



Examination of the thermal and metallographic characteristics at high temperatures of natural stones (andesite) extracted from different elevations

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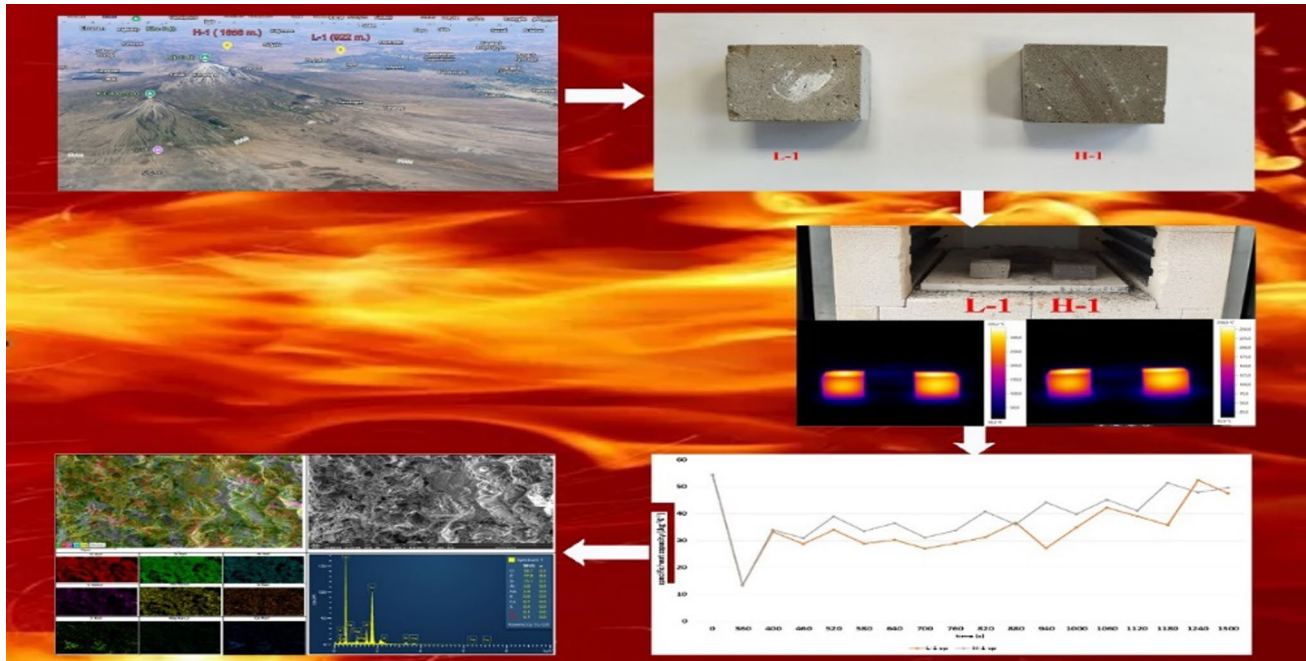
Abstract

This study examines the high-temperature thermal response of andesite stones extracted from two different elevations of Mount Ağrı (Türkiye) in order to improve material selection strategies for engineering applications. Thermal conductivity and density values of the samples were first measured under laboratory conditions. The specimens were then heated to 850 °C and cooled by natural convection while surface temperatures were recorded at fixed time intervals using a thermal camera. Based on these measurements, convective heat transfer coefficients were determined, and the time-dependent thermal diffusivity and Biot numbers were subsequently calculated using the first-term approximation of the Fourier series. Metallographic examinations were conducted to correlate the thermal behavior with microstructural characteristics. Results indicate a pronounced effect of elevation on thermal performance. The sample obtained from the higher elevation exhibited substantially greater thermal diffusivity, reaching $2.93 \times 10^{-5} \text{ m}^2 \text{ s}^{-1}$ at 360 s and decreasing to $8.96 \times 10^{-6} \text{ m}^2 \text{ s}^{-1}$ at 1300 s. In contrast, the lower-elevation andesite showed lower diffusivity values ($1.83 \times 10^{-5} \text{ m}^2 \text{ s}^{-1}$ at 360 s and $5.9 \times 10^{-6} \text{ m}^2 \text{ s}^{-1}$ at 1300 s). Conversely, Biot numbers were consistently higher for the lower-elevation sample, decreasing from 0.60 to 0.29 during the cooling process, whereas the high-elevation sample displayed values from 0.314 to 0.165. Metallographic analysis confirmed that variations in microstructure—linked to different geological formation conditions—directly influenced these thermophysical properties. Overall, the findings demonstrate that andesite sourced at higher elevations possesses superior thermal diffusivity and more favorable heat-transfer characteristics at elevated temperatures. These results highlight the importance of geological origin in the design, assessment, and selection of natural stone materials for high-temperature engineering applications.

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Graphical abstract



Keywords Energy · Time-dependent heat transfer · Natural convection · Natural stones

Abbreviations

t	Time (s)
T_0	Surface temperature ($^{\circ}\text{C}$)
T_{∞}	Ambient air temperature ($^{\circ}\text{C}$)
T_i	Initial temperature ($^{\circ}\text{C}$)
L_c	Characteristic length (m)
k	Thermal conductivity ($\text{Wm}^{-1} \text{K}^{-1}$)
ρ	Density (kgm^{-3})
cp	Specific heat ($\text{Jkg}^{-1} \text{K}^{-1}$)
β	Coefficient of volume expansion (K^{-1})
Bi	Biot number
h	Convective heat transfer coefficient ($\text{Wm}^{-2} \text{K}^{-1}$)
τ	Fourier number
Nu	Nusselt number
Gr	Grashof number
Ra	Rayleigh number
Pr	Prandtl number
α	Thermal diffusion coefficient ($\text{m}^{-2} \text{s}$)
ϑ	Kinematic viscosity ($\text{m}^{-2} \text{s}$)

Introduction

Andesite is a volcanic rock that is commonly used in the construction industry. It is preferred for use in various applications such as street surfacing, cladding, and sidewalk

blocks due to its high strength, abrasion resistance, and aesthetic appearance. Another important factor defining the areas of use of andesite is its thermal properties. Its reaction to the changes in temperature for applications in external spaces is highly important due to the long use time and the material's strength. Furthermore, it is also used in many industrial and architectural applications including industrial furnaces, foundries, and fireplaces.

Investigating the thermal characteristics, heat storage, heat transfer properties, and internal temperature gradient formation patterns of materials is important in terms of saving energy and characterizing materials [1–5]. Since natural stones have high thermal capacities, they can be used as effective heat storage materials in buildings. These stones help maintain the internal temperature in a more balanced way by slowly diffusing the heat they absorbed in the morning. Stones such as granite, marble, basalt, and andesite are particularly able to increase the thermal efficiency of buildings thanks to their thermal mass. In addition to maintaining warmth in winter and coolness in the summer, this feature also helps in both reducing heating and cooling costs and providing thermal comfort. Their long-lasting and maintenance-free nature makes natural stones a sustainable and environmentally friendly construction material. The potential of natural stones to be used for thermal comfort in buildings makes them attractive as high-value materials

commonly used in the construction industry. Natural stones are one of the world's most accessible and abundant natural resources [6]. A large portion of the quarry activities in the world are conducted in countries such as China, Italy, India, Iran, Spain, Türkiye, Brazil, Greece, and Portugal [7]. These stones are thought to contribute to the general aesthetic look of buildings whose facades, internal walls, and floors are built with stone, especially in Europe, and they are also thought to be useful in preserving cultural heritage. If the stones for construction are locally extracted, processed to a minimal extent, and used properly, they can be utilized as construction materials with low environmental impact [8, 9]. Many studies were conducted on the effects on thermal comfort of using natural stones in buildings [10–13]. Vigroux et al. identified thermal, chemical, and mechanical changes in the structure of limestone and sandstone when heated at high temperatures [14]. Uğur et al. exposed carbonate rock to thermal processing at temperatures from 100 to 500 °C and studied its effect on porosity characteristics from two different perspectives: pore shape factor and quality index. Genova and Fatta reviewed the results of thermal conductivity measurements conducted in Palermo in line with the ISO 9869 standard. Their study was conducted on a monumental structure made with chalcantinite, an essential element of historical architecture, and they aimed to collect thermal data about Palermo's architectural heritage [16]. Romero-Sánchez et al. processed natural stones with phase-change materials (PCMs) and developed innovative construction materials equipped with special heat-storing capabilities. Their study showed that natural stones processed with PCMs have a thermal energy-storing feature and can be effective in reducing the energy consumption of buildings [17]. Tufan and Kun investigated the thermal conductivity properties of different natural stone varieties in Türkiye and conducted ultraviolet thermographic analysis of marble, travertine, and andesite samples. From among those samples, they identified the most suitable stone for use in insulation in cladding [18]. Zhang and Yan utilized natural stones inside outer covering and a piping unit, thus developing a hybrid sensitive heat-storing system to increase the heat transfer of PCMs. The conducted tests revealed that stones of 25 mm in size provided an 8.3–92.6% increase in energy-storing capacity [19]. Zhang et al. investigated natural stones as a low-cost and environmentally friendly heat-storing medium and evaluated the potential of PCM to improve heat transfer. After conducting analyses on different stone types and filling heights, it was found that granite had high thermal diffusivity and provided the best heat transfer performance improvement by accelerating the melting process by 108% [20].

Elevation differences in volcanic terrains may influence cooling rate, degassing intensity, and crystallization dynamics during rock formation. Variations in cooling conditions can modify crystal size distribution, glassy phase content,

and microcrack development, thereby altering porosity and internal structural heterogeneity. These microstructural parameters directly control heat transport mechanisms in andesite by affecting phonon transfer efficiency and the continuity of solid heat conduction pathways. Previous studies have demonstrated that thermal conductivity and diffusivity in porous andesite decrease with increasing porosity due to the insulating effect of pore-filling air [21, 22]. Moreover, thermally induced microcracking significantly modifies effective heat transfer pathways [23], while mineralogical heterogeneity influences thermoelastic behavior and internal heat distribution [24, 25]. Therefore, elevation-dependent formation conditions may indirectly regulate thermal behavior through their influence on mineral composition, crack density, and pore structure. In this context, the present study evaluates how natural elevation-related differences contribute to variations in thermal conductivity, thermal diffusivity, and Biot number.

In this study, the thermal properties of andesite samples extracted from different elevations at the foot of Mount Ağrı in Türkiye were systematically investigated. Although the thermal behavior of volcanic rocks has been widely studied, the influence of elevation-dependent mineralogical and microstructural variations on time-dependent heat transfer characteristics has not been sufficiently addressed in the literature. Elevation differences may alter crystallization conditions, porosity distribution, and mineral phase composition, thereby affecting thermal conductivity, heat storage capacity, and diffusion behavior. In this context, thermal conductivity, Biot number, and thermal diffusivity were determined through time-dependent heat transfer calculations, and the results were correlated with detailed metallographic analyses. This integrated approach provides a mechanistic understanding of how microstructural variations govern heat transfer performance, offering both scientific insight and potential practical implications for the use of natural stones in thermal applications.

Materials and methods

Andesite stones are important materials commonly used in the construction and building industry due to their aesthetic appearance and durability. These stones are formed after different geological processes and may possess different properties based on the place of extraction, mineral composition, and physical characteristics. Andesite stone is a volcanic rock, and because it is highly favored as a construction material due to its durability, abrasion resistance, and aesthetic appearance, it is important to study its thermal properties in terms of thermal comfort and energy efficiency. Moreover, andesite is used in industrial and architectural applications that require high temperatures. Therefore, this

study investigated the thermal properties of andesite stone extracted from different elevations and evaluated the effect of the depth and formation conditions of the stone on these properties. Andesite's thermal conductivity, specific heat capacity, and thermal diffusion properties are the fundamental factors determining its use as a construction material. In this context, testing samples taken from different elevations and conducting a comparative analysis will contribute to the more effective use of andesite stones in terms of engineering. This study aimed to determine the thermal performance at high temperatures of andesite stones extracted from different elevations, identify their optimum areas of use, and provide scientific data about engineering criteria in choosing natural stones. The results may offer significant guidance in terms of energy efficiency in the construction industry.

Figure 1 shows the locations of andesite extracted from different elevations at the foot of Mount Ağrı.

Figure 1 shows a map view of the andesite extraction regions at the foot of Mount Ağrı in Iğdır province, located in the eastern part of Türkiye. The andesite stones extracted from the higher elevation were obtained at 1656 m above sea level, and those from the lower elevation were obtained at 922 m above sea level. Since Mount Ağrı was exposed to many volcanic activities in the past, there are abundant amounts of andesite in the vicinity.

Figure 2 shows a view of a house built with andesite stone in Iğdır province.

Andesite was used in the house shown in Fig. 2 due to its aesthetic appearance and durability. Such buildings are very popular in Europe and Türkiye.

Samples extracted from two different elevations are shown in Fig. 3. The sample extracted from the higher elevation is labeled as H-1 and the sample from the lower elevation is labeled as L-1.

Thermal conductivity and density were measured under laboratory conditions to determine the thermal properties of the samples presented in Fig. 3. Thermal conductivity measurements were performed at room temperature using a C-Therm Technologies TCi Thermal Conductivity Analyzer (Model TH89-05-00400), operating based on the modified transient plane source (MTPS) method. The instrument has a measurement range of $0\text{--}10\text{ W m}^{-1}\text{ K}^{-1}$, with a typical accuracy of $\pm 5\%$ and repeatability better than $\pm 2\%$. Prior to testing, specimen surfaces were carefully ground to obtain smooth and planar contact areas, thereby minimizing thermal contact resistance. In accordance with the manufacturer's specimen preparation requirements, samples were prepared with a minimum diameter of 25 mm and appropriate thickness. For each specimen group, three independent measurements were conducted, and the reported values represent the mean $\pm$ standard deviation. Accordingly, the thermal conductivity of the low-elevation sample (L-1) was determined as $0.302 \pm 0.023\text{ W m}^{-1}\text{ K}^{-1}$, whereas that of the high-elevation sample (H-1) was $0.577 \pm 0.050\text{ W m}^{-1}\text{ K}^{-1}$.

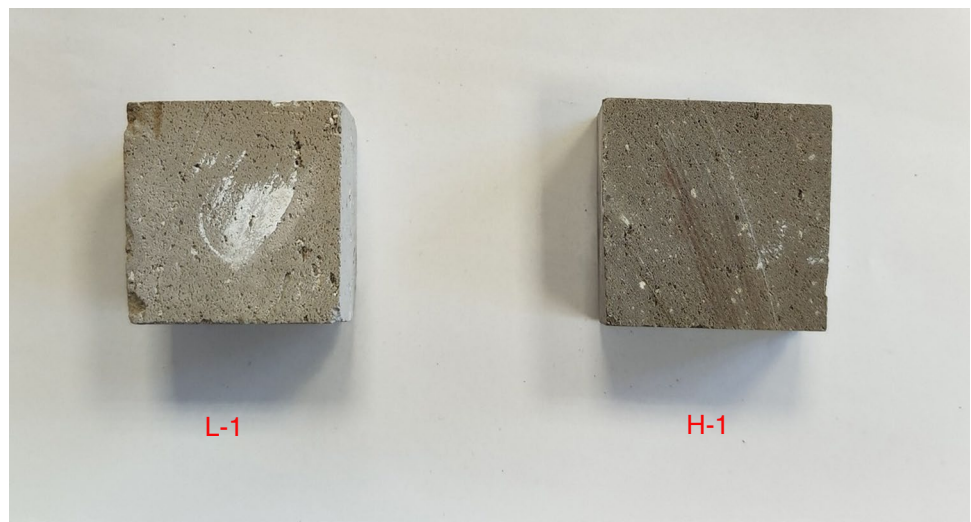


Fig. 1 Map view of locations of andesite stones extracted from different elevations

Fig. 2 House built using andesite stone in Iğdır province, Türkiye



Fig. 3 View of andesite samples extracted from different elevations (top view)



Bulk density was experimentally determined according to the Archimedes principle. The oven-dried mass of each specimen was first measured using a precision balance. The samples were subsequently vacuum-saturated in distilled water to ensure complete filling of open pores, after which the saturated mass in air and the apparent submerged mass in water were recorded. Bulk density was calculated as the ratio of dry mass to the bulk volume obtained from buoyancy measurements. All density measurements were performed in triplicate to ensure consistency and reliability.

Figure 4 shows thermal camera images taken at different intervals.

The temperatures recorded over time with the help of the thermal images shown in Fig. 4 enabled us to calculate the Biot numbers, specific heat capacities, and heat diffusion coefficients of the andesite samples and compare them.

Thermal measurements were performed using a Testo 885 thermal imaging camera (Testo SE & Co. KGaA, Germany). The device has a measurement range of -20 – 350 °C and an accuracy of ± 2 °C or $\pm 2\%$ of the measured value, with a reproducibility of ± 1 °C or $\pm 1\%$. The emissivity value was adjustable between 0.01 and 1.00 and was set according to the surface characteristics of the andesite samples. Prior to measurements, the thermal camera was calibrated using the manufacturer's internal calibration procedure, and emissivity corrections were applied manually. Reflected ambient temperature and atmospheric transmission parameters were also entered manually to minimize measurement uncertainty.

Andesite specimens were prepared in $49 \times 32 \times 53$ mm dimensions, and one specimen was analyzed for each elevation group.

The Biot number helps us to identify the size of the temperature gradients inside an object while heat is transferred

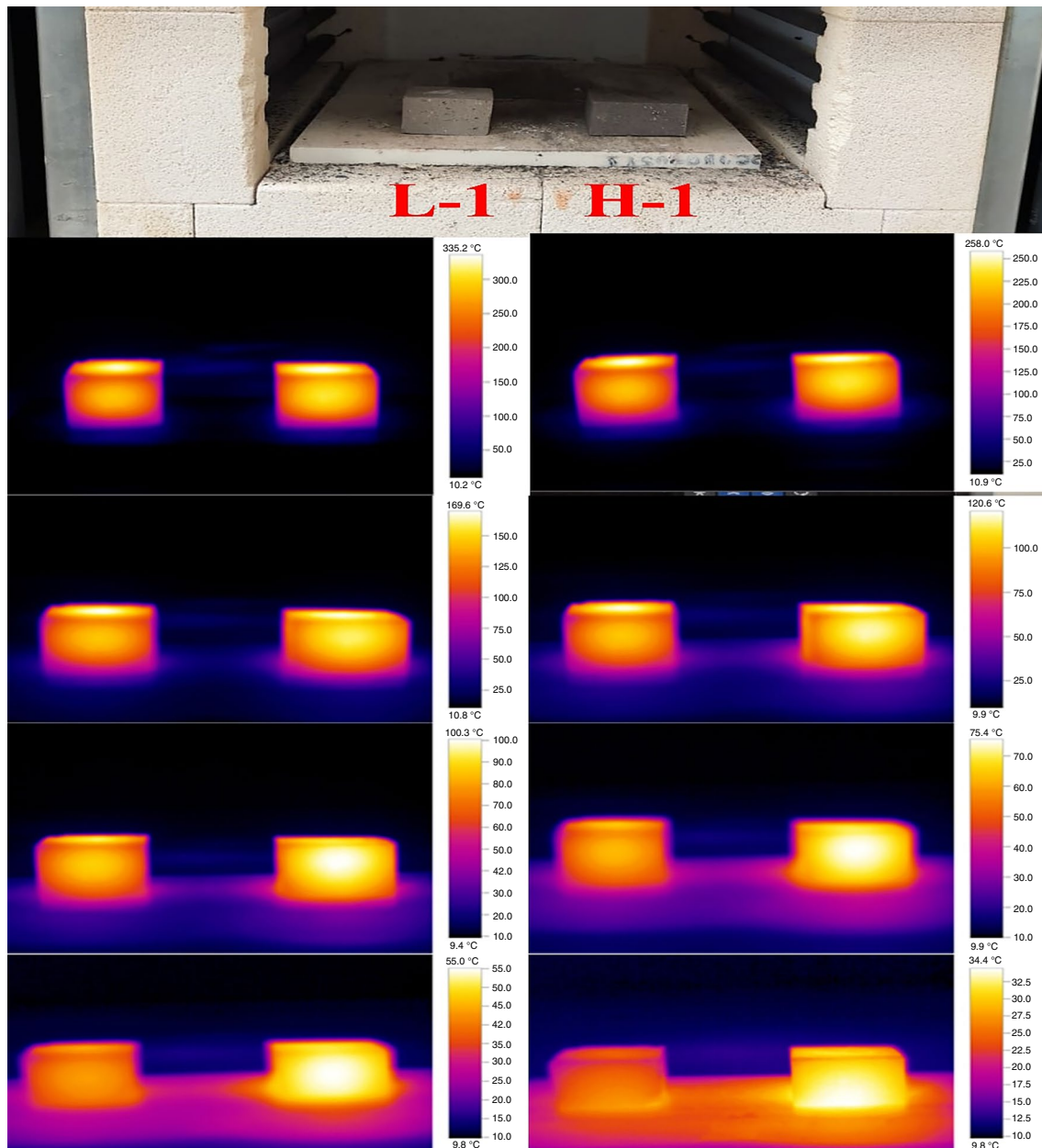


Fig. 4 Thermal images of samples H-1 (right) and L-1 (left)

from a hot object to a cooler environment. Physically, the Biot number is the ratio of heat convection to heat transfer inside a solid object. The higher the Biot number is, the larger the temperature gradient is inside an object. This helps us understand the thermal properties of the object. Equation 1 shows the formula for the Biot number [26].

$$Bi = \frac{h \times L_c}{k} \quad (1)$$

In Eq. 1, h ($\text{W m}^{-2} \text{K}^{-1}$) represents the heat convection coefficient, L_c (m) represents the characteristic length of

the samples, and k ($\text{W m}^{-1} \text{K}^{-1}$) represents the thermal conductivity. The characteristic length (L_c) was defined as half of the horizontal dimension of the specimen and was calculated as 0.0265 m. The heat convection coefficient, on the other hand, was determined by calculating the Nusselt number using the physical properties of the ambient air at different temperatures due to the natural convection between the samples and their environment. Equation 2 provides the formula for the Nusselt number in heat transfer through natural convection from vertical surfaces [26].

$$Nu = \left\{ 0.825 + \frac{0.387 \times Ra^{\frac{1}{6}}}{\left[1 + \left(\frac{0.492}{Pr} \right)^{\frac{9}{16}} \right]^{\frac{8}{27}}} \right\}^2 \quad (2)$$

Equation 2 applies to all Rayleigh numbers and is more sensitive than other possible formulas for calculating Nusselt numbers. The Prandtl number in Eq. 2 was found by interpolating from tables according to the temperature values of the air. The Rayleigh number was calculated using the formula given in Eq. 3 [26, 27].

$$Ra = Gr \times Pr \quad (3)$$

The Grashof number in Eq. 3 is important in calculating heat transfer through natural convection and it represents the ratio of buoyancy to the viscous forces. The Grashof number is calculated using the formula given in Eq. 4.

$$Gr = \frac{g \times \beta \times (T_0 - T_\infty) \times L_c^3}{\vartheta^2} \quad (4)$$

In Eq. 4, T_0 represents the samples' surface temperature, T_∞ is the ambient temperature at a point sufficiently far from the surface, g is gravity acceleration, β is the coefficient of cubical expansion, and ϑ indicates kinematic viscosity. All physical properties of air were found according to the air temperature through interpolation from tables.

After calculating the Nusselt number, the heat convection coefficient (h) for natural convection was calculated using the formula given in Eq. 5.

$$h = \frac{Nu \times k_{\text{air}}}{L_c} (\text{W m}^{-2} \text{K}^{-1}) \quad (5)$$

k_{air} in Eq. 5 represents the air's thermal conductivity.

The Fourier number (τ), thermal diffusion coefficient, and specific heat capacity were calculated using time-dependent heat transfer equations after the heat convection coefficient was calculated for different temperatures. Since the Biot number was >0.1 and the Fourier number was >0.2 in the conducted calculations, a single-term approach with a higher rate of accuracy was utilized. The single-term approach entails the first term of the Fourier series and provides an error rate below 2% in calculations [21]. Equation 6 presents a formula that applies to the Cartesian coordinate system for the single-term approach.

$$\frac{T_0 - T_\infty}{T_i - T_\infty} = A_1 \times e^{-\varepsilon_1^2 \times \tau} \quad (6)$$

In Eq. 6, T_0 represents the surface temperature of samples at any given time, T_∞ is the ambient temperature at a point sufficiently far from the surface, T_i is the initial temperature

of the samples, and A_1 and ε_1 are coefficients used in the single-term approach for time-dependent single-dimension heat conductivity based on the Biot number in the Cartesian coordinate system. These coefficients were determined by interpolation for the Biot numbers calculated for different temperatures. τ represents the Fourier number and its formula is given in Eq. 7.

$$\tau = \frac{\alpha \times t}{L_c^2} \quad (7)$$

The Fourier number, as given in Eq. 7, is dimensionless, and it represents the thermal diffusion coefficient α in the formula. The thermal diffusion coefficient is an important characteristic of a material that shows how fast heat spreads inside the material. t represents time in seconds. The formula for calculating thermal diffusion is given in Eq. 8.

$$\alpha = \frac{k}{\rho \times c_p} (\text{m}^2 \text{s}^{-1}) \quad (8)$$

In Eq. 8, k represents the samples' thermal conductivity and ρ represents their density. After the measurements, the density of sample L-1 was found to be $1240.06453 \text{ kg m}^{-3}$ and the density of sample H-1 was $1480.024 \text{ kg m}^{-3}$. c_p represents the specific heat capacity or the amount of heat stored by volume. However, when it is multiplied by density, it represents the amount of heat stored by mass. In Eq. 8, the numerator represents the material's heat transfer and the denominator represents the material's heat storage capacity.

Results and discussion

Thermal analysis

The time-dependent surface temperature graph reflecting values from the time when L-1 and H-1 were removed from the furnace after reaching 850°C to the time when they had cooled by natural convection is presented in Fig. 5.

As shown in Fig. 5, after the andesite samples reached 850°C in the furnace, they were left to cool by natural convection at an ambient air temperature of 13.6°C . As expected, the surface temperature declined rapidly at first and the slope of the temperature decrease accordingly decreased as time passed. Measurements performed with a thermal camera showed that after 1300 s, the surface temperature of sample H-1 was 37°C and that of sample L-1 was 29°C . Thus, H-1 cooled more slowly than sample L-1 did.

In the graph in Fig. 6, the samples' time-dependent heat convection coefficient is shown based on calculations using heat transfer through natural convection.

As shown in Fig. 6, the heat convection coefficient was highest at the beginning, as expected, and the difference

Fig. 5 Temperature changes of samples H-1 and L-1 over time

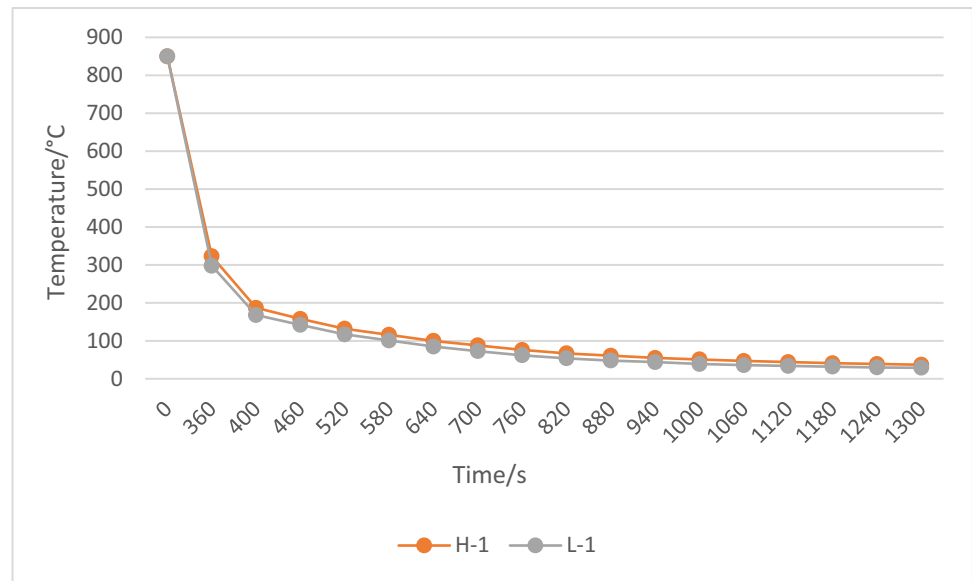
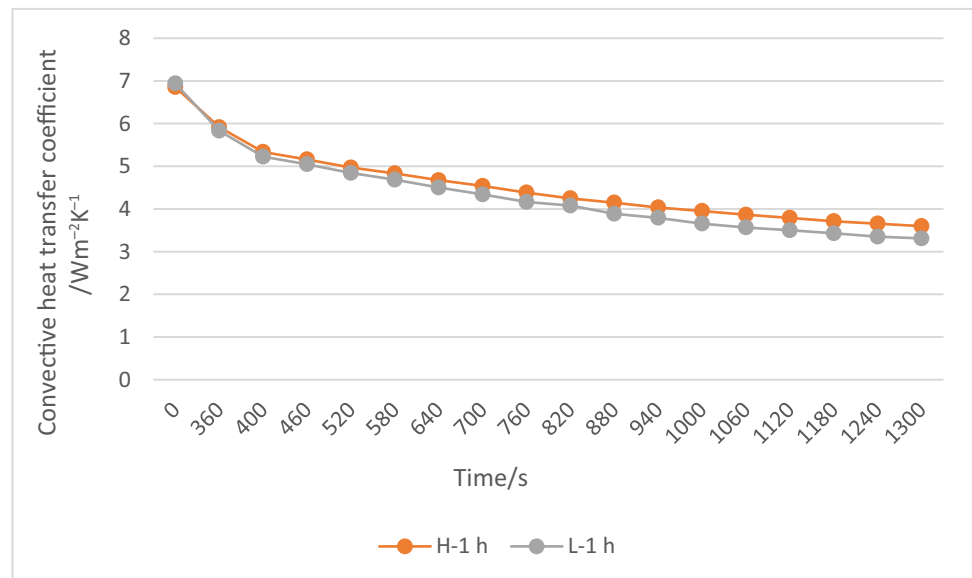


Fig. 6 Changes in the heat convection coefficients of samples H-1 and L-1 over time



between the surface temperature and ambient temperature of the samples was high, but as the temperature difference decreased over time, the heat convection coefficient decreased as well. Despite having the same initial temperature and being held in the same environment at first, the heat convection coefficient of sample H-1 increased in comparison to that of sample L-1 over time. This difference is attributed to the microstructural characteristics of the samples. Heat conducted within the solid is transferred from the surface to the surrounding air by convection; therefore, the material's structure significantly influences the convective heat transfer coefficient.

Figure 7 presents a graph of time-dependent changes in specific heat capacity, showing the heat storage characteristics of the andesite samples.

As shown in Fig. 7, the specific heat capacities of the samples were equal until the 400th second. After the 400th second, the heat storage capacity of sample H-1 was higher than that of sample L-1. The increasing divergence between H-1 and L-1 after approximately 400 s is attributed to the transition from the initial surface-dominated transient cooling stage to a regime in which internal heat conduction becomes more representative of the intrinsic material properties. As the temperature gradients within the specimens stabilize, differences in mineral composition, density, and microstructural characteristics more clearly influence the calculated specific heat capacity values.

The changes in the thermal diffusion coefficients of the samples over time are given in the graph in Fig. 8.

Fig. 7 Changes in the specific heat capacities of samples H-1 and L-1 over time

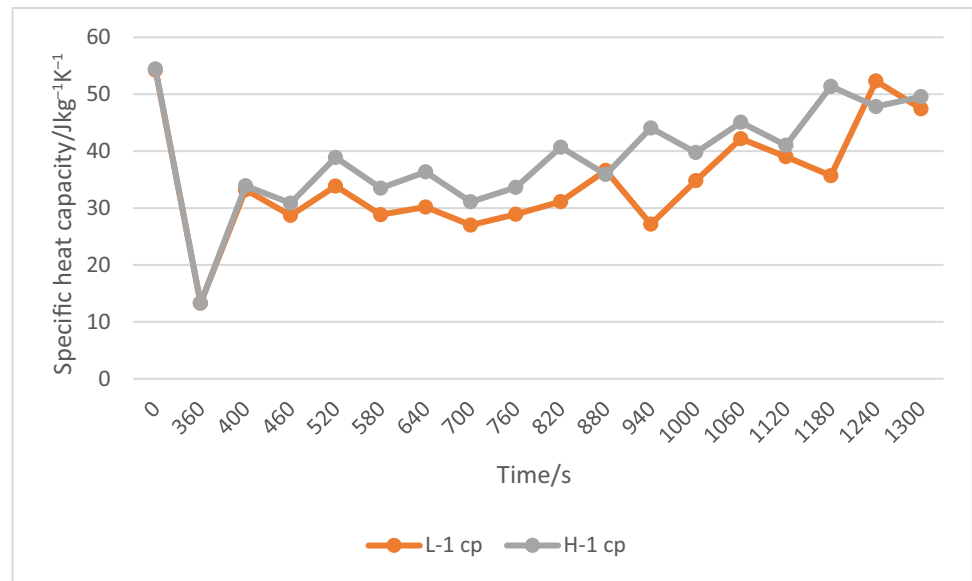
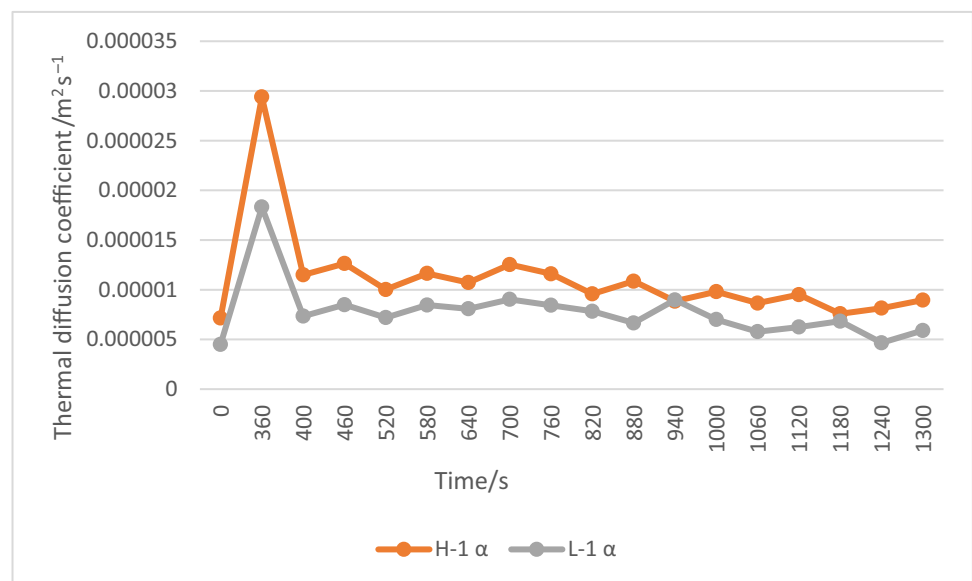


Fig. 8 Changes in the thermal diffusion coefficients of samples H-1 and L-1 over time

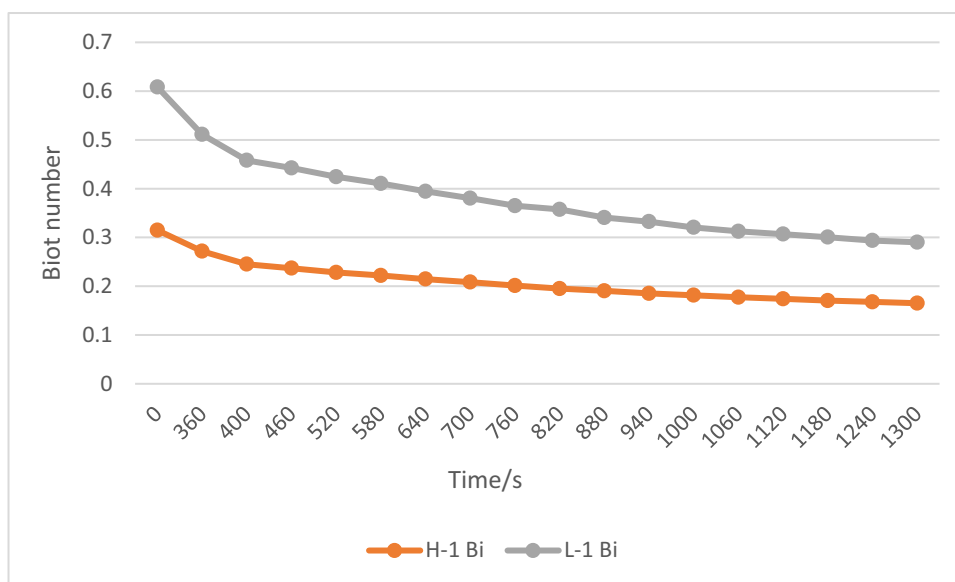


As shown in Fig. 8, in the first 360 s from the beginning of measuring the surface temperatures of the samples, the thermal diffusion coefficient rapidly increased and reached a maximum. A rapid decrease then occurred before the 400th second of the measurements. From the 400th second to the 1300th second, a slowly decreasing linear course was observed. Since the thermal diffusion coefficient physically constitutes the ratio of the amount of heat transfer of materials to the amount of heat storage, there was a very large difference between the surface temperatures of the samples and the ambient temperature in the first 360 s of the measurements. This difference in temperature helped to increase the thermal diffusion coefficient because it accelerated the heat transfer. While maximum values were obtained at the 360th second, the temperature difference

decreased slowly, and because the heat transfer decreased by the 400th second, a rapid decrease was observed in the thermal diffusion coefficient. Due to the difference in temperature, the heat storage amount did not increase at the same rate as the decrease in the heat transfer. Since the rate of the decrease in heat transfer amount reached a saturation point from the end of the 400th second until the 1300th second, an unvarying course was observed. The thermal diffusion value was small at all temperatures, revealing that the heat storage performance of the andesite stone samples was better than their heat transfer performance. These characteristics of the samples justify the use of andesite in buildings to ensure thermal comfort.

Figure 9 provides a graph of the change in the Biot numbers of the samples over time.

Fig. 9 Changes in the Biot numbers of samples H-1 and L-1 over time



The Biot number provides information about the temperature gradient forming inside materials. It is shown in Fig. 9 that, at all measurement times, the Biot number of sample L-1 was higher than that of sample H-1. This not

only indicates different temperature gradients forming inside sample L-1; it also shows that the molecular structure of sample H-1 was more regular than that of sample L-1. These findings were supported by evaluating the Biot numbers in

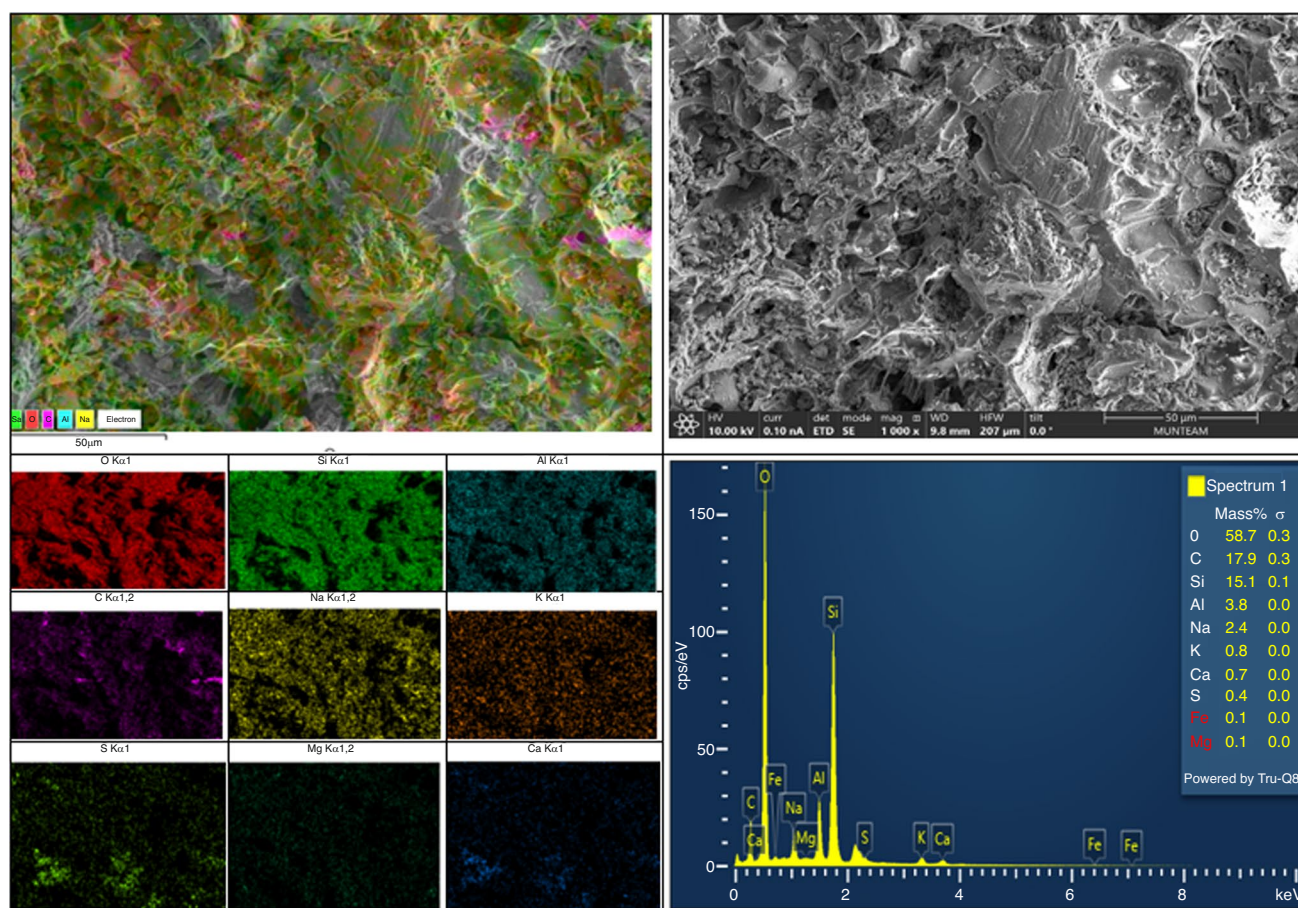


Fig. 10 SEM, mapping, and EDS analysis of sample L-1

more detail via examinations of the metallographic structure of both samples.

Morphological analysis

Figures 10 and 11 present the results of scanning electron microscopy (SEM), mapping, and energy-dispersive X-ray spectroscopy (EDS) analyses of the metallographic structures of andesite samples L-1 and H-1.

When the metallographic images and analysis results of the samples used in this study are examined, it is seen that samples L-1 and H-1 are andesite magmatic surface rocks consisting of O, C, Si, Al, Na, K, Co, S, Fe, and Mg. In the SEM and mapping images of sample L-1, Na and Al can be seen in the main structure with O, C, and Si, with compounds created by these elements. Smaller amounts of Ca, K, S, Fe, and Mg are present, and they spread homogeneously throughout the structure. Comparing the SEM images of L-1 and H-1, the structural density of sample H-1 is seen to be higher than that of sample L-1. In the mapping images of sample H-1, a structure similar to that of L-1 is observed. When the EDS and mapping analyses are considered together, the Si ratio of sample L-1 can be calculated as 15.1%, while it is 19.8% for sample H-1. Thus, compared to

L-1, the Si ratio of H-1 is higher, which causes the material to have more SiO_2 compounds and an increase in structural density. This explains why the Biot number of sample L-1 was higher than that of H-1 at all measured temperatures. The SiO_2 compounds creating higher molecular density in the internal structure of sample H-1 enabled the heat inside H-1 to spread more homogeneously and caused the thermal diffusion coefficient to be higher.

Overall, the differences observed between H-1 and L-1 in thermal conductivity, specific heat capacity, and related thermal parameters can be attributed to variations in mineral composition, structural density, and microstructural characteristics associated with elevation-dependent formation conditions. Variations in crystallization history and cooling processes may influence phase distribution, grain size, and microcrack density, which in turn affect both heat storage capacity and heat transfer efficiency within the rock matrix. Therefore, the systematic thermal differences between H-1 and L-1 are consistent with their distinct formation environments.

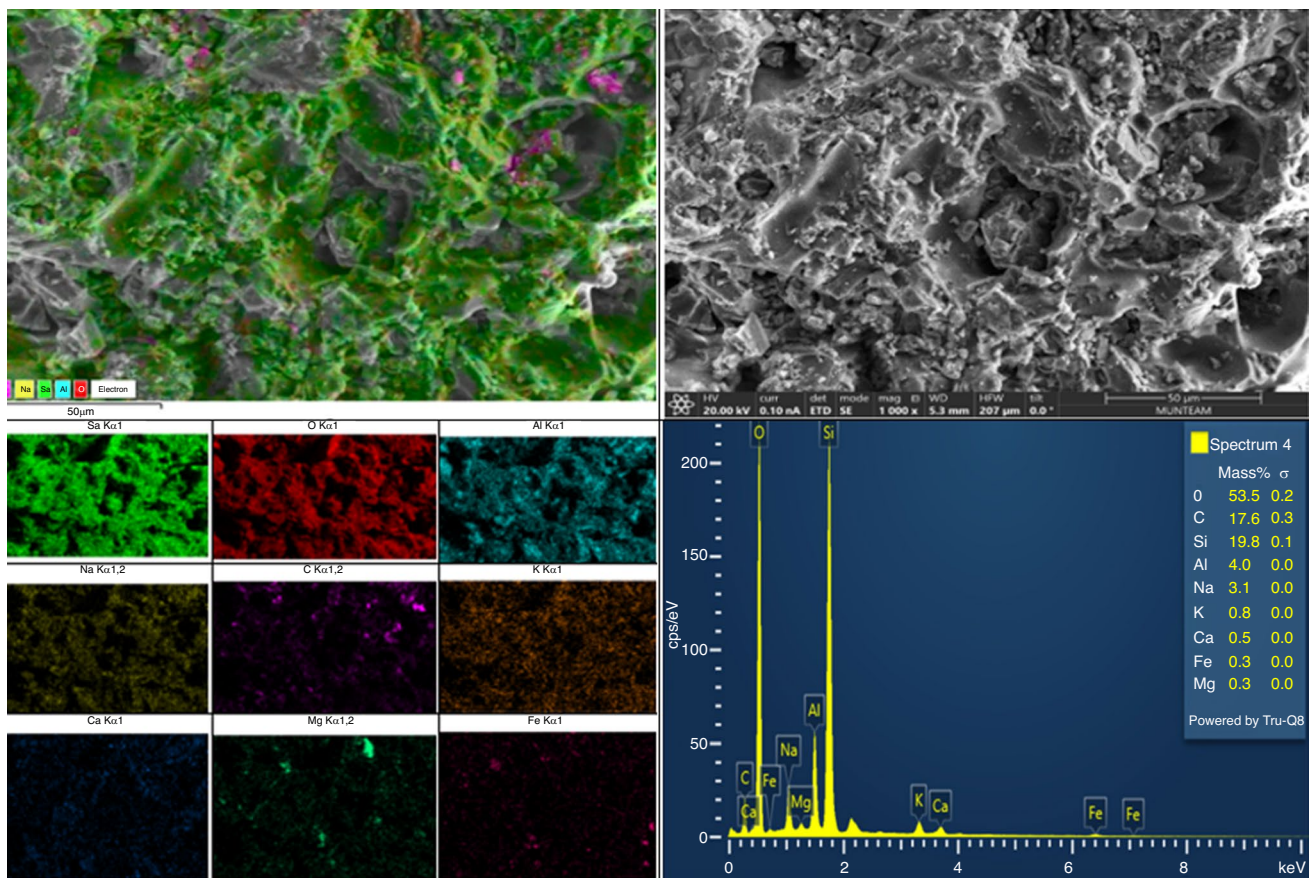


Fig. 11 SEM, mapping, and EDS analysis of sample H-1

Conclusions

This study investigated the high-temperature thermal behavior of andesite samples extracted from different elevations (H-1 and L-1) under identical heating (850 °C) and natural cooling conditions. Despite being subjected to the same thermal environment, the samples exhibited significant quantitative differences in their thermal responses.

The thermal diffusivity of H-1 reached a maximum value of $2.93 \times 10^{-5} \text{ m}^2 \text{ s}^{-1}$ at 360 s and decreased to $8.96 \times 10^{-6} \text{ m}^2 \text{ s}^{-1}$ at 1300 s, whereas L-1 showed a lower maximum value of $1.83 \times 10^{-5} \text{ m}^2 \text{ s}^{-1}$ and decreased to $5.9 \times 10^{-6} \text{ m}^2 \text{ s}^{-1}$ over the same period. This indicates that H-1 exhibited a faster internal heat propagation capacity under transient cooling conditions. In parallel, the Biot number of L-1 decreased from 0.60 to 0.29 but remained consistently higher than that of H-1, which decreased from 0.314 to 0.165, suggesting that L-1 experienced more pronounced internal temperature gradients throughout the cooling process. Regarding the specific heat capacity, H-1 varied between 13.26 and 49.57 kJ kg⁻¹ K⁻¹, generally remaining slightly higher than L-1 (13.3–47.45 kJ kg⁻¹ K⁻¹).

The combined evaluation of thermal diffusivity, Biot number, and specific heat capacity reveals a coherent thermal behavior pattern. Higher thermal diffusivity together with lower Biot numbers in H-1 indicates more efficient internal heat distribution and reduced thermal gradients under transient conditions. At the same time, the relatively higher specific heat capacity of H-1 suggests an enhanced thermal energy storage capability, contributing to a more stable thermal response during cooling. In contrast, the comparatively higher Biot numbers of L-1 imply stronger internal temperature gradients, which may increase thermal stress development during rapid temperature changes.

Metallographic and elemental analyses revealed that H-1 contains a higher SiO₂ content (19.8%) compared to L-1 (15.1%), resulting in a denser microstructure. This difference in mineral composition and structural density provides a physical explanation for the observed variations in thermal diffusivity and Biot number. The denser internal structure of H-1 facilitates more uniform heat conduction pathways, whereas the relatively less compact structure of L-1 contributes to non-uniform heat propagation under transient thermal loading.

From an engineering perspective, these findings suggest that elevation-dependent mineralogical and microstructural characteristics should be considered in the selection and design of andesite for high-temperature applications. Andesites with higher SiO₂ content and denser internal structures may offer improved thermal diffusivity, enhanced energy storage capacity, and reduced internal temperature gradients, which are advantageous in

geothermal systems, furnace linings, and other elevated-temperature environments. Conversely, materials exhibiting higher Biot numbers may require careful design consideration in applications involving rapid thermal cycling due to the increased risk of thermally induced stresses.

Overall, this study quantitatively demonstrates that elevation-related compositional differences significantly influence the transient thermal performance of andesite, thereby providing a scientific basis for more informed engineering material selection and design.

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