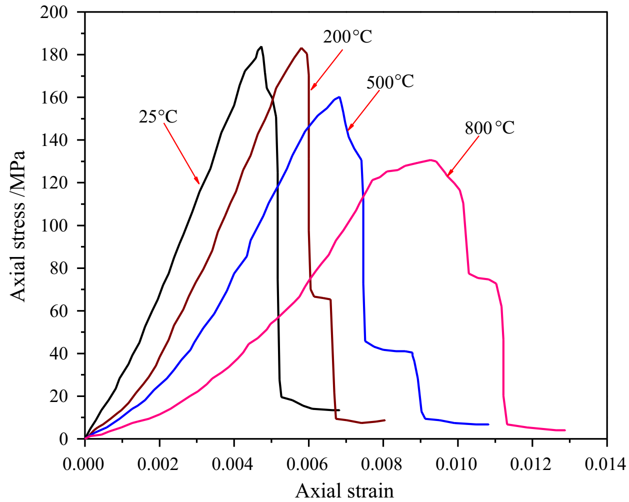

Fig. 3 Curves of stress–strain of granite samples after different temperature

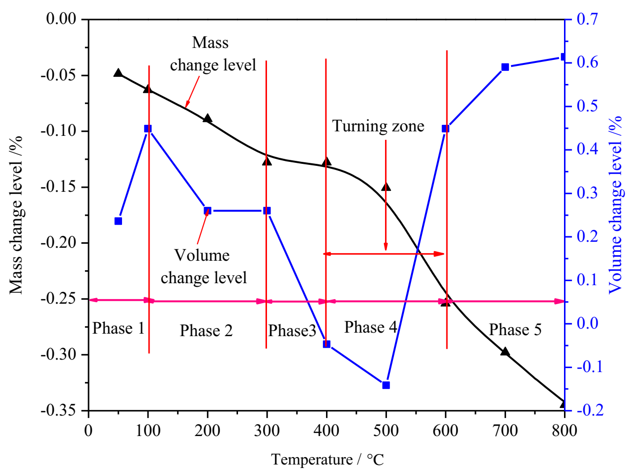

Fig. 4 Relationship between mass, volume, and temperature of granite

The results of uniaxial compression tests are shown in Figs. 3 and 5. Generally, the peak stress decreases and the peak strain increases as the temperature increases. Figure 3 demonstrates the variation of stress–strain curves with heating temperature. In each stress–strain curve of heated granite, four stages can be identified: (1) the compaction stage, when microcracks are folded by external loads; (2) the elastic stable cracking stage with continuous compaction at the beginning and micro-fractures developed later; (3) the yielding stage, when the stress reaches the maximum value at the end; (4) the softening stage, when the stress–strain curve declines steeply and the rock specimen fractures rapidly. Figure 5 shows that when the heating temperature is below 400 °C, the effect of temperature on the peak stress and elastic modulus of the specimen is relatively small; when the heating temperature

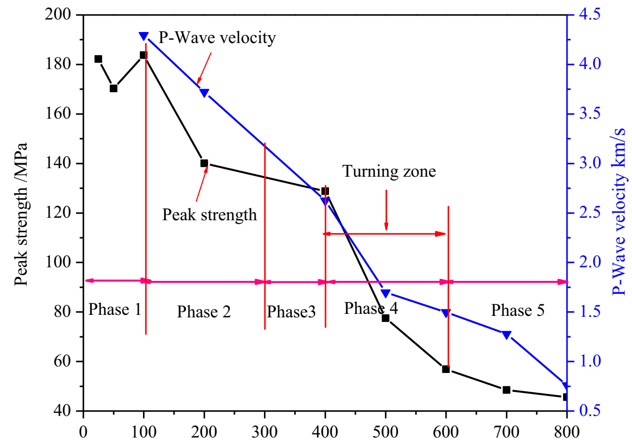

Fig. 5 Relationship between strength, P-wave velocity, and temperature

exceeds 400 °C, the peak stress and elastic modulus of the specimen decreases significantly with the increase of heating temperature.

Analysis and discussion

This decrease in the strength of heated granite is caused by the variation of internal structure induced by heat. Since granite is composed of mineral particles with different thermal expansion coefficients and thermo–elastic characteristics, high temperature may lead to inhomogeneous thermal expansion of mineral particles or phase transition of some mineralogical components, generating internal stress and microcracks in granite.

With the increase of temperature, internal defects would grow and change the physical and mechanical properties of granite. Moreover, in the process of heating, the water inside granite changes its existing form, i.e., the absorbed water, bounded water, and mineral water (e.g., crystal water, structural water, or zeolite water) would escape from granite under different temperature. It is known that the absorbed water would escape around 100 °C; the bounded water escape between 100 and 300 °C; crystal water would escape below 400 °C; and structural water of mineral would escape above 300 °C (Sun et al. 2013). The loss of crystal water and structural water leads to the damage of mineral crystal lattice skeleton, increasing the defects of granite.

Accordingly, variation of the measured compressive strength, P-wave velocity, and mass quality with temperature may be divided into five phases (as shown in Figs. 4, 5):

1. Room temperature –100 °C. In this phase, the absorbed water would be lost and the mineral grains of

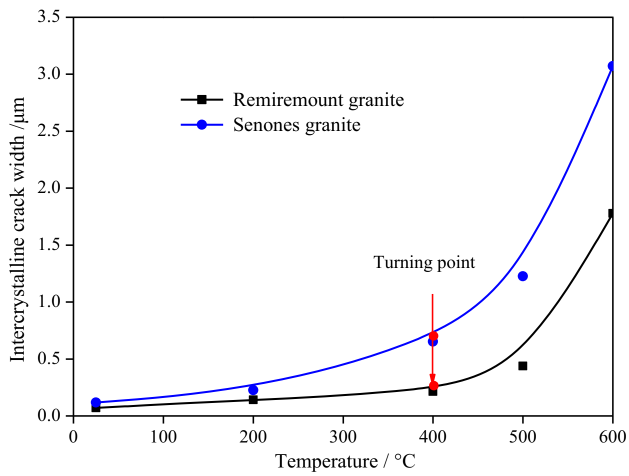

Fig. 6 Intercrystalline crack widths variations of Senones and Remiremont granite as a function of the temperature (Etienne and Poupert 1989)

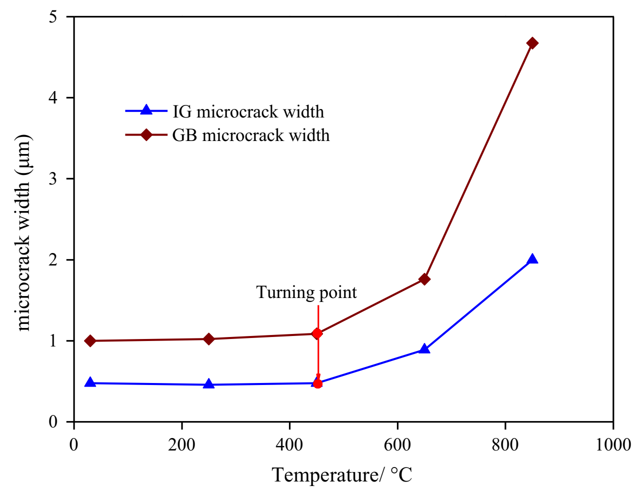

Fig. 7 Evolution of intra-granular (IG) and grain boundary microcrack (GB) widths as a function of the temperature for Westerly granite (Nasseri et al. 2007)

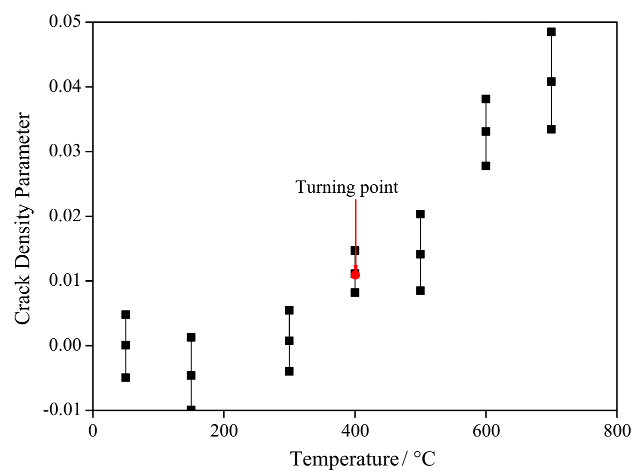

Fig. 8 Change in crack density parameter calculated from the compressional and shear wave velocities (Jones et al. 1997)

granite be expanded, so porosity and P-wave velocity decrease slightly.

2. 100–300 °C. In this phase, bounded water and crystal water escape, porosity increases slightly, and P-wave velocity decreases slightly.
3. 300–400 °C. In this phase, the crystal water and structural water of mineral escape, so porosity increases significantly and P-wave velocity decreases. A review of previous work on thermally treated granites found that the permeability has increased significantly (as shown in Fig. 6, Etienne and Poupert 1989), which was considered to be caused by increased defects and connectivity due to the loss of crystal and structural water. Moreover, in this phase, the water reaches its critical temperature (i.e., 374 °C), at which the water may turn into supercritical fluid, causing internal stress in the granite and increased thermal damage.

   The existing form of water around the critical temperature has significant influence on the solubility, physical, and chemical properties of granite minerals. The test of Zhang et al. (2008) showed fluctuation in the dissolution rates when passing the critical state of water, i.e., over the temperature range of 300–400 °C. Experiments show that the maximum release rate of Si is released at 300 °C. Variation of the water properties and kinetic behavior of water–rock interactions also affect other features of granite mineral, such as the release of Silica, and breaking of silicate framework of minerals.
4. 400–600 °C. In this phase, the physical and chemical features of granite minerals would change (shown in Figs. 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18). Between 400 and 600 °C, especially 500 and 600 °C, the minerals (such as ankerite, siderite, magnetite, pyrrhotite, pyrite, illite, and kaolinite) of granite have chemical changes (Jana and Agnes 2012). At roughly 573 °C and under atmospheric conditions, quartz has a phase transformation from α phase to β phase, which can be used to explain the large variation of mechanical and physical properties.
5. Above 600 °C. Under the influenced of solid mineral inflation and fracture of metallic bonding (such as Al–O, K–O, Na–O, and Ca–O), the strength and wave velocity continue to reduce, and the permeability and porosity continue to increase. In this phase, part of the minerals would melt, leading to enlarged defects.

In the first three phases, the variations of compressive and tensile strength are different from what was found in previous studies. Uniaxial compressive strength and elastic

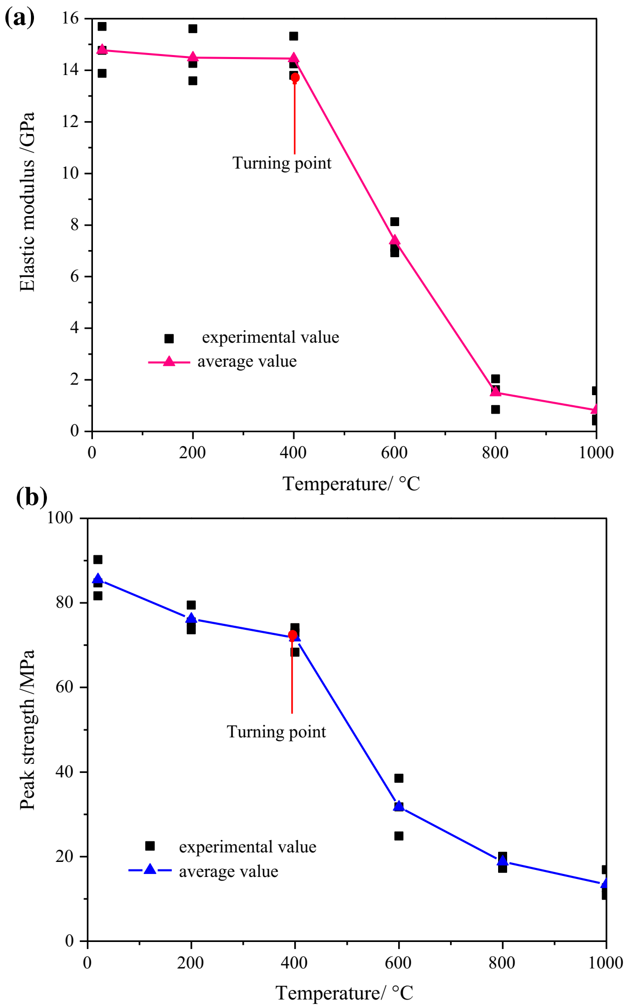

Fig. 9 Relationship between strength, elastic modulus, and temperature (Chen et al. 2012). **a** Elastic modulus against the temperatures. **b** Peak strength against the temperatures

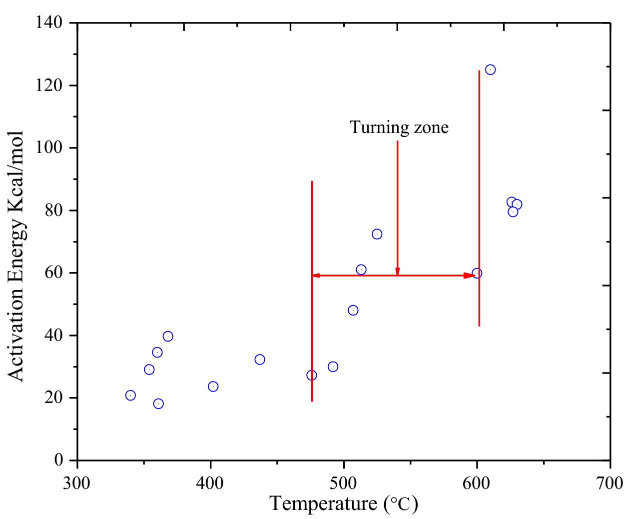

Fig. 10 Experimental activation energy at different temperature for sliding at 2.5 × 10^5 kPa pressure (Stesky 1978)

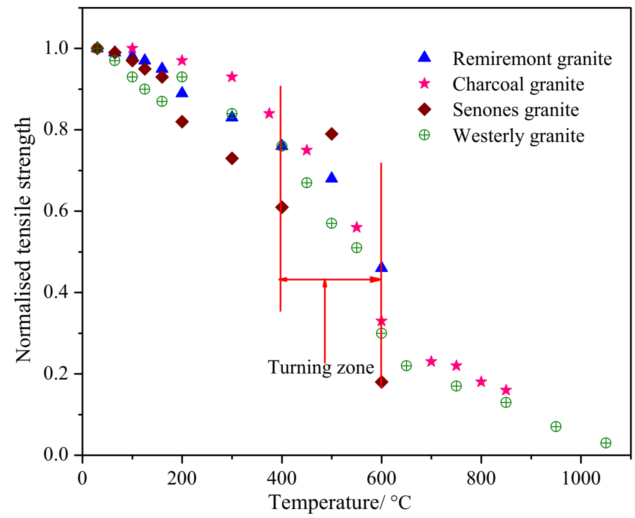

Fig. 11 Normalized tensile strength vs. temperature at atmospheric pressure (Dwivedi et al. 2008)

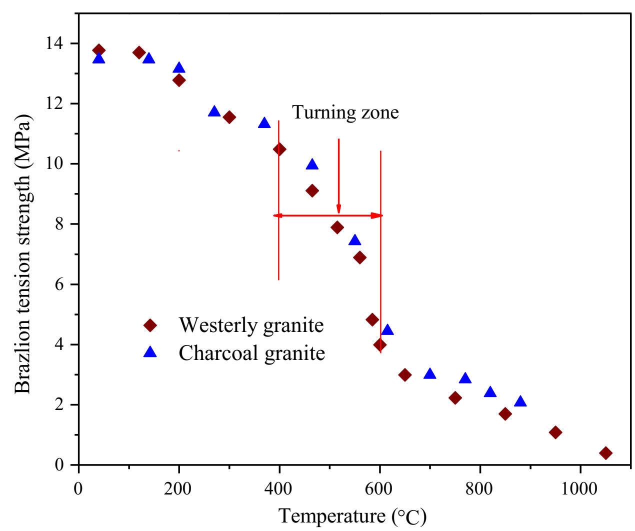

Fig. 12 Tensile strength of granites vs. temperature (Heuze 1983)

modulus decrease with temperature until 400 °C, while porosity, permeability, and AE significantly increase (Bauer and Johnson 1979; Etienne and Poupert 1989; Géraud 1994; Du et al. 2004; Chaki et al. 2008).

However, interestingly, numerous studies have shown that when the temperature is over 400 °C, some physical and mechanical properties of granite, such as density of microcracks, porosity, permeability, wave velocity, fracture roughness, fracture toughness, and peak strength (as shown in Figs. 5, 16), would change significantly, consistent with our experimental result. Bauer and Johnson (1979) pointed out that although microcracking starts in granite at about 80–120 °C, most of the mineral grains are microcracked at about 400 °C. Chaki et al. (2008) observed a small increase in porosity between 105 and 500 °C, and a

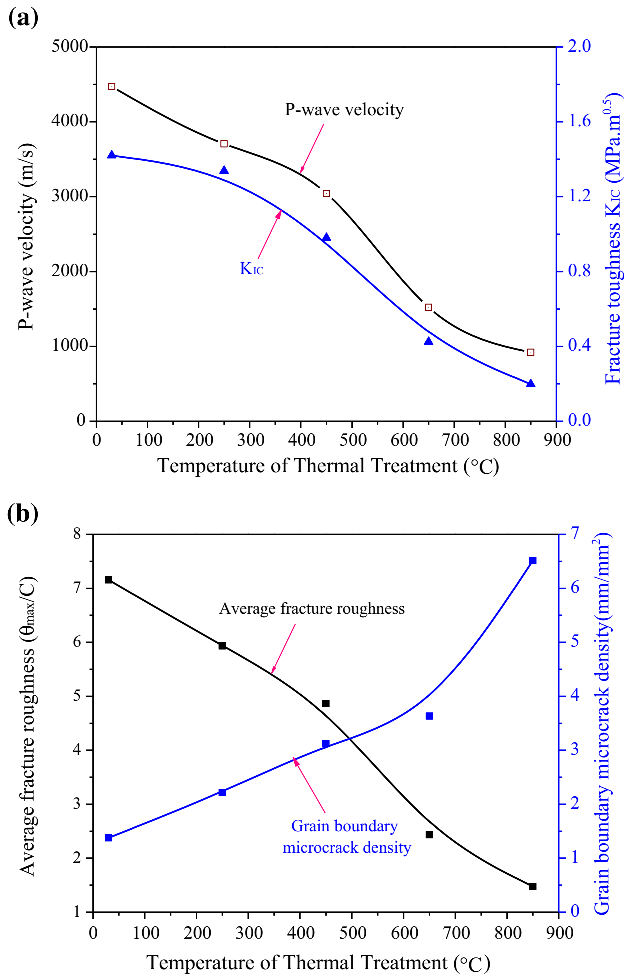

Fig. 13 Variation of the average fracture roughness, fracture toughness, P-wave velocity, and grain boundary microcrack density as a function of the temperature of thermal treatment (Nasseri et al. 2009). **a** Variation of the average fracture toughness and P-wave velocity. **b** Variation of the average fracture roughness and grain boundary microcrack density

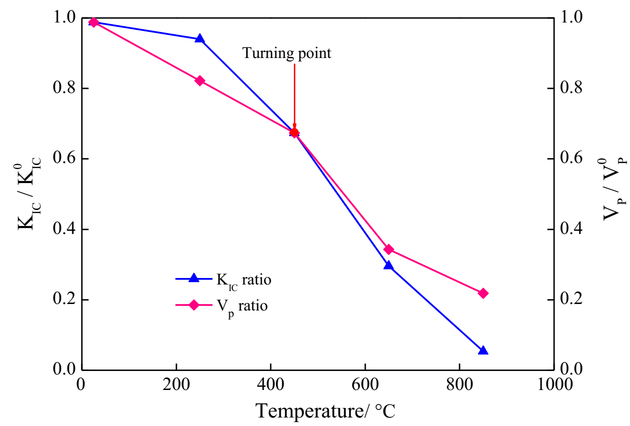

Fig. 14 A comparison of the fracture toughness (K_{IC}) and the mean P-wave velocity as a function of temperature treatment. Both K_{IC} and the V_P were normalized to that of the untreated specimens (K_{IC}^0 and V_P^0) (Nasseri et al. 2007)

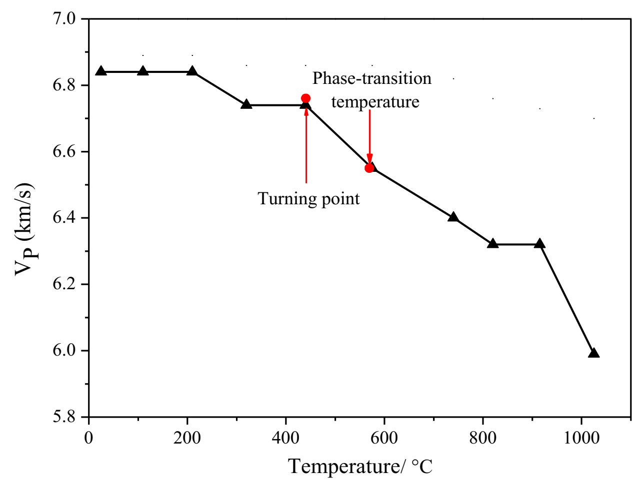

Fig. 15 Evolution of P-wave velocity vs. heat treatment temperature of Huanan granite (type I) under 500 MPa (Yang et al. 1997)

significant increase between 500 and 600 °C (anisotropic expansion linked to the α/β quartz transition which occurs at 573 °C). Géraud et al. (1992) showed that the porosity of granite increases above 300 °C. The largest increase of surface roughness occurred between 450 and 600 °C, corresponding to the largest decreases in both *Vp* and K_{IC}.

Bauer and Johnson (1979) observed that the strength of granite heated up to 400 °C was slightly lower than that of the granite at room temperature. Etienne and Poupert (1989) pointed out that the Remiremont granite showed slightly higher strength at 200 °C, but the Sennones granite showed a larger increase in strength at 400 °C. The increase of strength at 400 °C was also observed by Alm et al. (1985), although Rao and Murthy (2001) showed that the strength of granite at 400 °C and room temperature is comparable.

The mechanical behavior of rocks essentially depends upon their mineralogy, structure, temperature, and stress history (Etienne and Poupert 1989). Granite is polycrystalline containing minerals with different thermal expansion coefficients, so inter-granular compressive and tensile forces are generated under heating. When these forces exceed the local strength, microcracks are generated. Depending on the temperature, thermal cracking can occur either between adjacent crystalline grains (inter-granular cracks) (Jason et al. 1993) or within grains (intra-granular cracks) such as the case of α/β phase transition in quartz (Glover et al. 1995). Analysis of mineral–mineral contact types along the test fracture path in thermally treated granite specimens showed that pre-existing thermal damage mainly around grain boundaries leads to a larger volume of rock affected by fracture propagation (Fredrich and

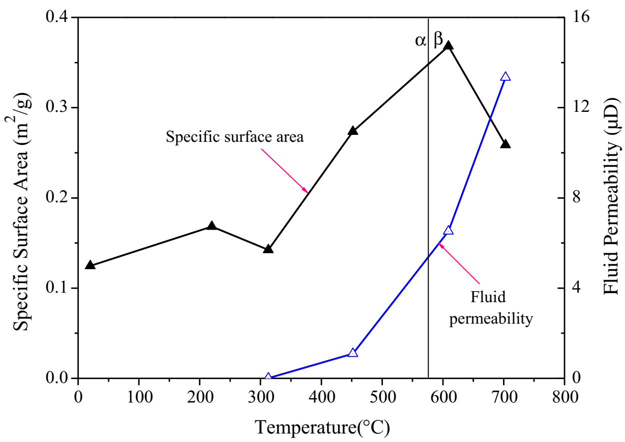

Fig. 16 Measurements made upon samples of La Bresse mylonite (DLB1 and DLB2). The variation of BET total internal surface area and fluid permeability with heat treatment temperature (Glover et al. 1995)

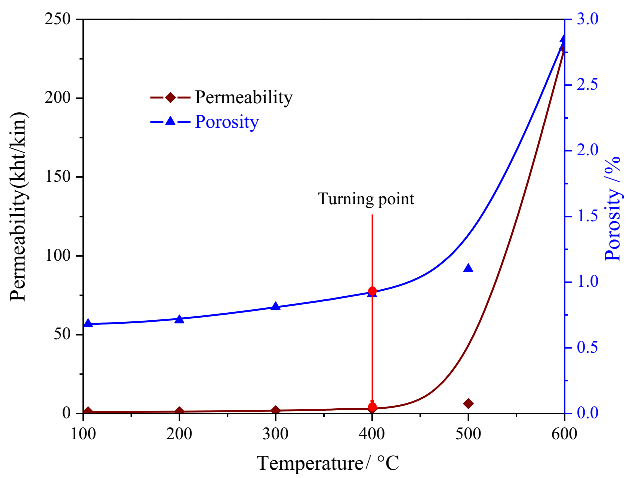

Fig. 17 Evolution of porosity and gas permeability vs. heat treatment temperature (Chaki et al. 2008)

Wong 1986; Nasseri et al. 2007). With the growth of microcracks due to thermal damage, the mechanical strength, elastic modulus and wave velocity decrease, plastic deformation, acoustic emission (AE), and permeability increase.

Chen et al. (2012) pointed out that 400 °C may be a critical value for the strength of granite. Nasseri et al. (2007, 2009) reported that above 450 °C, grain boundary opening and cracking, and intra-granular cracking and mineral grain dissection linked to the quartz α/β phase transition, induced a significant increase in the total density of cracks.

Our experimental results also suggest that 400 °C could be a critical threshold of the thermal damage of granite, corresponding to the transition from the brittle state to plasticity (or ductility). Therefore, significant changes in

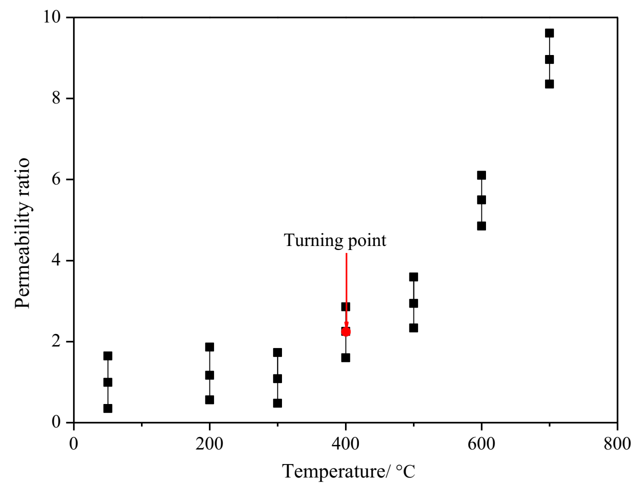

Fig. 18 Permeability change after heat treatment (Jones et al. 1997)

the physical and mechanical properties of granite specimens were observed in the temperature range of 300–600 °C, especially 400–600 °C.

Conclusion

In order to find out how the mechanical and physical properties of granite vary with temperature, uniaxial compression tests of granite specimens were conducted to measure the mechanical properties of granite rocks heated up to 800 °C, and their physical properties such as porosity, permeability, and ultrasonic wave propagation are also measured.

Based on the results and the data reported in previous studies, the process and critical threshold of the thermal damage of granite are discussed, and the following conclusions can be drawn:

1. temperature has a significant impact on the physical and mechanical properties of granite.
2. Generally, the temperature range of 300–600 °C, especially 400–600 °C, corresponds to the transition from the brittle state to plasticity (or ductility) of granite, and 400 °C maybe a critical threshold of the thermal damage of granite.
3. The results indicate five phases in the variation of physical and mechanical properties with temperature: from room temperature to 100, 100–300, 300–400, 400–600, and 600–800 °C. The first phase corresponds to the vaporization-escaping interval of adhered water, bound water, and structural water. Larger changes of physical and mechanical parameters in the temperature range of 300–600 °C, mostly 400–600 °C, are probably caused by the transition of granite from the brittle state to plasticity (or ductility). Between 400 and

600 °C, especially from 500 to 600 °C, the minerals (such as ankerite, siderite, magnetite, pyrrhotite, pyrite, illite, and kaolinite) in granite have chemical changes, which are demonstrated as volume increase, reduction of bearing capacity, increased connectivity, and abrupt change of wave velocity.

Acknowledgments This research was supported by the State Basic Research and Development Program of China (No. 2013CB036003), the Priority Academic Program Development of Jiangsu Higher Education Institutions, Transport project (2013318J12330), and the National Science Youth Foundation of China (Grant No.41102201, No.41302233, No.51309222).

References

Albaric J, Déverchère J, Petit C, Perrot J, Gall BL (2009) Crustal rheology and depth distribution of earthquakes: insights from the central and southern East African rift system. Tectonophysics 468:28–41

Alm O, Jaktlund LL, Kou SQ (1985) The influence of microcrack density on the elastic and fracture mechanical properties of stropa granite. Phys Earth Planet Inter 40:161–171

Anderson CA, Bridwell RJ (1980) A finite element method for studying the transient non-linear thermal creep of geological structures. Int J Rock Mech Min Sci Geomech Abstr 4:255–276

Bauer S J, Johnson B (1979) Effects of slow uniform heating on the physical properties of the westerly and charcoal granites. In: Proceedings of the 20th US symposium on rock mechanic, Austin, 4–6 June 1979, pp 7–18

Björnsson A (2008) Temperature of the Icelandic crust: inferred from electrical conductivity, temperature surface gradient, and maximum depth of earthquakes. Tectonophysics 447:136–141

Blanpied ML, Marone CJ, Lockner DA, Byerlee JD, King DP (1998) Quantitative measure of the variation in fault rheology due to fluid-rock interactions. J Geophys Res 103(B5):9691–9712

Chaki S, Takarli M, Agbodjan WP (2008) Influence of thermal damage on physical properties of a granite rock: porosity, permeability and ultrasonic wave evolutions. Constr Build Mater 22:1456–1461

Chen Y, Wang CY (1980) Thermally induced acoustic emission in Westerly granite. Geophys Res Lett 7(12):1089–1092

Chen Y, Wu XD, Zhang FQ (1999) Experimental research on rock thermal cracking (in Chinese). Chinese Sci Bull 44(8):880–883

Chen YL, Ni J, Shao W, Azzam R (2012) Experimental study on the influence of temperature on the mechanical properties of granite under un-axial compression and fatigue loading. Int J Rock Mech Min 56:62–66

Craig TJ, Copley A, Jackson J (2012) Thermal and tectonic consequences of India underthrusting Tibet. Earth Planet Sci Lett 353–354:231–239

Du SJ, Liu H, Zhi HT, Chen HH (2004) Testing study on mechanical properties of post-high-temperature granite (in Chinese). Chin J Rock Mech Eng 23(14):2359–2364

Dwivedi RD, Goel PK, Prasad VVR, Sinha Amalendu (2008) Thermo-mechanical properties of Indian and other granites. Int J Rock Mech Min 45:303–315

Etienne FH, Poupert R (1989) Thermally induced microcracking in granites: characterization and analysis. Int J Rock Mech Min Sci 26(2):125–134

Foulger GR (1995) The Hengill geothermal area, Iceland: variation of temperature gradients deduced from the maximum depth of seismogenesis. J Volcanol Geoth Res 65:119–133

Fredrich JT, Wong T (1986) Micromechanics of thermally induced cracking in three crustal rocks. J Geophys Res 91(B12): 12743–12764

Géraud Y (1994) Variations of connected porosity and inferred permeability in a thermally cracked granite. Geophys Res Lett 21(11):979–982

Géraud Y, Mazerolle F, Raynaud S (1992) Comparison between connected and overall porosity of thermally stressed granites. J Struct Geol 14(8/9):981–990

Glover PWJ, Baud P, Darot M, Meredith PG, Boon SA, LeRavalec M, Zoussi S, Reuschlé T (1995) α/β phase transition in quartz monitored using acoustic emissions. Geophys J Int 120:775–782

Hajpal M (2002) Changes in sandstone of historical monuments exposed to fire or high temperature. Fire Technol 38(4):373–382

Heuze FE (1983) High-temperature mechanical, physical and thermal properties of granitic rocks—a review. Int J Rock Mech Min Sci Geomech Abstr 20(1):3–10

Jana J, Agnes K (2012) Thermally induced alterations of minerals during measurements of the temperature dependence of magnetic susceptibility: a case study from the hydrothermally altered soultz-sous-Forêts granite, France. Int J Earth Sci 101:819–839

Jason DP, Carlson SR, Young RP, Hutchins DA (1993) Ultrasonic imaging and acoustic emission monitoring of thermally induced microcracks in Lac du Bonnet Granite. J Geophys Res Solid Earth 98(B12):22231–22243

Jones C, Keaney G, Meredith PG et al (1997) Acoustic emission and fluid permeability measurements on thermally cracked rocks. Phys Chem Earth 22:813–817

Knapp RB, Norton D (1981) Preliminary numerical analysis of processes related to magma crystallisation and stress evolution in cooling pluton environments. Am J Sci 281:35–68

Koide H, Bhattacharji S (1975) Formation of fractures around magmatic intrusions and their role in ore localization. Econ Geol 70:781–799

Liu JR, Qin JS, Wu XD (2005) Experimental study on relation between temperature and rock permeability (in Chinese). J China Univ Pet Nat Sci 24(12):51–53

Lockner DA, Summers R, Byerlee JD (1986) Effects of temperature and sliding rate on frictional strength of granite. Pure appl Geophys 124(3):446–468

Lokajícek T, Rudajev V, Dwivedi RD et al (2012) Influence of thermal heating on elastic wave velocities in granulite. Int J Rock Mech Min 54:1–8

Mereer JJ (1973) Finite element approach to the modeling of hydrothermal systems. PhD dissertation, University of Illinois, Urbana

Nasseri MHB, Schubnel A, Young RP (2007) Coupled evolutions of fracture toughness and elastic wave velocities at high crack density in thermally treated westerly granite. Int J Rock Mech Min Sci 44:601–616

Nasseri MHB, Tatone BSA, Grasselli G, Young RP (2009) Fracture toughness and fracture roughness interrelationship in thermally treated Westerly granite. Pure Appl Geophys 166:801–822

Parish DK, Krivz AI, Carter NI (1976) Finite element folds of similar geometry. Tectonophysics 32:183–207

Pracht WE (1971) A numerical method for calculating transient creep flows. J Comp Phys 7:46–60

Ramdani F (1998) Geodynamic implications of intermediate-depth earthquakes and volcanism in the intraplate Atlas mountains (Morocco). Phys Earth Planet Inter 108:245–260

Rao GMN, Murthy CR (2001) Dual role of microcracks: toughening and degradation. Can J Earth Sci 38(2):427–440

Shimamoto T, Hara I (1976) Geometry and strain distribution of single-layer folds. Tectonophysics 30:1–34
Stesky RM (1978) Mechanisms of high temperature frictional sliding in Westerly granite. Can J Earth Sci 15:361–375
Sun Q, Zhang ZZ, Xue L, Zhu SY (2013) Physical–mechanical properties variation of rock with phase transformation under high temperature. (in Chinese). Chin J Rock Mech Eng 32(5):935–942
Xi BP, Zhao JC, Zhao YS, Zhu HH, Wu JW (2011) Key technologies of hot dry rock drilling during construction (in Chinese). Chin J Rock Mech Eng 30(11):2234–2243
Xu XC, Liu QS (2000) A preliminary study on basic mechanical properties for granite at high temperature (in Chinese). Chin J Geotech Eng 22(3):332–335
Xu XL, Gao F, Shen XM, Jin CH (2010) Research on mechanical characteristics and micropore structure of granite under high-temperature (in Chinese). Rock Soil Mech 31(6):1752–1758
Yang SF, Chen H, Jiang JS, Zhu GQ, Xie HS, Hou W, Zhang YM, Xu HG (1997) Testing study on elastic wave velocities and electrical conductivity of crustal rocks (in Chinese). Sci China Ser D 27(1):33–38
Yin TB (2012) Study on dynamic behavior of rocks considering thermal effect (in Chinese). Ph.D. Thesis, Central south university, Changsha
Zhang ZX, Yu J, Kou SQ, Lindqvist PA (2001) Effects of high temperatures on dynamic rock fracture. Int J Rock Mech Min 38(2):211–225
Zhang Y, Zhao YS, Wan ZJ, Qu F, Dong FK, Feng ZJ (2008) Experimental study on effect pore pressure on feldspar fine sandstone permeability under different temperatures (in Chinese). Chinese J Rock Mech Eng 27(1):53–58
Zhang Y, Zhao YS, Wu G (2010) Meso-structure and pattern of thermal cracking of Luhui granite (in Chinese). J Lanzhou Univ Technol 36(6):115–118
Zhi LP, Xu JY, Liu ZQ, Liu S, Chen TF (2012) Research on ultrasonic characteristics and Brazilian splitting-tensile test of granite under post-high temperature (in Chinese). Rock Soil Mech 33(s1):61–66