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Effect of thermal damage on brittleness and chemical properties of sandstone

Termal hasarın kumtaşının kırılganlık ve kimyasal özellikleri üzerindeki etkisi

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Abstract

Mine fires may cause many ground collapses that threaten the safety of the underground coal mining applications due to the coal meassure rocks exposed to varying heat. This research focuses on investigating the changes in thermal damage and brittleness properties of sandstone from the Zonguldak Coal Basin at temperatures ranging from 25 to 600°C. In the determination of rock brittleness, five different approaches calculated depending on the strength parameters were considered. According to the findings of this study, statistical analysis (regression analysis) were revealed over 0.85 between rock thermal damage (Dt) and rock brittleness of sandstone. Moreover, new estimation models have also been developed that can predict the brittleness properties from the thermal damages of the thermally exposed sandstone. On the other hand the chemical composition of the rocks can be used to determine the thermal damage and thus the brittleness. In this context, a negative linear relationship was obtained between Dt and Al_2O_3, while a positive linear relationship was obtained between Na_2O and SiO_2.

Anahtar kelimeler: Mine fires, Temperature, Brittleness, Thermal damage, Sandstone

Öz

Maden yangınları, değişen ısıya maruz kalan kömür çevre kayaçlarında birçok zemin çökmesine neden olabilmekte ve bu durum yeraltı kömür madenciliği uygulamalarının güvenliğini tehdit etmektedir. Bu araştırma, oda sıcaklığından 600°C'ye kadar değişen sıcaklıklarda Zonguldak Kömür Havzası'ndan elde edilen kumtaşının termal hasar ve kırılganlık özelliklerindeki değişiklikleri incelemeye odaklanmaktadır. Kayaç kırılganlığının belirlenmesinde, dayanım parametrelerine bağlı olarak hesaplanan beş farklı yaklaşım dikkate alınmıştır. Bu çalışmanın bulgularına dayanarak, istatistiksel analiz (regresyon analizi), kaya termal hasarı (Dt) ile kumtaşının kaya kırılganlığı arasında 0,85'in üzerinde bir ilişki olduğunu ortaya koymuştur. Ayrıca, termal olarak maruz kalan kumtaşının termal hasarlarından kırılganlık özelliklerini tahmin edebilen yeni tahmin modelleri de geliştirilmiştir. Öte yandan, kayaçların kimyasal bileşimlerinin termal hasarın ve dolayısıyla kırılganlığı belirlenmesinde kullanılabileceği belirlenmiştir. Bu bağlamda, Dt ile Al_2O_3 arasında negatif doğrusal bir ilişki elde edilirken, Na_2O ile SiO_2 arasında pozitif doğrusal bir ilişki elde edilmiştir.

Keywords: Maden yangınları, Sıcaklık, Kırılganlık, Termal hasar, Kumtaşı

1 Introduction

Various engineering processes are influenced by the evolution of thermal damage in rocks, including the safe exploitation of geothermal resources, nuclear waste storage, borehole drilling, post-fire reconstruction, underground coal gasification (UCG) and spontaneous coal fires [1-3]. A wide variety of investigations have been done to physico-mechanical behaviour of rocks under the influence of temperature over the years [1-25]. Furthermore, some researchers have also investigated the changes of chemical and petrographical properties of rocks at different temperatures [26-28]. Consequently, heat treatment has a significant impact on rock properties as it induces many thermal cracks in the rock mass resulting in substantial material degradation. Continued thermal effects cause the microstructure to degrade. including thermal expansion and chemical changes [29].

There have been spontaneous fires of coal resources and coal fires that reach temperatures exceeding 800 °C [30, 31], which affect the surrounding rock. Moreover, in the gasification application of coal in situ, temperatures can reach up to 1000-2000 ºC [32, 33]. It is important to note that sandstone is one of the most important load-bearing constituents of coal measure rocks. Sandstone is not only involved as a coal environmental rock but also encountered rock type in many engineering applications such as nuclear waste disposal, UCG, geothermal resource exploitation. Considering this, the failure mechanism of the sandstone after being heated at varying temperatures needs to be investigated. Numerous researchers have conducted investigations into the effects of varying temperatures on sandstones. In these studies, the effect of the temperatures of the <400 °C type is not significant. As temperatures <400°C, the rock structure is generally compact, microcracks occur infrequently, and mineral composition remains unaffected. Specifically, at these temperatures, microcracks are sealed, resulting in an increase in mechanical properties. Mineral grains expand with an increase in temperature and fill the

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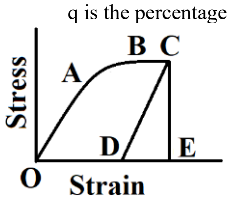
gaps [34, 35]. However, continued thermal effect causes the microstructure to degrade. Sun et al. [36] stated that sandstone develops more thermal damage and have less mechanically strength after thermal treatment. The critical value at which the effects of temperature begin to be experienced by the sandstone is between 400 and 600 °C [35 - 37]. Sirdesai et al. [29] stated that when heat treatment is applied, sandstone samples lose strength, elasticity and internal cohesion above 500 °C, indicating that increasing heat treatment results in weakening of the specimens. They also expressed the temperature of 500 °C as the critical temperature (CT) or critical temperature zone (CTZ) for sandstones. Researchers studying the effects of thermal treatment on various rock types have reported similar results in Liu and Xu [14], Lü et al. [38] and Tian et al [39]. Pathiranagei and Gratchev [40] emphasized that the decrease in the strength of the rock material cannot be ignored at temperatures exceeding 600 °C. Moreover, at 800°C, sandstone nearly loses its bearing capacity due to its decreasing mechanical strength [41, 42]. This is due to the changes in the internal structure and mineralogical properties of the rocks at high temperatures. Furthermore, Gautam et al [7] stated that temperatures ranging from 400 to 600°C result in brittle to semi-brittle behavior, whereas ductile behavior is observed at temperatures above 600°C.

In engineering practices, determination of rock brittleness, which is one of the most basic properties of rocks, is very important. There are a number of factors that influence rock brittleness, such as internal as well as external factors [43]. It has been established that general approaches and methods (Table 1) can be used to determine rock brittleness, but no universal definition of brittleness has yet been developed [44 - 46].

Additionally, the approaches proposed to determine the rock brittleness are valid for room temperature. However, heat treatment influences the rock's characteristics and causes the evolution of brittleness. Therefore, the applicability of the proposed brittleness approaches to heat-treated rocks under room temperature conditions remains unclear [58]. In this context, the variations between heat-treatment and brittleness approaches have been studied by different researchers. It has been reported by Sha et al. [58] that B11 and B12, depending on the strength parameters, are useful for determining the degree of brittleness of heat-treated sandstones and granites. Moreover, they emphasized the decrease in tensile strength caused by high temperatures is more important than that in compressive strength. Additionally, an important factor in this weakening is the transformation of quartz and feldspar minerals from brittle to ductile behavior at high temperatures, which leads to the reduction of the rock's brittleness. Moreover, Jarvie et al. [59] stated that a higher quartz and lower clay content are associated with a higher brittleness of rocks. Not only in the work of Sha et al. [58], but also in the work of Li et al. [60] in their study on sandstones revealed that B11 and B12 brittleness indices were more important than B4 and B5 to assess the thermal damage of rocks. Srinivasan et al [61] in their study on shale samples, found a strong negative correlation between brittleness indices B11 and heat

Table 1. Rock brittleness equations (Yagiz and Gokceoglu [47], Meng vd. [48]).

Eq. No	Brittleness Equation	Measurement Method (or parameters	Application areas A	B	C	Source
1	$B1 = q.\sigma c$	Protodyakonov impact test q is the percentage of fines		√		Protodyakonov [49]
2	$B2 = \frac{DE}{OE}$	 Stresses-strain curve	√			
3	$B3 = \frac{\text{AreaDCE}}{\text{AreaOABCE}}$	Stresses-strain curve	√			Hucka and Das [50]
4	$B4 = \sigma c/\sigma t$	Strength Parameters	√	√		
5	$B5 = \frac{(\sigma c - \sigma t)}{(\sigma c + \sigma t)}$	Strength Parameters	√	√		
6	$B6 = \sin(\varphi)$	Mohr's envelope, φ: Angle of internal friction			√	
7	$B7 = \varepsilon_{1i}.100, \%$	Stresses-strain curve	√			George [51]
8	$B8 = S20$	Brittleness test		√		Dahl [52]
9	$B9 = \frac{Fmax}{\rho}$	Penetration test		√		Yagız [53]
10	$B10 = \frac{P_{inc}}{P_{dec}}$	Penetration test		√		Copur et al. [54]
11	$B11 = (\sigma c.\sigma t)/2$	Stregnth Parameters		√		Altındağ [54]
12	$B12 = \sqrt{(\sigma c * \sigma t)/2}$	Stregnth Parameters		√		Altındag [55]
13	$B13 = (\sigma c * \sigma t)^{0.72}$	Stregnth Parameters		√		Yaralı and Kahraman [56]
14	$B14 = (\sigma c + \sigma t)/2$	Stregnth Parameters		√		Özfırat et al. [57]

treatment, while a weak correlation with B5 showed an uneven trend. Wang et al [62] in their paper, an improved brittleness model for geothermal reservoirs that incorporates thermal effects on crack volumetric strain calculated under different stress levels. They consider the thermal microcrack density at the crack closure stage and crack propagation because of external stresses. They emphasized that higher brittleness represents more thermal microcracks and more developed fracture networks with external loading. Another study examining the relationship between brittleness and heat treatment by considering the volumetric strain-stress curve is Xiao et al. [21] made by on sandstones. They found that quadratic function between the brittleness and temperature, according to the test results. According to them, 400°C is the critical temperature for enhancing the brittleness of sandstone and then subsequent temperatures cause sudden deterioration and instability. Moreover, at temperatures between 600-1000°C, there is a serious reduction in the brittleness of sandstone. Xu et al [1], in their research on granite samples, they stated that the brittleness, which is defined depending on the energy drop coefficient, exhibits a logistic behaviour as temperature increases.

Heat-treated rocks' thermal damage and brittleness evolution have been an important parameter in evaluating the failure characteristics, as they are crucial to fractability assessment [2]. When the temperature exceeds a critical temperature threshold, the mechanical strength of the rocks begins to degrade. For this reason, it is of great importance to investigate the effect of heat treatment during underground coal fires. Therefore, it is believed that a study on the temperature threshold will make an important contribution to understanding the thermal failure mechanism of rocks. This study aims to scientifically understand the mineralogical and mechanical processes that may occur in coal surrounding rocks in a mine fire that may occur during underground coal production or UCG process. In this context, sandstone samples collected from an underground coal mine were subjected to heat treatment at temperatures up to 600 °C. Then, the relationships between rock brittleness, thermal damage and changing temperatures are discussed. Meanwhile, a new model based on the thermal damage parameter has been proposed to characterize the brittleness of heat-treated rocks. The study also explored the brittleness behaviour of heat-treated sandstone, based on its chemical properties, specifically elemental contents, to analyze mineral transitions.

2 Materials and methods

2.1 *Experimental methodology*

In this study, 41 mm cylindrical cores were taken from suitable sandstone samples from the field and prepared for the experiment by considering the standards recommended by the International Society of Rock Mechanics (ISRM)[63]. The samples to be subjected to the experiment were divided into 7 groups according to the temperature values (25-600°C) to be applied. The sandstone samples were heat treated using a 1200 °C furnace with a temperature error of ± 5 °C. The heating rate was set at 5 °C/min and the waiting time at the target temperature was set as 2 hours, taking into account the studies in the literature on the subject [14,16] (Figure 1). Considering the ISRM [63], core samples with a length/diameter ratio of 2 and a diameter of 41 mm were tested for uniaxial compressive strength (UCS). Furthermore, elastic modulus (E) was calculated from stress-strain curves at a stress level equal to 50% of the final UCS. Meanwhile, Brazilian tensile strength (BTS) tests were conducted on 41 mm disc specimens with a height-to-diameter ratio of 0.5, as recommended by ISRM [63]. In addition, X-ray fluorescence (XRF) analysis data are presented in the Table 2 for changing temperature conditions. The petrographic analysis was performed using a polarized optical microscope, with thin sections of the sandstone shown in Fig. 2.

2.2 *Thermal damage*

In order to quantify how much damage was caused to a specimen, measurements can be made of the mechanical and physical properties depending on the amount of microcrack network present, compared to the initial values of the thermally non-treated samples [29]. Hueckel et al. [64] presented a quantitative approach (Equation 1) to measure how thermally affected of marble and granite are subjected to heat treatment.

$$D_T = 1 - \frac{E_T}{E_0} \tag{1}$$

Where D_T is the extent of damage, E_T: elastic modulus at a certain temperature and E_0 elastic modulus at room temperature (E_0).

If the elastic modulus of any sample increases with increasing temperature, thermal damage will be negative. However, this increase in elastic modulus may have occurred due to the closure of microcracks in the early stages. Therefore, thermal damage will be positive as the rock loses its elastic properties at high temperatures. So the Equation 1 that given above can be used to describe the induction of plasticity in a sample. This approach has been used by different researchers [29,61,64] in the determination of thermal damage in rocks [29].

3 Result and discussion

3.1 *Mechanical properties of rocks at varying temperatures*

The mechanical properties of sandstones were investigated by Sakız [25] in a previous study. Based on these findings, Table 3 presents the brittleness values of sandstone subjected to different temperature treatments, indicating a clear trend of decreasing mechanical strength and brittleness with increasing thermal damage.

3.2 *Evaluation of brittleness properties*

In the relevant literature, as can be seen in Table 1, there are different ways to determine the brittleness properties of rocks.

Table 2. XRF analysis results.

Temperature (°C)	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	Cl	K_2O	CaO	TiO_2	MnO	Fe_2O_3
25	1.81	2.72	19.72	62.17	0.20	0.19	0.02	3.02	1.63	0.99	0.12	7.41
100	1.85	2.71	20.09	62.45	0.21	0.06	0.01	3.07	1.58	0.99	0.09	6.87
200	1.82	2.85	20.53	61.47	0.21	0.10	0.01	3.15	1.57	1.01	0.10	7.17
300	1.93	2.50	18.77	64.33	0.21	0.06	0.03	2.81	1.93	0.95	0.10	6.39
400	1.89	2.76	19.48	62.23	0.20	0.09	0.02	2.98	1.79	0.89	0.11	7.56
500	1.86	2.73	19.20	62.48	0.22	0.09	0.01	2.92	2.11	0.94	0.12	7.32
600	2.00	2.61	18.37	64.85	0.20	0.08	0.01	2.69	1.71	0.84	0.10	6.54

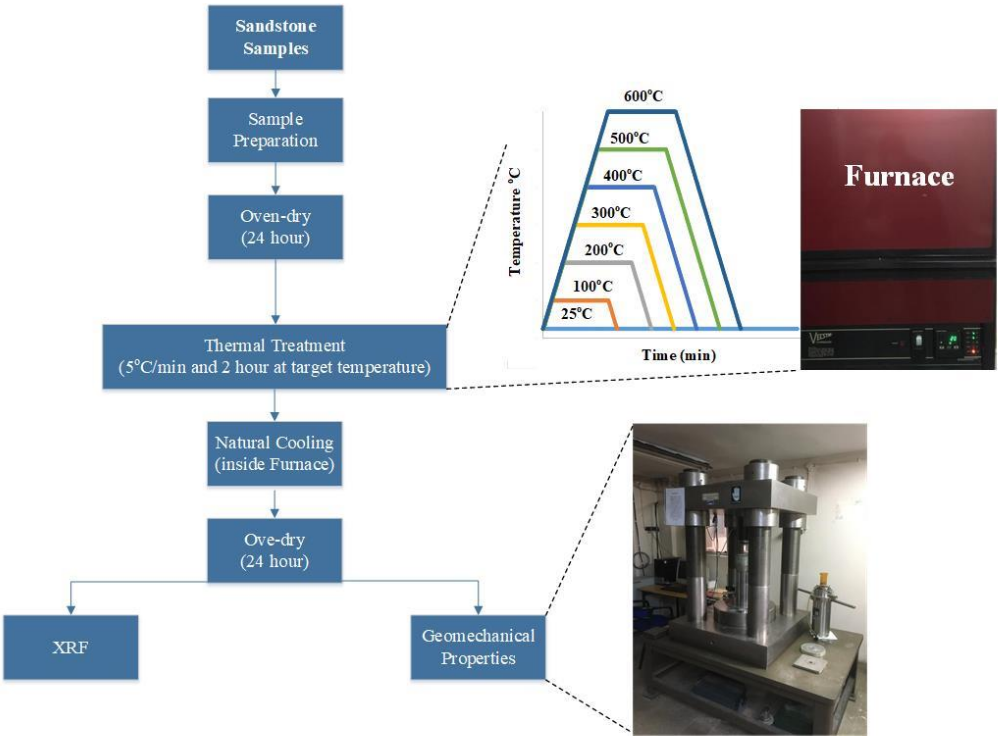


Figure 1. Thermal treatment procedure and experiments.

In this study, based on empirical relationships, brittleness properties of sandstone are determined based on strength parameters (compressive and tensile strength). In this context, five common brittleness (B4, B5, B11, B13 and B14) approaches proposed by the researchers are considered. Figure 3 shows the behavior of different brittleness approaches under varying temperature conditions. The results reveal that the B4 and B5 brittleness indices show a fluctuating variation and gradually increase at temperatures above 400 °C. However, other brittleness indices (B11, B13 and B14) tend to decrease significantly at heat treatment especially exceeds 500 °C. As the treatment temperature increases, the rock transitions from brittle to ductile behavior; this phenomenon has been emphasized by previous research [8, 14, 65, 66]. As the temperature exceeds 500°C, the increase in thermal stresses leads to the formation of additional microcracks, along with mineral expansion and desorption, which facilitates the transition from brittle to ductile behavior. Sakız [25], in his previous work, revealed that the geotechnical properties of sandstones drop sharply above 500 °C, which is the critical temperature of sandstones. Sha et al. [58], studied sandstone samples, stated that the heat treatment temperature value is 400 °C and the brittleness values showed a fluctuating change at temperatures below this value. However, as seen in the results obtained from this study and Li et al [60] study, the main downward trend for brittleness values develops after 500 °C. There is no doubt that rock brittleness is reduced by high temperatures. Therefore, the results of this study indicate that B4 and B5 brittleness indices cannot accurately describe changes of sandstone brittleness with varying heat treatment. On the other hand, this study shows that the other brittleness indices (B11, B13 and B14) provide better estimates of brittleness than B4 and B5 under varying heat treatment conditions. Similar results are seen in the study by Srinivasan et al [61] on shale samples The results obtained from the analyzes showed that the brittleness properties of the sandstone decreased with increasing temperature.

Table 3. Thermal and mehcanical properties of sandstone samples.

Temperature (ºC)	UCS (MPa)	BTS (MPa)	E (GPa)	D_T	B4	B5	B11	B13	B14
25	140.2	14.31	40.16	0.00	9.80	0.81	1003	145	77
100	137.18	13.59	38.62	0.04	10.09	0.82	932	137	75
200	128.14	13.19	38.21	0.05	9.71	0.81	845	128	71
300	124.62	14.13	-	-	8.82	0.80	880	132	69
400	122.11	14.18	35.57	0.11	8.61	0.79	866	130	68
500	122.86	12.64	27.34	0.32	9.72	0.81	776	120	68
600	90.7	10.01	19.96	0.50	9.06	0.80	454	82	50

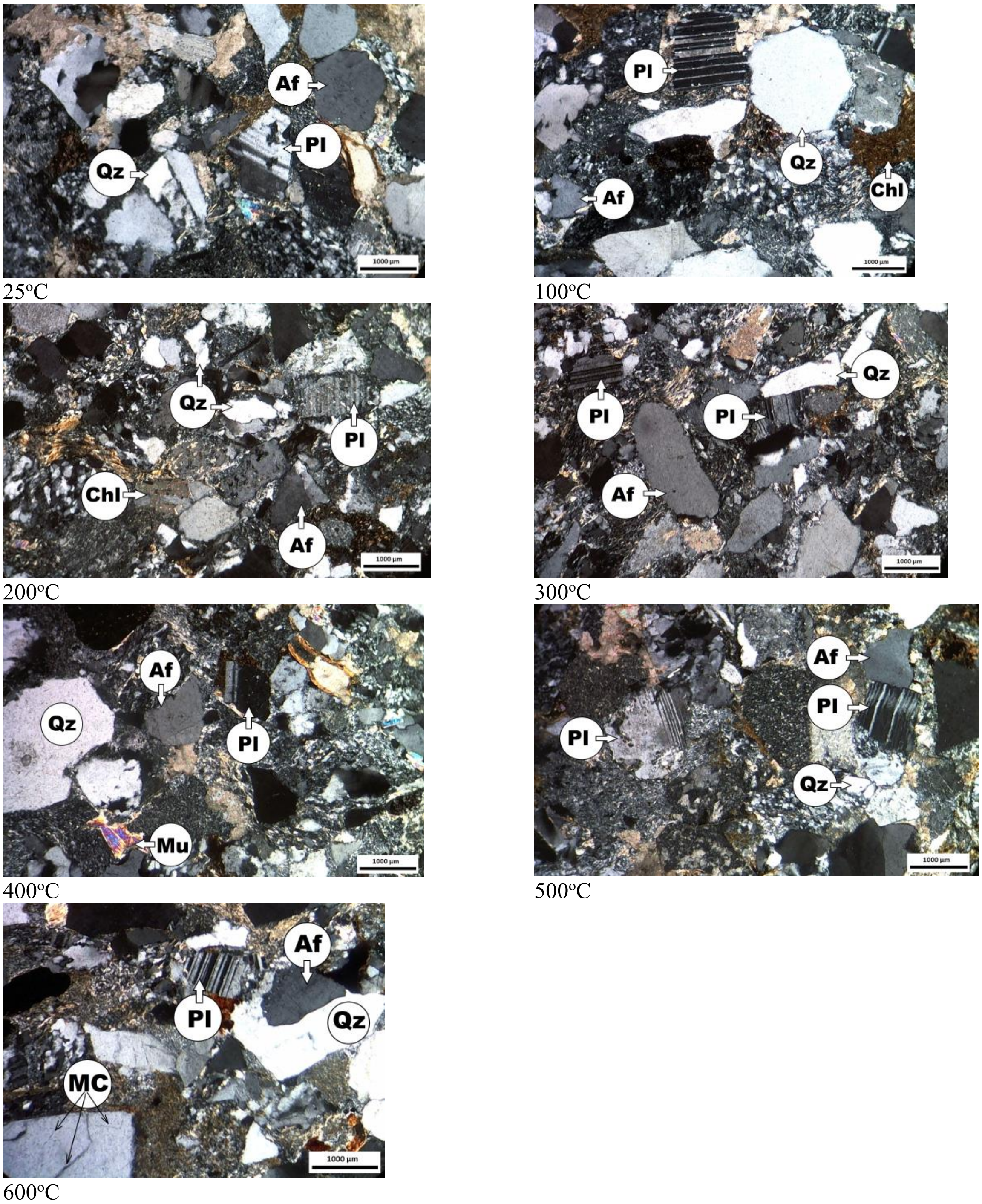


Figure 2. Thin section of sandstones at varying temperatures. Qz: Quartz, Af: Alkaline feldspar, Pl: Plajiyoklaz, Chl: Klorit, Mu: Muscovite, Mc: Micro cracks

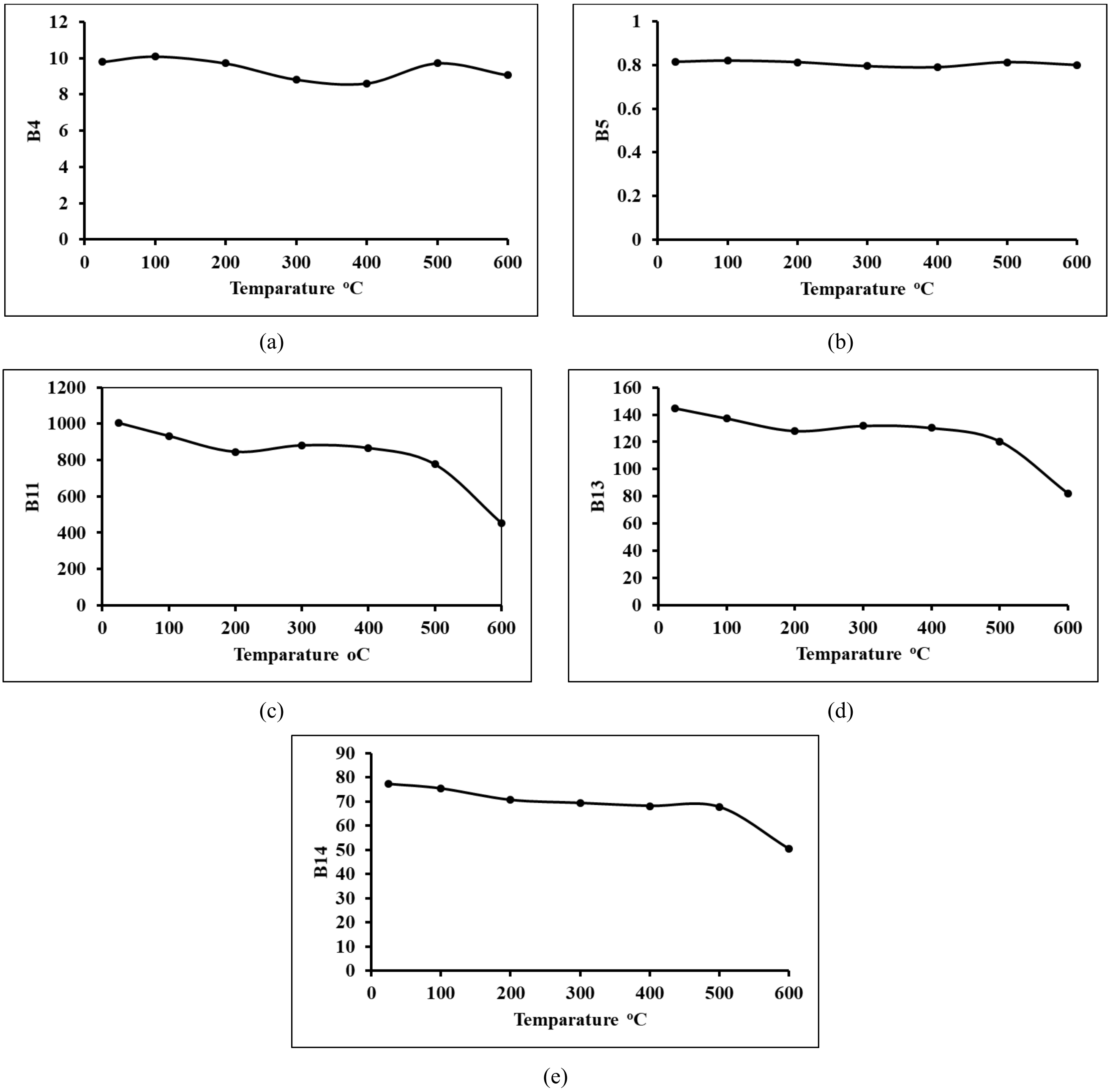


Figure 3. Effect of heat treatment on the Brittleness indices on the investigated Zonguldak sandstone.

In this context, a new models based on the estimation of thermal damage related to the brittleness indices calculated according to the strength parameters of the sandstone sample has been proposed. Previous studies [7, 29, 61, 64, 67] on the estimation of thermal damage have used the modulus of elasticity to express the damage of rock material. As seen in Figure 3, as the temperature rises, the brittleness of the sandstone samples exhibits a declining trend. The thermal damage values show that higher temperatures result in more pronounced thermal damage in the samples (Figure 4a). Regression analysis between brittleness and thermal damage are given in Figure 4b-d. The obtained results showed that there are negative linear relationship between thermal damage and brittleness indices. Moreover, statistically significant results were obtained with a regression coefficient of over 0.85.

The brittleness behavior of rocks is directly related to their mineral composition. Especially, quartz and feldspar minerals, which constitute the main mineral composition in the sandstones, are brittle minerals. The reason for the high brittleness is related to the high brittle mineral content of the rock. In particular, quartz and feldspar minerals can undergo alteration at temperatures above 500°C [12, 19, 68]. In this context, the effect of heat treatment on the brittleness of minerals is very significant.

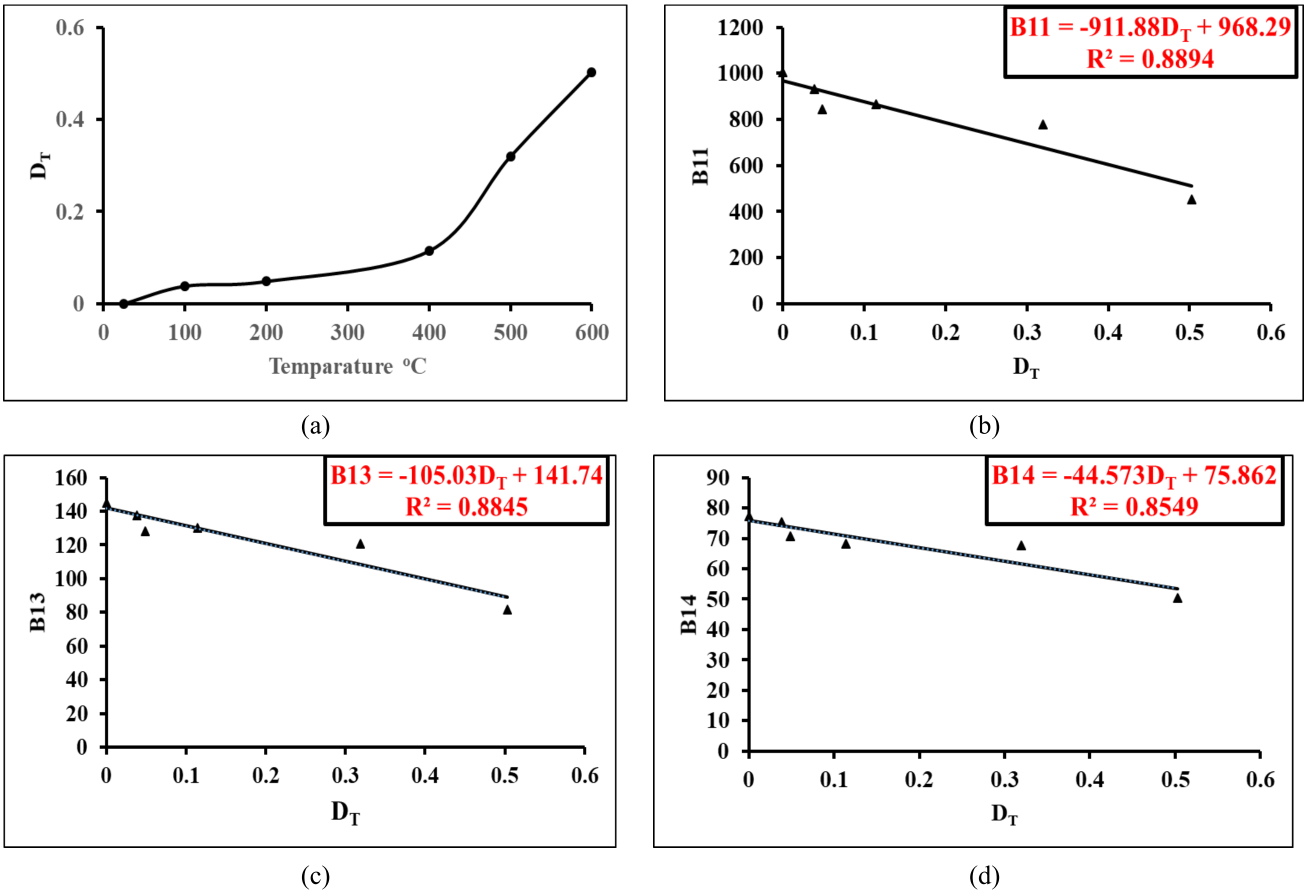


Figure 4. Relations betweeen the thermal damage and Brittleness indices of Zonguldak sandstone samples.

Sakız [25] revealed that the critical temperature value for the examined sandstone is determined as 500°C. Therefore, above this temperature, the brittleness of sandstone decreases mainly due to mineral expansion and decomposition. As the heat treatment temperature reaches the critical threshold, brittle minerals begin to transition to ductility, leading to a decrease in the brittleness of the heat-treated rocks. In addition to mineralogical properties, the chemical composition of the rocks can be used to determine the thermal damage and, thus, the brittleness (Figure 5).

Zhang et al. [43] emphasized that mineral composition plays a crucial role in determining the brittleness of rocks. The mineral composition of rocks is also related to their chemical composition and thus directly affects the brittleness of the rocks. Bilen [69] proposed a new approach to estimate the brittleness properties of basaltic rocks using major oxide element components. Therefore, in this study, the effect of chemical properties changing with increasing temperature on thermal damage of rocks has been considered. As shown in Figure 5, chemical properties have significant relations with calculated thermal damage. In this context, a negative linear relationship was obtained between Dt and Al_2O_3, while a positive linear relationship was obtained between Na_2O and SiO_2.

In this study, physical and chemical changes developed in sandstone samples exposed to varying temperatures. Wu et al. [70] stated that when the temperature is < 300 °C, the bound and attached water evaporates and this is one of the physical reasons. The authors also emphasized that the phase transition of minerals and changes in mineral composition occur at T > 300 °C conditions. According to them, especially at temperatures between 300 and 500 °C, cracks form in the rock, where the mineral structure deteriorates as a result of the crystalline water escaping and the breakdown of H+ and OH-. Sirdesai et al. [19] stated that when the temperature exceeds 500°C, the phase transition of quartz, along with the decomposition of feldspar and clay minerals, may take place, potentially leading to the formation of numerous cracks. In this study, no significant changes such as any visible cracks were observed for the Sandstone sample studied up to 400 °C. After 400°C, changes began to occur in the color, mechanical and brittleness properties of sandstone. Significant changes in rock properties such as mechanical properties and brittleness of the sandstone were observed, especially when the temperature exceeded 500 °C.

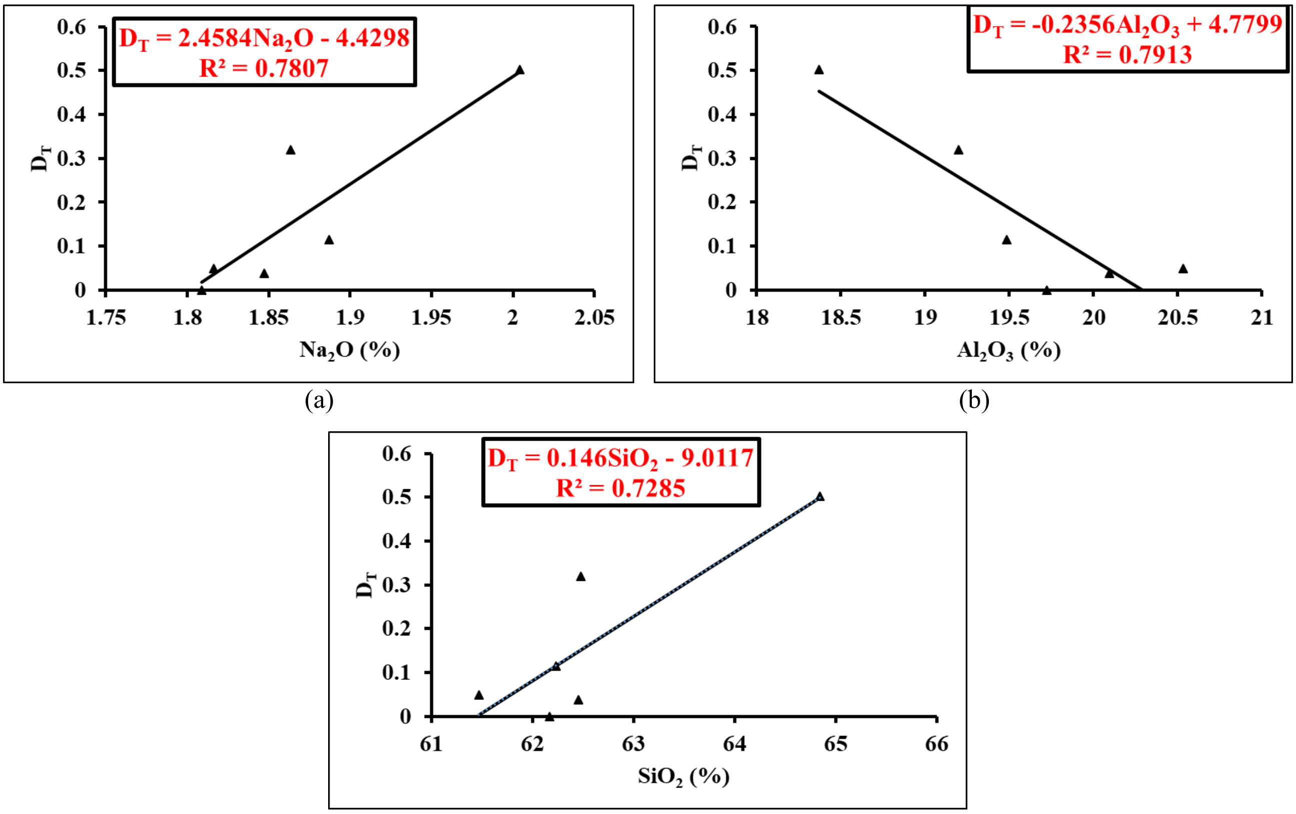


Figure 5. Relations betweeen the thermal damage and chemical composition of samples.

4 Conclusion

This study aims to examine the impact of heat treatment on the brittleness characteristics of sandstone within the temperature range of 25 to 600 °C. The obtained results are summarized below:

1- In sandstone samples, mineral expansion and chemical reactions take place at high temperatures. Especially when 500°C is exceeded, the physical and chemical reactions occurring in the minerals of the sandstone cause a decrease in brittleness.
2- Although five brittleness indices (B4, B5, B11, B13 and B14) are calculated from rock strength (compressive and tensile) properties in this study, only B11, B13 and B14 indices are determined to more effectively characterize brittleness of sandstone at varying temperatures. Especially B4 and B5 show an uneven trend, while the B11, B13 and B14 indices tend to decrease with increasing temperature.
3- Beyond 400 °C, thermal damage increases exponentially. On the other hand, there is a negative relationship between Dt values and rock brittleness. With a significant decrease in rock brittleness as Dt values increase. Additionally, statistically significant (R^2 >0.85) results were obtained.
4- Chemical properties have significant relations with calculated thermal damage. In this context, a negative linear relationship was obtained between D_t and Al_2O_3, while a positive linear relationship was obtained between Na_2O and SiO_2.

The findings of this study could be valuable for the thermal identification of rock properties relevant to future applications, such as mine fires and potentially UCG in coal basins.

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Conflict of interest

The author declares that there are no conflicts of interest

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Kaynaklar

[1] X. Xu, C. Yue, L. Xu, Thermal damage constitutive model and brittleness index based on energy dissipation for deep Rock, Mathematics. 10, 1–16, 2022. https://doi.org/10.3390/math10030410.

[2] T. Yin, J. Ma, Y. Wu, D.D. Zhuang, Z. Yang, Effect of high temperature on the brittleness index of granite: an experimental investigation, Bulletin of Engineering Geology and the Environment. 81, 2022. https://doi.org/10.1007/s10064-022-02953-z.

[3] S. Ge, B. Shi, S. Zhang, X. Zhai, C. Wu, Thermal damage and mechanical properties of high temperature

sandstone with cyclic heating–cooling treatment, Bulletin of Engineering Geology and the Environment. 81, 2022. https://doi.org/10.1007/s10064-022-02781-1.

[4] S. Chaki, M. Takarli, W.P. Agbodjan, Influence of thermal damage on physical properties of a granite rock: Porosity, permeability and ultrasonic wave evolutions, Construction and Building Materials. 22, 1456–1461,2008. https://doi.org/10.1016/j.conbuildmat.2007. 04.002.

[5] S. Chen, C. Yang, G. Wang, Evolution of thermal damage and permeability of Beishan granite, Applied Thermal Engineering. 110, 1533–1542, 2017. https://doi.org/10.1016/j.applthermaleng.2016.09.075.

[6] B. Dehghani, V. Amirkiyaei, R. Ebrahimi, H. Ahmadi, D. Mohammadzamani, S.B. Zavareh, Thermal loading effect on P-wave form and power spectral density in crystalline and non-crystalline rocks, Arabian Journal of Geosciences. 13, 2020. https://doi.org/10.1007/s12517-020-05779-9.

[7] P.K. Gautam, M.K. Jha, A.K. Verma, T.N. Singh, Evolution of absorption energy per unit thickness of damaged sandstone, Journal of Thermal Analysis and Calorimetry. 136, 2305–2318, 2019. https://doi.org/10.1007/s10973-018-7884-5.

[8] W.S. González-Gómez, P. Quintana, A. May-Pat, F. Avilés, J. May-Crespo, J.J. Alvarado-Gil, Thermal effects on the physical properties of limestones from the Yucatan Peninsula, International Journal of Rock Mechanics and Mining Sciences. 75, 182–189, 2015. https://doi.org/10.1016/j.ijrmms.2014.12.010.

[9] J. Hao, L. Qiao, Z. Liu, Q. Li, Effect of thermal treatment on physical and mechanical properties of sandstone for thermal energy storage: a comprehensive experimental study, Acta Geotechnica. 8, 2022. https://doi.org/10.1007/s11440-022-01514-8.

[10] S. Huang, K. Xia, Effect of heat-treatment on the dynamic compressive strength of Longyou sandstone, Engineering Geology. 191, 1–7, 2015. https://doi.org/10.1016/j.enggeo.2015.03.007.

[11] F. Kang, T. Jia, Y. Li, J. Deng, C. Tang, X. Huang, Experimental study on the physical and mechanical variations of hot granite under different cooling treatments, Renewable Energy. 179, 1316–1328, 2021. https://doi.org/10.1016/j.renene.2021.07.132.

[12] M. Keppert, J. Fořt, A. Trník, D. Koňáková, E. Vejmelková, J. Pokorný, P. Svora, Z. Pavlík, R. Černý, Behavior of Sandstones Under Heat Treatment, International Journal of Thermophysics. 38, 2017. https://doi.org/10.1007/s10765-017-2191-0.

[13] W.G. Liang, S.G. Xu, Y.S. Zhao, Experimental study of temperature effects on physical and mechanical characteristics of salt rock, Rock Mechanics and Rock Engineering. 39, 469–482, 2006. https://doi.org/10.1007/s00603-005-0067-2.

[14] S. Liu, J. Xu, An experimental study on the physico-mechanical properties of two post-high-temperature rocks, Engineering Geology. 185, 63–70, 2015. https://doi.org/10.1016/j.enggeo.2014.11.013.

[15] M. Li, X. Liu, Effect of Thermal Treatment on the Physical and Mechanical Properties of Sandstone: Insights from Experiments and Simulations, Rock Mechanics and Rock Engineering. 2022. https://doi.org/10.1007/s00603-022-02791-1.

[16] X. Liu, W. Lu, M. Li, N. Zeng, T. Li, The thermal effect on the physical properties and corresponding permeability evolution of the heat-treated sandstones, Geofluids. 2020. https://doi.org/10.1155/2020/8838325.

[17] A. Ozguven, Y. Ozcelik, Effects of high temperature on physico-mechanical properties of Turkish natural building stones, Engineering Geology. 183, 127–136, 2014. https://doi.org/10.1016/j.enggeo.2014.10.006.

[18] N. Sengun, Influence of thermal damage on the physical and mechanical properties of carbonate rocks, Arabian Journal of Geosciences. 7, 5543–5551, 2014. https://doi.org/10.1007/s12517-013-1177-x.

[19] N.N. Sirdesai, T.N. Singh, P.G. Ranjith, Thermal alterations in the poro-mechanical characteristic of an Indian sandstone – A comparative study, Engineering Geology. 226, 208–220, 2017. https://doi.org/10.1016/j.enggeo.2017.06.010.

[20] Q. Sun, C. Lü, L. Cao, W. Li, J. Geng, W. Zhang, Thermal properties of sandstone after treatment at high temperature, 2016. https://doi.org/10.1016/j.ijrmms.2016.03.006.

[21] W. Xiao, D. Zhang, H. Yang, B. Yu, S. Li, Evaluation and analysis of sandstone brittleness under the influence of temperature, Geomechanics and Geophysics for Geo-Energy and Geo-Resources. 8, 1–19, 2022. https://doi.org/10.1007/s40948-021-00324-8.

[22] S.Q. Yang, P.G. Ranjith, H.W. Jing, W.L. Tian, Y. Ju, An experimental investigation on thermal damage and failure mechanical behavior of granite after exposure to different high temperature treatments, Geothermics. 65, 180–197,2017. https://doi.org/10.1016/j.geothermics.2016.09.008.

[23] H. Yavuz, S. Demirdag, S. Caran, Thermal effect on the physical properties of carbonate rocks, International Journal of Rock Mechanics and Mining Sciences. 47, 94–103, 2010. https://doi.org/10.1016/j.ijrmms.2009.09.014.

[24] H. Ersoy, H. Kolaylı, M. Karahan, H. Harputlu Karahan, M.O. Sünnetci, Effect of thermal damage on mineralogical and strength properties of basic volcanic rocks exposed to high temperatures, Bulletin of Engineering Geology and the Environment. 78, 1515–1525, 2019. https://doi.org/10.1007/s10064-017-1208-z.

[25] U. Sakız, Invesitgation of the thermo physico - mechanical and drilling characteristics of sandstone in Zonguldak hard coal basin, Geomechanics and Geophysics for Geo-Energy and Geo-Resources. 5 2023. https://doi.org/10.1007/s40948-023-00682-5.

[26] H. Somerton, W, Thermal Properties and Temperature-Related Behavior of Rock/ Fluid Systems., 1992.

[27] M. Hajpál, Changes in sandstones of historical monuments exposed to fire or high temperature, Fire Technology. 38, 373–382, 2002. https://doi.org/10.10

23/A:1020174500861.
[28] N.I. Den'gina, V.N. Kazak, V. V. Pristash, Changes in rocks at high temperatures, Journal of Mining Science. 29, 472–477, 1993. https://doi.org/10.1007/BF00733026.
[29] N.N. Sirdesai, A. Singh, L.K. Sharma, R. Singh, T.N. Singh, Determination of thermal damage in rock specimen using intelligent techniques, Engineering Geology. 239, 179–194, 2018. https://doi.org/10.1016/j.enggeo.2018.03.027.
[30] B. Shi, H. Su, J. Li, H. Qi, F. Zhou, J.L. Torero, Z. Chen, Clean power generation from the intractable natural coalfield fires: Turn harm into benefit, Scientific Reports. 7, 1–5, 2017. https://doi.org/10.1038/s41598-017-05622-4.
[31] J. Deng, F. Zhou, B. Shi, J.L. Torero, H. Qi, P. Liu, S. Ge, Z. Wang, C. Chen, Waste heat recovery, utilization and evaluation of coalfield fire applying heat pipe combined thermoelectric generator in Xinjiang, China, Energy. 207, 2020. https://doi.org/10.1016/j.energy.2020.118303.
[32] N.N. Sirdesai, R. Singh, T.N. Singh, P.G. Ranjith, Numerical and experimental study of strata behavior and land subsidence in an underground coal gasification project, Proceedings of the International Association of Hydrological Sciences. 372, 455–462, 2015. https://doi.org/10.5194/piahs-372-455-2015.
[33] X. Liu, G. Guo, H. Li, Study on the propagation law of temperature field in surrounding rock of underground coal gasification (UCG) combustion cavity based on dynamic thermal parameters, Results in Physics. 12, 1956–1963, 2019. https://doi.org/10.1016/j.rinp.2019.02.006.
[34] X. Wu, Z. Huang, H. Song, S. Zhang, Z. Cheng, R. Li, H. Wen, P. Huang, X. Dai, Variations of Physical and Mechanical Properties of Heated Granite After Rapid Cooling with Liquid Nitrogen, Rock Mechanics and Rock Engineering. 52, 2123–2139, 2019. https://doi.org/10.1007/s00603-018-1727-3.
[35] Y.J. Shen, Y.L. Zhang, F. Gao, G.S. Yang, X.P. Lai, Influence of temperature on the microstructure deterioration of sandstone, Energies. 11, 1–17, 2018. https://doi.org/10.3390/en11071753.
[36] Q. Sun, J. Geng, F. Zhao, Experiment study of physical and mechanical properties of sandstone after variable thermal cycles, Bulletin of Engineering Geology and the Environment. 79, 3771–3784, 2020. https://doi.org/10.1007/s10064-020-01779-x.
[37] B. Mahanta, P.G. Ranjith, V. Vishal, T.N. Singh, Temperature-induced deformational responses and microstructural alteration of sandstone, Journal of Petroleum Science and Engineering. 192, 107239, 2020. https://doi.org/10.1016/j.petrol.2020.107239.
[38] C. Lü, Q. Sun, W. Zhang, J. Geng, Y. Qi, L. Lu, The effect of high temperature on tensile strength of sandstone, Applied Thermal Engineering. 111, 573–579, 2017. https://doi.org/10.1016/j.applthermaleng.2016.09.151.
[39] H. Tian, T. Kempka, S. Yu, M. Ziegler, Mechanical Properties of Sandstones Exposed to High Temperature, Rock Mechanics and Rock Engineering. 49, 321–327, 2016. https://doi.org/10.1007/s00603-015-0724-z.
[40] S. Vidana Pathiranagei, I. Gratchev, Engineering properties of sandstone heated to a range of high temperatures, Bulletin of Engineering Geology and the Environment. 80, 2415–2432, 2021. https://doi.org/10.1007/s10064-020-02065-6.
[41] M. Li, D. Wang, Z. Shao, Experimental study on changes of pore structure and mechanical properties of sandstone after high-temperature treatment using nuclear magnetic resonance, Engineering Geology. 275, 105739,2020. https://doi.org/10.1016/j.enggeo.2020.105739.
[42] B. Kong, E. Wang, Z. Li, X. Wang, X. Liu, N. Li, Y. Yang, Electromagnetic radiation characteristics and mechanical properties of deformed and fractured sandstone after high temperature treatment, Engineering Geology. 209, 82–92, 2016. https://doi.org/10.1016/j.enggeo.2016.05.009.
[43] Y. Zhang, X.T. Feng, C. Yang, Q. Han, Z. Wang, R. Kong, Evaluation Method of Rock Brittleness under True Triaxial Stress States Based on Pre-peak Deformation Characteristic and Post-peak Energy Evolution, Rock Mechanics and Rock Engineering. 54, 1277–1291, 2021. https://doi.org/10.1007/s00603-020-02330-w.
[44] S. Yagiz, J. Rostami, Indentation test for the measurement of rock brittleness, 46th US Rock Mechanics / Geomechanics Symposium 2012. 1, 511–516, 2012.
[45] Y. Xia, H. Zhou, C. Zhang, S. He, Y. Gao, P. Wang, The evaluation of rock brittleness and its application : a review study, European Journal of Environmental and Civil Engineering. 1–41, 2019. https://doi.org/10.1080/19648189.2019.1655485.
[46] U. Sakız, Predicting the brittleness of sandstones from the Leeb hardness test, Petroleum Science and Technology. 42 (11), 1360-1384, 2024. https://doi.org/10.1080/10916466.2022.2143810
[47] S. Yagiz, C. Gokceoglu, Application of fuzzy inference system and nonlinear regression models for predicting rock brittleness, Expert Systems with Applications. 37, 2265–2272, 2010. https://doi.org/10.1016/j.eswa.2009.07.046.
[48] F. Meng, L.N.Y. Wong, H. Zhou, Rock brittleness indices and their applications to different fields of rock engineering: A review, Journal of Rock Mechanics and Geotechnical Engineering. 13, 221–247, 2021. https://doi.org/10.1016/j.jrmge.2020.06.008.
[49] M.M. Protodyakonov, Mechanical properties and drillability of rocks. In Proceedings of the fifth symposium rock mechanics, University of Minnesota USA. 1962.
[50] V. Hucka, B. Das, Brittleness determination of rocks by different methods, International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts. 11, 389–92, 1974.

[51] E.A. Goerge, Brittle failure ofrock material-test results and constitutive models, AA Balkema/Rotterdam/Brolkfield. 123–8, 1995.
[52] F. Dahl, DRI, BWI, CLI standards, NTNU. 20, 2003.
[53] S. Yagiz, Assessment of brittleness using rock strength and density with punch penetration test, Tunnelling and Underground Space Technology. 24, 66–74, 2009. https://doi.org/10.1016/j.tust.2008.04.002.
[54] R. Altindag, Correlation of specific energy with rock brittleness concepts on rock cutting, Journal of The South African Institute of Mining and Metallurgy. 103, 163–171, 2003.
[55] R. Altindag, Assessment of some brittleness indexes in rock-drilling efficiency, Rock Mechanics and Rock Engineering. 43, 361–370, 2010. https://doi.org/10.1007/s00603-009-0057-x.
[56] O. Yarali, S. Kahraman, The drillability assessment of rocks using the different brittleness values, Tunnelling and Underground Space Technology. 26, 406–414, 2011. https://doi.org/10.1016/j.tust.2010.11.013.
[57] M.K. Özfirat, H. Yenice, F. Şimşir, O. Yarali, A new approach to rock brittleness and its usability at prediction of drillability, Journal of African Earth Sciences. 119, 94–101, 2016. https://doi.org/10.1016/j.jafrearsci.2016.03.017.
[58] S. Sha, G. Rong, J. Tan, R. He, B. Li, Tensile strength and brittleness of sandstone and granite after high-temperature treatment: a review, Arabian Journal of Geosciences. 13, 2020. https://doi.org/10.1007/s12517-020-05647-6.
[59] D.M. Jarvie, R.J. Hill, T.E. Ruble, R.M. Pollastro, Unconventional shale-gas systems: The Mississippian Barnett Shale of north-central Texas as one model for thermogenic shale-gas assessment, American Association of Petroleum Geologists Bulletin. 91, 475–499, 2007. https://doi.org/10.1306/12190606068.
[60] X. Li, K. Peng, J. Peng, D. Hou, Effect of thermal damage on mechanical behavior of a fine-grained sandstone, Arabian Journal of Geosciences. 14, 2021. https://doi.org/10.1007/s12517-021-07607-0.
[61] V. Srinivasan, A. Tripathy, T. Gupta, T.N. Singh, An Investigation on the Influence of Thermal Damage on the Physical, Mechanical and Acoustic Behavior of Indian Gondwana Shale, Rock Mechanics and Rock Engineering. 53, 2865–2885, 2020. https://doi.org/10.1007/s00603-020-02087-2.
[62] D. Wang, F. Zhou, Y. Dong, D. Sun, B. Yu, Experimental Investigation of Thermal Effect on Fracability Index of Geothermal Reservoirs, Natural Resources Research. 30, 273–288, 2021. https://doi.org/10.1007/s11053-020-09733-0.
[63] ISRM, The complete ISRM suggested methods for rock characterization,testing and monitoring: 1974–2006, 2007.
[64] T. Hueckel, A. Peano, R. Pellegrini, A constitutive law for thermo-plastic behaviour of rocks: an analogy with clays, Surveys in Geophysics. 15, 643–671, 1994. https://doi.org/10.1007/BF00690178.
[65] H. Tian, M. Ziegler, T. Kempka, Physical and mechanical behavior of claystone exposed to temperatures up to 1000°C, International Journal of Rock Mechanics and Mining Sciences. 70, 144–153, 2014. https://doi.org/10.1016/j.ijrmms.2014.04.014.
[66] H. Tian, G. Mei, G.S. Jiang, Y. Qin, High-Temperature Influence on Mechanical Properties of Diorite, Rock Mechanics and Rock Engineering. 50, 1661–1666, 2017. https://doi.org/10.1007/s00603-017-1185-3.
[67] X. biao MAO, L. ying ZHANG, T. zhen LI, H. shun LIU, Properties of failure mode and thermal damage for limestone at high temperature, Mining Science and Technology. 19, 290–294, 2009. https://doi.org/10.1016/S1674-5264(09)60054-5.
[68] Q. Liu, Z. Qian, Z. Wu, Micro/macro physical and mechanical variation of red sandstone subjected to cyclic heating and cooling: an experimental study, Bulletin of Engineering Geology and the Environment. 78, 1485–1499, 2019. https://doi.org/10.1007/s10064-017-1196-z.
[69] C. Bilen, A new approach for the prediction of brittleness index based on chemical properties of basaltic rocks, Acta Geodynamica et Geomaterialia. 18, 285–299, 2021. https://doi.org/10.13168/agg.2021.0020.
[70] X. Wu, Z. Huang, Z. Cheng, S. Zhang, H. Song, X. Zhao, Effects of cyclic heating and LN2-cooling on the physical and mechanical properties of granite, Applied Thermal Engineering. 156, 99–110, 2019. https://doi.org/10.1016/j.applthermaleng.2019.04.046.