Influence of Heating on Tensile Physical-Mechanical Properties of Granite

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Abstract: Heating procedures dramatically influence the physical-mechanical properties of rock. In this paper, via both numerical simulation and laboratory experiments, we examine the influence of constant temperature period (CTP), from 0.5 to 5 h) and predetermined temperature (PDT, from room temperature to 1,000°C) on the tensile mechanical properties of the Qinling granite, China. Results indicate that: CTP has a significant impact on the tensile mechanical properties of granite. For different PDTs, the density, longitudinal wave velocity (LWV) and tensile strength (TS) of granite decrease with increasing CTP. When CTP reaches the constant temperature turning-point (CTT), heating has fully affected the granite samples. The variation in LWV and TS versus temperature can be divided into four stages: 25–200°C, 200–600°C, 600–800°C and 800–1,000°C. LWV and TS are negatively related to temperature and are more sensitive to temperature at higher PDTs. In addition, TS is more sensitive to temperature than LWV when PDT increases. The effects of CTP and PDT on LWV are similar to that of TS. Since the measurement of LWV is lossless, researchers can safely determine the appropriate CTP or CTT for any PDT and predict the tensile mechanical properties of rock by LWV analysis.

Keywords: heating procedure, high temperature, Brazilian disc, numerical simulation, tensile strength, granite

Introduction

Rock tensile strength (TS) is an important factor for design and stability analysis of underground rock structures, as it dictates the maximum roof span of underground openings, the maximum internal pressure of unlined storage caverns, and the borehole pressure for hydraulic fracturing [1]. Furthermore, some special modern rock engineering applications (such as deep geological disposal of nuclear waste, geothermal heat extraction and underground coal gasification) usually locate in hot environments, where rocks generally experience high temperatures up to several hundred degrees Celsius [2–5], or even more than a thousand [6, 7]. Consequently, the tensile mechanical behavior of rock subjected to high temperatures is of interest and still a challenge to scientists and researchers. Although there is plenty of research focused on the effects of high temperatures on mechanical properties, deformation characteristics or crack revolution [8, 9], the effects of heating have hardly been examined.

Almost all the previous researchers adopted an identical method to heat rock samples. That is to heat a sample to a predetermined temperature (PDT) by a certain rate under atmospheric pressure using a furnace. The temperature is maintained for a given period to guarantee heating uniformity inside the sample. Finally, the samples are cooled to room temperature in the furnace chamber. During the heating procedure, the most important factors influencing the mechanical properties of rock are the heating rate (HR), constant temperature period (CTP) and PDT. Once it was suggested that samples should be kept at a constant temperature for at least 20 min prior to mechanical testing or cooling [10]. Subsequent research commonly increases the CTP to 0.5–2 h, even to 24 h. However, there were no arguments rigorous enough to prove that a sample can reach the uniform temperature state after a period of constant temperature.

In this paper, we explore a new method of determining the termination of CTP for one temperature condition. Firstly, the finite element method (FEM) software Ansys was utilized to simulate the temperature field distribution of cylindrical samples under different HRs and different CTPs, which validated that under other constant conditions, the slower the HR is and longer the CTP is, the better the uniformity of samples’ temperature field distribution is. Next, utilizing an ultrasonic detection analyzer, a box-type furnace and an electro-hydraulic servo uniaxial compression testing system, the influence of...
different CTPs (0.5–5 h) and different PDTs (25–1,000°C) on density, longitudinal wave velocity (LWV) and TS of granite Brazilian disc samples was studied. LWV is also called P-wave, which is strongly related to the physical properties of rock [11]. Results can be used to assess thermal damage and support a theoretical guide for the repair and reinforcement in rock structures exposed to high temperature (Table 1).

Simulations of heating procedures

Simulation models and some related details

Ansys is a common FEM software set, of which the thermal process module satisfies the demands of the thermal transient analysis presented in this paper. In actual thermal experiments, the heating procedure involves heating the air inside the furnace to PDT via the heating silicon carbide rods and holding a constant temperature. Hence, the temperature of a sample is raised by the heat exchange between the air inside the furnace and the sample.

Considering the symmetry of the sample, a demisemi model of Brazilian disc sample is built (size of a complete sample is 50 mm × 25 mm) as shown in Figure 1. Thermal contacts are present between the faces A, B, C and the air while symmetric boundaries are set on faces D, E. To simplify the calculations, the effect of temperature on the material characteristics is ignored and the sample is considered isotropic. Take granite [24] for example, of which some basic parameters are: density $\rho = 2,800 \text{ kg/m}^3$, heat conductivity coefficient $\lambda = 2.76 \text{ W/(m°C)}$ and specific heat capacity $C = 1.18 \times 10^3 \text{ J/(kg°C)}$. The heat exchange coefficient between air and the sample is set to 36.1 W/(m°C). The hexahedral element Solid 70, which is commonly used in 3-D thermal transient analysis, is adopted for the simulation. This element has eight nodes (each node has only one thermal freedom degree). It can transfer heat in three orthogonal directions. Samples are meshed by the mapped meshing method, while the minimum element size is 2 mm, as shown in Figure 2.

Simulation results and analysis

In order to quantitatively analyze the gap between the present temperature and target temperature as well as the homogeneity of the distribution of sample’s temperature field, we define the rate of deviation and the dispersion of node temperatures as follows:

| References       | Heating rate (°C/min) | Constant temp. period (h) | Rock type       | Sample size $D \times H$ (mm) | Sample shape |
|------------------|-----------------------|---------------------------|-----------------|-----------------------------|--------------|
| Araújo et al. [12] (1997) | 1.5                   | U                         | Sandstone       | 50 × 100                    | Cylinder     |
| Hajpúl et al [13] (1998)   | U                     | 6                         | Sandstone       | 40 × 80                     | Cylinder     |
| Rao et al. [14] (2007)    | 30                    | 2                         | Sandstone       | 50 × 50                     | Cylinder     |
| Wu et al. [15] (2007)     | 5                     | 2                         | Sandstone       | 50 × 100                    | Cylinder     |
| Zhang et al. [16] (2009)  | 120                   | 2                         | Marble, limestone| 20 × 45                     | Cylinder     |
| Qin et al. [17] (2009)    | 5–10                  | 1                         | Sandstone       | 50 × 50                     | Cube         |
| Yin et al. [18] (2009)    | 20                    | 5                         | Sandstone       | 50 × 100                    | Cylinder     |
| Zhao et al. [19] (2010)   | 30                    | 5                         | Sandstone       | 50 × 100                    | Cylinder     |
| Vishal et al. [20] (2011) | U                     | 24                        | Khondalite      | 50 × 30                     | Cylinder     |
| Zhang et al [9] (2016)    | 5                     | 2                         | Granite, sandstone| 50 × 100                   | Cylinder     |
| Lü et al [21] (2017)      | 30                    | 0.5                        | Sandstone       | 50 × 30                     | Cylinder     |
| Chen et al [22] (2017)    | 1–15                  | U                         | Granite         | 50 × 100                    | Cylinder     |
| Zhang et al [23] (2017)   | 5                     | 2                         | Limestone       | 50 × 100                    | Cylinder     |

P.S.: “U” represents that the condition was unmentioned in the reference; “$D \times H$” represents “Diameter × Height”.

Figure 1: Complete model and demisemi model for sample in numerical simulation.
![Solid70](image)

**Figure 2:** Finite element model of demisemi sample.

\[ \text{Dev} = \frac{T_{\text{max}} - T_{\text{min}}}{T_P} \times 100\% \]  

(1)

\[ \text{Dis} = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (T_i - \bar{T})^2} \]  

(2)

\[ \bar{T} = \frac{1}{n} \sum_{i=1}^{n} T_i \]  

(3)

where Dev represents the deviation rate of the sample’s node temperature, the larger the Dev is, the farther the sample’s temperature is from PDT; \( T_{\text{max}} \) and \( T_{\text{min}} \) represent the maximum and minimum value of all node temperatures in the sample, respectively; \( T_P \) represents the PDT; Dis represents the dispersion of sample’s node temperatures, which is equal to the standard deviation, reflecting the homogeneity of sample’s temperature field distribution. The larger the Dis is, the less uniform the distribution of temperature field is; \( T_i \) represents the temperature of the \( i \)th node; \( \bar{T} \) represents the average value of all the node temperatures; \( n \) represents the number of nodes.

To study the effects of HR and CTP on the sample’s temperature field distribution, we simulated heating the sample from 25°C to 1,000°C via six different HRs, of which the simulated results are displayed in Table 2 and Figure 3. In order to compare the simulated results more intuitively, we mirror on the demisemi model to half model to check the temperature field nephogram, as shown in Figures 3 and 4.

It should be noted that although the PDT is 1,000°C, during the simulation, it is the air surrounding the sample which is heating up via designed HR while the sample is heating up by thermal exchange between sample’s faces and the air. So when the air has already reached 1,000°C, all the node temperatures of sample are lower than 1,000°C. Figure 3 indicates that for different HRs, the final temperature field distributions are relatively similar. The \( T_{\text{min}} \) is located in the central point of the sample while the \( T_{\text{max}} \) is located symmetrically in the intersecting lines of face C and faces A, B.

| Heating rate (°C/min) | 2.5 | 5   | 7.5  | 10  | 15  | 20  |
|-----------------------|-----|-----|------|-----|-----|-----|
| \( T_{\text{max}} \) (°C) | 955.37 | 933.05 | 910.79 | 888.74 | 867.08 | 826.16 |
| \( T_{\text{min}} \) (°C)  | 919.99 | 880.00 | 840.11 | 800.617 | 761.91 | 689.14 |
| Dev (%)                | 3.54 | 5.31 | 7.07  | 8.81  | 10.52 | 13.70 |
| Dis (°C)               | 8.36 | 12.54 | 16.71 | 20.84 | 24.87 | 32.40 |

**Table 2:** Numerical calculation results of node temperatures with different HRs.

![Tmax node](image)

(a): HR=2.5 °C/min  
(b): HR=20 °C/min

**Figure 3:** Sample’s temperature field nephograms for HR = 2.5, 20°C/min.
It indicates that the sample temperatures increases from outside to inside. With increasing HR, both $T_{\text{min}}$ and $T_{\text{max}}$ decrease while the Div and Dis both increase, which illustrates that the higher the HR is, the farther the sample’s temperature is from PDT and the more heterogeneous the temperature distribution is inside the sample. Therefore, to some extent, a lower HR is more beneficial to produce a uniform temperature field inside the sample.

Next, after the sample has been heated to 1,000°C via a HR of 7.5°C/min, we continued to simulate the process of keeping the sample at a constant temperature with five different CTPs (from 0.5 to 2.5 h). The simulated results are displayed in Table 3 and Figure 4.

It can be inferred from Table 3 that with increasing of CTP, both $T_{\text{min}}$ and $T_{\text{max}}$ increase gradually. When CTP = 1.0 h, $T_{\text{min}}$ and $T_{\text{max}}$ are, respectively, 999.72°C and 999.31°C, which are rather close to 1,000°C, as shown in Figure 4. With increasing CTP, both Div and Dis decrease, which indicates that the longer the CTP is, the more uniform the temperature distribution of sample is and the closer the sample temperature is to PDT. For the example presented in this paper, the sample temperature will absolutely meet the PDT when CTP exceeds 1.5 h, especially when CTP reaches 2 h.

Although this numerical simulation was carried out under ideal conditions that ignore the influence of temperature on the material properties as well as consider the material as isotropic, the simulation results can still reflect the thermal characteristics of the heating procedures to a certain extent.

**Sample preparation and selection**

To bring more practical engineering significance, the granites adopted in our work were excavated from a waste disposal-engineering site on Mountain Qinling, where the rock masses are subjected to high temperatures. The mineral components of this granite are shown in Table 4.

**Table 3**: Numerical calculation results of node temperatures with different CTPs.

| Constant temp. period (h) | 0.5  | 1.0  | 1.5  | 2.0  | 2.5  |
|---------------------------|------|------|------|------|------|
| $T_{\text{max}}$ (°C)     | 995.42 | 999.72 | 999.98 | 999.99 | 1,000 |
| $T_{\text{min}}$ (°C)     | 988.86 | 999.31 | 999.96 | 999.98 | 1,000 |
| Dev (%)                   | 0.656  | 0.41  | 2.5E-03 | 1.0E-03 | 0      |
| Dis (°C)                  | 1.57   | 0.097 | 0.012 | 0    | 0    |

**Table 4**: Components of Qinling granite (%).

| Plagioclase | Biotite | Quartz | Amphibole | Orthoclase | Diopside | Magnetite | Others |
|-------------|---------|--------|-----------|------------|----------|-----------|--------|
| 38          | 18      | 16     | 14        | 7          | 3        | 3         | 1      |
Samples are disc-shaped with a diameter $D = 50 \pm 1.5\, \text{mm}$ and a thickness $T = 25 \pm 1.5\, \text{mm}$, according to the stipulations of International Society for Rock Mechanics (ISRM) [25]. In order to study the influence of different CTPs on the tensile mechanical properties of granite after they have been heated up to one PT, we designed 11 temperature conditions, which were 25°C, 100°C, 200°C, 300°C, 400°C, 500°C, 600°C, 700°C, 800°C, 900°C and 1,000°C. The 25°C group is the room temperature control group. Except for 25°C group, we designed 10 CTP grades for the other 10 temperature conditions. These 10 CTP grades were 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5 and 5.0 h. According to the previous simulation, taking the test efficiency into consideration, we chose $10^\circ\text{C}/\text{min}$ to be the HR of our tests. For reducing the deviation caused by sample discreteness, we prepared three duplicate samples for each PDT and CTP. The complete test needed at least 303 Brazilian disc samples. We measured the masses and volumes of the samples to calculate their densities and used the ultrasonic detection to measure LWV. To insure that all samples were almost identical in their material properties, samples with similar densities and LWV were selected for the next mechanical experiments. Finally, the average density and LWV of Qinling granite samples used herein are 2,764 kg/m$^3$ and 4,450 m/s, respectively.

**Test apparatus and experimental methods**

Before heating, a RSM-SYS5N non-metallic ultrasonic detection analyzer (Figure 5(a)) was utilized to take lossless measurements of the LWV for the 303 granite samples. Then, a box-shaped furnace RX3-20-12 (Figure 5(b)) was used to heat the samples. The PDTs were set to be 100–1,000°C while the control group was at room temperature, i.e. 25°C. The HRs of all the groups were set to $10^\circ\text{C}/\text{min}$. Except for the control group, we altered the CTP from 0.5 to 5 h, of which the starting point is when the temperature had already reached the PDT, as shown in the furnace control screen. So, the CTP is actually a period of time when the inside of the furnace is kept constant at the PDT.

The Brazilian split test [26] is a generally accepted method to measure the indirect TS, which can be calculated by eq. (4).

$$TS = \frac{2P}{\pi DT}$$

where $TS$ represents the tensile strength; $P$ represents the maximum compressive load; $D$ and $T$ represent the diameter and thickness of a sample, respectively (Figure 5(b)).

![Figure 5: Schematic diagrams for the sample preparations and Brazilian splitting tests. (a) The ultrasonic detection analyzer; (b) the box-shaped furnace and its control system; (c) the electro-hydraulic servo uniaxial compression testing system; (d) the stress diagram of a Brazilian disc.](image-url)
After heating, samples were cooled to room temperature naturally inside the furnace chamber. Afterwards, we measured the density and LWV of the samples again. Next, we used an electro-hydraulic servo uniaxial compression testing system (Figure 5(c)) to carry out the Brazilian tests with a constant vertical loading rate of 5 KN/min.

**Test results and analysis**

**Effects of constant temperature period**

Variations in mean density, LWV and TS versus CTP for different PDTs are displayed in Figure 6, where CTP = 0 h corresponds to the density, LWV and TS at room temperature. In addition, for convenience of comparison, we normalized test values of CTP = 0.5–5.5 h by dividing the test value of CTP = 0 h. It can be concluded from Figure 6 that, for different PDTs, the density, LWV and TS of granite decrease with increasing CTP. However, their evolution laws are rather different.

When PDT is between 100°C and 300°C, the density–CTP curve can be divided into two stages, of which the demarcation point is located at CTP = 3.0 h (Figure 6(a) and (c)). In Stage I, the density decreases gradually with increasing CTP but tends to be steady in Stage II. Meanwhile, the LWV–CTP curve and TS–CTP curve can be divided into three stages: in Stage I (CTP = 0–1.0 h), LWV and TS decrease slowly with increasing CTP, and even increase further when PDT is 100°C; in Stage II (CTP = 1.0–3.5 h), LWV and TS decrease relatively quickly with increasing CTP; and in Stage III (CTP = 3.5–5.5 h), LWV and TS both tend to be steady.

![Figure 6: Graphs showing variations in density, LWV and TS versus CTP with different PDTs. (a) PDT = 100°C; (b) PDT = 200°C; (c) PDT = 300°C; (d) PDT = 400°C; (e) PDT = 500°C; (f) PDT = 600°C; (g) PDT = 700°C; (h) PDT = 800°C; (i) PDT = 900°C; (j) PDT = 1,000°C.](image-url)
When PT is between 400–700°C, the density–CTP curve can be divided into two stages, of which the demarcation point is located at CTP = 2.5 h (Figure 6(d)–(g)). The evolution of both Stage I and Stage II are identical to the density–CTP curve of 100–300°C. Meanwhile, the LWV–CTP curve and TS–CTP curve can be divided into two stages as well, of which the demarcation point is located at CTP = 3.0 h. Their evolution laws also decrease in Stage I but almost keep stable in Stage II.

When PDT is between 800–1,000°C, the density–CTP curve can be divided into two stages, of which the demarcation point is located at CTP = 2.0 h, while the evolution trends are rather similar to the density–CTP curves above (Figure 6(h)–(j)). Meanwhile, the LWV–CTP curve and TS–CTP curve can be divided into two stages as well, of which the demarcation point is located at CTP = 2.5 h, while the evolution laws are identical to the curves of 400–700°C.

Above all, it can be concluded that variations in density, LWV and TS are all characterized by obvious stages with increasing CTP, but hold steady when CTP reaches a single value, which is defined as constant temperature turning-point (CTT). When CTP reaches the CTT, we deem that this temperature has fully influenced the granite samples, since their density, LWV and TS tend to keep steady with further increasing CTP. According to Figure 6, when PDT = 400–700°C, CTT = 3.0 h; and when PDT = 800–1,000°C, CTT = 2.5 h. It can be found that with increasing PT, the CTT decreases gradually. One of the reasons is that it takes a longer period to heat up the sample from room temperature to a higher PT. For instance, under the experimental conditions in this paper, it takes about 1.6 h to heat up a sample from 25°C to 1,000°C, during which the thermal damage has already taken place.

Effects of high temperature

Based on the work above, we can further analyze the influence of high temperature on the tensile mechanical properties of the Qinling granite. To guarantee each temperature has fully affected the granite samples, the test results for analysis included mean CTP values of 4.0, 4.5 and 5.0. Some typical failure modes of Qinling granite under different temperature conditions are displayed in Figure 7, from which we discover that typical samples were all split out into two halves, similar to the standard splitting failure mode according to ISRM [25]. For different temperature conditions, the primary cracks of the samples all develop normal to the top and bottom of the disc, which ensures the validity of the tests.

Some typical vertical load–displacement curves are drawn in Figure 8, where the measured loads and
displacements are in the vertical direction, i.e. the y-axis in Figure 1. Figure 8(a) shows that vertical load-displacement curves under different temperature conditions are similar. There is a sudden decrease in the load immediately after the peak. Then, the load directly drops to the minimum, which reflects obvious brittle deformation. On the whole, with increasing PDT, the peak load decreases while the corresponding displacement increases. The higher PT is, the greater the damage to the granite samples is. Figure 8(b) shows a typical form of a vertical load-displacement curve of this paper. We can discover that the sample experience the stage of nonlinear compaction and the stage of linear evolution in order. Then, after the sample reaches the peak stress, it quickly loses load-bearing capacity. So there is almost no stage after the peak. Compared to representative load-displacement curve of compression tests, the softening stage (or yield stage) before the peak and the failure stage after the peak are absent in Figure 8(b).

The variation of LWV and TS versus temperature is plotted in Figure 9. With increasing PDT, both LWV and TS decrease with evident stages. With increasing PDT, in Stage I (25–200°C), LWV and TS slowly decrease; in Stage II (200–600°C), LWV and TS decrease lightly faster; in Stage III (600–800°C), the downtrend of LWV and TS is more sharper than Stage II; and in Stage IV (800–1,000°C), the downtrend of LWV and TS slows. By normalizing the longitudinal coordinates of Figure 9(a), we can obtain Figure 9(b), from which we can see the four stages of LWV and TS’s downtrend are more pronounced. In Stage I, the two curves almost overlap; however, after Stage II, the descend range of TS is larger than that of LWV.
For further analysis on whether LWV or TS is more influenced by temperature, we introduce sensitive factor analysis from economics [27]. The sensitivity coefficient of LWV and TS versus temperature can be defined as follows:

\[
Sen_{\frac{LWV}{Tem}} = \frac{\Delta LWV}{LWV} \frac{1}{\Delta Tem}\ (5)
\]

\[
Sen_{\frac{TS}{Tem}} = \frac{\Delta TS}{TS} \frac{1}{\Delta Tem}\ (6)
\]

where \(Sen_{\frac{X}{Tem}}\) represents the sensitivity coefficient for LWV or TS versus temperature (\(X\) might be LWV or TS); \(\Delta LWV, \Delta TS\) and \(\Delta Tem\) represent the variation of LWV, TS and temperature, respectively.

According to the definition of sensitivity coefficient, if \(Sen_{\frac{X}{Tem}} > 0\), it represents that this variable quantity \(X\) (LWV or TS) is positively related to temperature. Otherwise, it is negatively related. The higher the absolute value of \(Sen_{\frac{X}{Tem}}\) is, the more sensitive the variable quantity \(X\) is to temperature.

The evolution laws of \(Sen_{\frac{LWV}{Tem}}\) and \(Sen_{\frac{TS}{Tem}}\) versus temperature are drawn in Figure 10, from which it is found that both sensitive coefficients are negative, which implies temperature is negatively related to both LWV and TS, which corresponds to the analysis above. With rising temperature, the absolute values of both \(Sen_{\frac{LWV}{Tem}}\) and \(Sen_{\frac{TS}{Tem}}\) increase, which means LWV and TS are more sensitive to temperature at higher temperatures. In addition, the LWV and TS versus temperature curves show similar stages as well. With rising temperature, in Stage I (25–200°C), the sensitive coefficients decrease rather slowly; in Stage II (200–500 °C), the sensitive coefficients tend to reduce faster; in Stage III (500–700°C), the downtrend of sensitive coefficients is more sharper than Stage II; and in Stage IV (700–900°C), the downtrend of sensitive coefficients decreases. Apparently, the evolution laws of \(Sen_{\frac{LWV}{Tem}}\) and \(Sen_{\frac{TS}{Tem}}\) versus temperature are similar to that of LWV and TS versus temperature (Figure 9). Moreover, after Stage II, the absolute value of \(Sen_{\frac{TS}{Tem}}\) is larger than that of \(Sen_{\frac{LWV}{Tem}}\). In Stage III and Stage IV, the disparity between \(Sen_{\frac{LWV}{Tem}}\) and \(Sen_{\frac{TS}{Tem}}\) further expands. This demonstrates that TS is more sensitive to temperature at higher temperatures.

**Discussion**

Rock materials experience a series of physical and chemical changes after high temperature treatment. Physical changes mainly include: (1) The evaporation of free water, which produces open pores and initial micro-cracks; (2) Thermal expansion of mineral particles. Since thermal expansion coefficients of the minerals are different, during the heating procedure, a thermal stress will form, leading to breaking of the connection between
the mineral particles and development of micro-fissures, i.e. the thermal damage; (3) Other macro physical changes in the sample, such as changes in volume, mass and density. Chemical changes mainly include: (1) Dehydration of the aqueous minerals; (2) Crystal phase changes as well as thermal chemical reactions between minerals, which produces new compositions. All of the above changes result in the degradation of the mechanical properties of rock, producing decrease in mechanical parameters.

For a detailed discussion, we analyze the effect of heating based on different temperature ranges:

(1) **25–200°C**: In this stage, free water inside the granite will escape by evaporation at about 100°C, while parts of weakly bound water escape at about 150°C, leading to some micro-pores developments. However, the expansion of minerals will compensate for these pores to some extent, which makes the inner structures relatively compact. Consequently, LWV and TS both decrease slowly in this stage. Furthermore, the escape of water costs time. It is inferred that after samples have been heated up to PDT, when CTP = 0–1.0 h, only parts of free water and a little weakly bound water escaped; when CTP = 1.0–3.5 h, a significant amount of free water and weakly bound water escaped, leading to a dramatic decline of density, LWV and TS. When CTP is longer than 3.5 h, there were no more other physical changes.

(2) **200–600°C**: In this stage, strongly bound water, as well as some composition water inside the minerals, starts to escape at 200–300°C. Specifically, according to the combined firm degree of water molecule and crystal lattice structure, mineral combined water is divided into constituent water and crystal water. Constituent water starts to separate from aqueous minerals at around 450–500°C and escapes in the form of vapor. Crystal water vaporizes and escapes in less than 400°C. The loss of constituent water and crystal water can lead to damage of the mineral crystalline structure, resulting in a relatively fast decline in LWV and TS. According to Figure 6(c)–(f), the water loss and dehydration of granite are not accomplished until CTP reaches 3.0 h. After that, those parameters hardly vary. It is worth noting that quartz inside the granite experiences a phase transformation at approximately 573°C (from α phase to β phase) which makes the volume of quartz increase so that the micro-fissures would develop and extend [28]. Those micro-fissures would be partially retained if β quartz returns to α quartz when cooled to room temperature. Since quartz is a rather general mineral particle in rock, this may explain why 600°C has been considered as threshold temperature in many rock thermal mechanics studies.

(3) **600–800°C**: In this stage, many minerals would melt [29] and metallic bonds would fracture, such as Ca-O, K-O, Na-O, Al-O, Fe-O and Mg-O. For the Qinling granite, these minerals mainly refer to plagioclase (Ca-O, K-O, Na-O, Al-O), biotite (Fe-O, Mg-O) and amphibole (Ca-O). Meanwhile, the CO₂ generated from those minerals’ decomposition increases the porosity rapidly. The phase transformation of quartz which occurs at approximately 573°C [28] also contributes to the development of micro-fissures. Thus, LWV and TS start to decrease quickly. According to Figure 6(g)–(h), the decomposition reactions are not accomplished until CTP reaches 3 h.

(4) **800–1,000°C**: In this stage, quartz has a phase transformation from β phase to β-tridymite at approximately 870°C [28], which makes the volume of quartz increase by 16%, causing further development of thermal stress and micro-fissures. However, almost all physical and chemical changes completed in this stage, so the decline of LWV and TS are somewhat slower than the previous stage. According to Figure 6(h)–(i), LWV and TS tend to be steady after CTP reaches 2.5 h.

**Conclusion**

The work in this paper brings forth useful information about the tensile mechanical properties of the Qinling granite due to changes in thermal treatment, including CTP and predetermined high temperature (PDT). With the combination of numerical simulations and laboratory tests, we focus on the study of the evolution laws of granite’s tensile mechanical properties in a CTP range of 0.5–5.0 h and a PDT range of 25–1,000°C. The main conclusions can be drawn as:

(1) CTP has a significant impact on the tensile mechanical properties of granite. For different PDTs, the density, LWV and TS of granite decrease with increasing CTP. When CTP reaches the CTT, we deem that the temperature has fully affected the granite samples. For PDT = 100–300°C, 400–700°C and 800–1,000°C, CTT = 3.5 h, 3.0 h and 2.5 h in order.

(2) The variation of LWV and TS versus temperature can be divided into four stages: 25–200°C, 200–600°C, 600–800°C, 800–1,000°C. LWV and TS both decreases slowly in Stage I, get a little faster in Stage II, descend sharply in Stage III and finally tend to slow again in Stage IV.

(3) LWV and TS are negatively related to temperature, and they are more sensitive to temperature at higher PTs.
In addition, TS is more sensitive to temperature than LWV when PT gets higher.

(4) According to the analysis herein, the effects of CTP and PT on LWV are similar to that of TS. Since the measure of LWV is lossless, researchers can safely determine the appropriate CTP or CTT and predict the tensile mechanical properties of rock by LWV analysis.

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List of abbreviations/symbols

| Abbreviation | Description |
|--------------|-------------|
| CTP          | Constant temperature period |
| LWV          | Longitudinal wave velocity |
| TS           | Tensile strength |
| CTT          | Constant temperature turning-point |
| PDT          | Predetermined temperature |
| FEM          | Finite element method |
| Dev          | Deviation rate of sample’s node temperature |
| Dis          | Dispersion of sample’s node temperatures |
| ISRM         | International Society for Rock Mechanics |
| $\text{Sen}_{\text{LWV}/\text{Tem}}$ | Sensitivity coefficient for LWV versus temperature |
| $\text{Sen}_{\text{TS}/\text{Tem}}$ | Sensitivity coefficient for TS versus temperature |

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