

Article

Evaluation of Mechanical and Thermal Properties of Heat-Treated Natural Analcime-Bearing Rock: Based on Mineralogical Structure

Yasemin Akgün ¹, Mithat Akgün ², Erdem Türkeli ^{1,*} and Mehmet Can Altınışık ³

¹ Construction Department, Vocational School of Technical Sciences, Ordu University, Ordu 52200, Türkiye; yakgun@odu.edu.tr

² Department of Renewable Energy, Institute of Science and Technology, Ordu University, Ordu 52200, Türkiye; makgun@odu.edu.tr

³ Ordu Directorate of Industry and Technology, Ministry of Industry and Technology, Ordu 52200, Türkiye; mcaltinisik@hotmail.com

* Correspondence: erdemturkeli@odu.edu.tr or erdem18turkeli@hotmail.com

Abstract

The present study aimed to investigate the mineralogical–petrographic, physical, chemical, mechanical, and thermal properties of natural analcime-bearing rocks, evaluating their feasibility for prospective engineering and material applications. Natural analcime-bearing rocks are widely utilized in various sectors due to their ease of processing and distinctive thermal performance characteristics. To determine the physical–mechanical and thermal pathways of the material under thermal stress, specimens were exposed to high temperatures in a laboratory furnace using a gradient threshold (Untreated, 300 °C, 400 °C, 500 °C, 600 °C, 700 °C, 800 °C, 900 °C, and 1000 °C) and variable holding durations (1, 2, and 3 h). The specific heat capacity (C_p) values of both the untreated and post-treated specimens, evaluated strictly at a standardized isothermal DSC measurement temperature of 25 °C, exhibited a progressive enhancement following dynamic thermal soaking. While the baseline C_p value of the untreated natural rock was $0.616 \text{ J} \cdot \text{g}^{-1} \cdot \text{K}^{-1}$, the specific heat capacities of the samples pre-heated at 300 °C, 400 °C, 500 °C, 600 °C, 700 °C, 800 °C, 900 °C, and 1000 °C were determined as 0.754, 0.679, 0.605, 0.541, 0.693, 0.499, 0.660, and $0.472 \text{ J} \cdot \text{g}^{-1} \cdot \text{K}^{-1}$, respectively. Regarding heat transfer, the baseline thermal conductivity of the untreated rock was $1.000 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$. A precise reduction of 40.5% was observed after a 3 h heating process at 300 °C (dropping to $0.595 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$), while exposure to 1000 °C for 3 h caused the thermal conductivity to contract by 44.9% (to $0.551 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$) due to lattice alterations. The results indicate that the highest compressive and flexural strengths were generally observed around 600 °C, strongly depending on the treatment duration. Beyond the peak thresholds, the samples exhibited a progressive decline; however, the retention of a substantial portion of the baseline strength even at 1000 °C suggests a notable thermal durability for the natural analcime-bearing rock. In conclusion, the empirical findings indicate that natural analcime-bearing rock possesses promising characteristics that support its potential candidate suitability for prospective utilization in thermal insulation elements and eco-efficient construction matrices, provided that long-term life-cycle durability cycles are validated in future research lines.



Academic Editor: Alexander Mikhailovich Kalinkin

Received: 27 August 2026

Revised: 19 September 2026

Accepted: 20 September 2026

Published: 22 September 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and

conditions of the [Creative Commons](https://creativecommons.org/licenses/by/4.0/)

[Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

Keywords: natural analcime-bearing rock; compressive-flexural strength; heat-treated; thermal insulation; heat storage

1. Introduction

Recently, architecture designs increasingly focus on sustainable material and green buildings that can supply natural climatic conditions [1–4]. Therefore, building materials that have the properties of both thermal insulation and heat storage are quietly important to minimize system-based heating and cooling demands [5,6]. In this context, discovering alternative, eco-friendly, and low-cost natural resources has become an important aim for researchers [7]. Natural zeolites have seriously attracted interest in recent decades due to their extraordinary physical and chemical properties [8,9]. Among the group of zeolites, analcime stands out as a valuable mineral [10]. Analcime is a natural hydrated sodium aluminosilicate (zeolite) mineral with the chemical formula $\text{NaAlSi}_2\text{O}_6 \cdot \text{H}_2\text{O}$, belonging to the tectosilicates subclass [11]. The regular nano-scale channels, intra-crystalline cages, and weakly bound “zeolitic water” molecules within its three-dimensional framework endow analcime with high-value physical and chemical properties [12]. Originating from the hydrothermal alteration of volcanic and pyroclastic deposits, analcime features a highly stable three-dimensional crystal framework filled with microscopic empty spaces and naturally trapped water molecules [13]. This specific structure allows for the mineral to trap a large amount of still air, which severely restricts heat flow, while its internal zeolitized water acts as an endothermic buffer to efficiently absorb and store heat energy [14]. When subjected to high temperatures, these minerals undergo thermal expansion due to the rapid evaporation of structurally bound water, resulting in a highly porous and lightweight framework. Accordingly, engineered expanded zeolite rocks exhibit distinctive properties, such as low bulk density, substantial porosity, and robust mechanical strength, rendering them quietly suitable for the fabrication of lightweight structural components in many sectors [15]. Owing to its superior exchange capacity, low thermal conductivity, and unique heat storage performance, it is intensively utilized in green sustainable buildings and environmental engineering filtration systems. In the literature, studies on the thermal insulation and heat storage applications of the analcime mineral are available [16–18].

Although Türkiye possesses massive natural zeolite reserves, the vast majority of commercial mining and academic research has focused on other types, such as clinoptilolite. The quantity of clearly mapped analcime reserves across Türkiye is low compared to clinoptilolite. However, it occurs as a minor component or a dominant local phase within billions of tons of potential rock masses associated with industrial clays and tuffs in Central Anatolia and the Aegean region [19].

However, the Eastern Black Sea region presents analcime distinct and underutilized geological formation. Previous investigations indicate that the Upper Cretaceous volcanic formations in the Perşembe region host natural analcime deposits. Notably, these deposits exhibit analcime-specific co-existence where it occurs alongside vermiculite, a layered clay mineral famous for its thermal insulation and expansion capabilities [20,21]. This natural blend provides analcime-promising precursor material that combines mechanical sufficiency with good thermal insulation properties. Despite the high industrial potential of this regional resource, a comprehensive investigation linking its mineralogical structure directly to its engineering performance remains limited. To bridge this gap, this study evaluates the mineralogical, mechanical, and thermal properties, of natural analcime-bearing rocks exposed to high temperatures from the Ordu-Perşembe region. This research, incorporating preliminary characterizations, aims to evaluate the raw rock’s physical–mineralogical properties, strength, thermal conductivity, and heat storage behaviors.

This paper demonstrates the potential suitability of the investigated analcime-bearing rock as a sustainable alternative material for heat storage and thermal insulation applications in green buildings, while maintaining acceptable mechanical performance under thermal exposure.

2. Materials and Methods

2.1. Materials

The natural analcime-bearing rock samples used in this study were obtained from the geological formations in the particularly the Ordu (Perşembe) province, located in the Eastern Black Sea province of Türkiye. The representative analcime-bearing rock samples were collected from three different locations within the studied region, with 6 blocks obtained from each location (totaling 18 blocks) as indicated in Figure 1. To mitigate potential spatial heterogeneity and ensure a comprehensive evaluation of the formation, all 18 collected blocks were pooled into a single composite batch. To maintain experimental consistency across the thermal treatments, the samples prepared from this shared pool were distributed evenly and systematically among the baseline (untreated) and high-temperature groups (300 °C, 600 °C, 800 °C, and 1000 °C).



Figure 1. The raw view of natural analcime rocks used in the study.

The investigation area is located in the Northeastern (NE) Türkiye. The region's Late Cretaceous submarine volcanism (tuffs and igneous rocks) underwent alteration under alkaline environmental conditions, giving rise to these magnificent analcime deposits [19,22]. These constitute the world-renowned main basin of Neogene-age lacustrine sedimentary analcime deposits in Türkiye. The existing zeolite (including analcime) deposits in Türkiye are presented as locationally on the map in Figure 2 [23] and as nominal in Table 1.

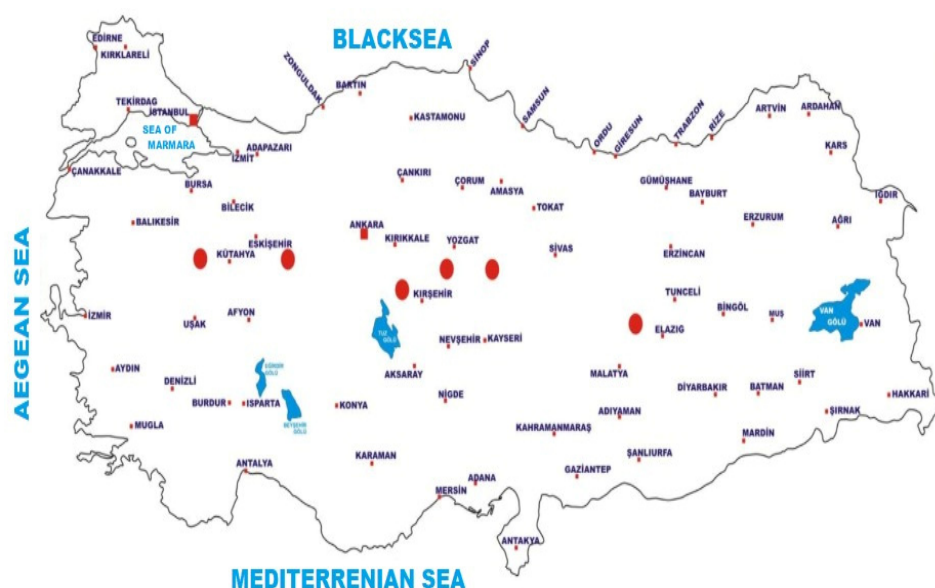


Figure 2. Map of zeolite resources in Türkiye [23].

Table 1. Reserve areas of analcime in Türkiye [24,25].

Reserve Areas of Analcime in Türkiye	
Ankara	Nallıhan (Çayırhan), Ayaş (Mülk), Polatlı (Oğlakçı), Gölbaşı (Ahiboz), Beypazarı (Bahçecik), Kalecik (Hasayaz), Haymana
Eskişehir	Mihallıççık
Çankırı	Şabanözü, Merkez (Çandır)
Bilecik	Gölpazarı
Bolu	Göynük
Cappadocia–Erciyes Basin	Nevşehir, Niğde, Kayseri
Western Anatolia Region	Kütahya, Balıkesir-Bigadiç, Manisa-Göğdes
Marmara Region	Yalova, Karamürsel-İzmit

Prior to tests, the raw rock samples were cleaned to remove surface impurities. To conduct the tests in this study, raw analcime rock had to be processed into standard test samples. To process the rock, the wet cutting process was utilized, as shown in Figure 3.

**Figure 3.** Natural analcime-bearing rock wet cutting process.

Initially, a total of 18 blocks (6 from each of the three locations) were prepared for the wet cutting process. During this preparation phase, two blocks—each originating from a different sampling location—sustained partial fragmentation and structural macro-cracking due to mechanical stresses during cutting, failing to meet the integrity criteria required for core/prismatic extraction. Consequently, these two damaged blocks were discarded, and the experimental program was successfully completed using the remaining 16 blocks. No visible lithological or macroscopic structural differences were detected between the discarded blocks and those that remained intact, confirming that the rejections did not introduce a systemic selection bias.

Raw analcime rock masses (approximately 30–70 kg) were shaped into $50 \times 50 \times 50$ mm cubes, $40 \times 40 \times 160$ mm prisms, and disc-shaped samples (50 mm diameter, 28 mm thickness) for compressive–flexural strength, and thermal conductivity tests, respectively (Figures 4 and 5).

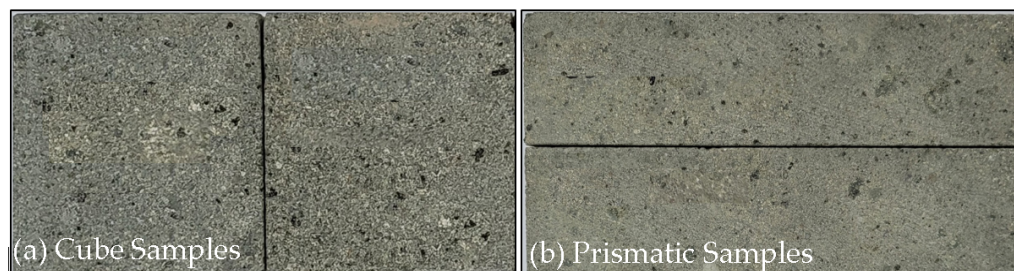


Figure 4. The top views of the samples prepared for (a) compressive and (b) flexural strength tests.



Figure 5. The views of the samples prepared for thermal conductivity tests.

The cylindrical samples were shaped using the water jet method following wet cutting. For heat storage characterization definitions, a portion of heat-treated analcime test samples was finely ground into powder form (at weight approximately 10 g) as complies with analysis standards. The powdered forms of heat-treated analcime test samples are shown in Figure 6.



Figure 6. The powdered form of heat-treated analcime test samples.

2.2. Methods

The physical properties of rock were performed on cube samples. The density-apparent porosity and water absorption of the cubic rock samples were determined in accordance with EN 1936 [26] and EN 13755 [27], respectively. To determine the dry density, water absorption percentage, and apparent porosity of the natural analcime rock, Archimedes' hydrostatic weighing principle was utilized. In this method, the dry mass of the sample in air (w_{dry}) was first measured using a precision balance after being dried in an oven until reaching a constant mass in compliance with the EN 1936 standard. Subsequently,

the sample, with its pores fully saturated with water, was immersed in a water-filled container using an Archimedes balance system, and its suspended mass in water (w_{water}) was determined. Finally, the mass of the fully water-saturated sample in air (w_{air}) was measured. Utilizing the obtained mass data, the dry density of the material was calculated precisely using Equation (1).

$$d_{\text{dry}} = \frac{w_{\text{dry}}}{w_{\text{air}} - w_{\text{water}}} \quad (1)$$

Also, its water absorption percentage was determined using Equation (2).

$$w_a(\%) = \frac{w_{\text{air}} - w_{\text{dry}}}{w_{\text{dry}}} \times 100 \quad (2)$$

Additionally, the apparent porosity of the rock was calculated by using Equation (3).

$$p_o(\%) = \frac{w_{\text{air}} - w_{\text{dry}}}{w_{\text{air}} - w_{\text{water}}} \times 100 \quad (3)$$

The chemical composition of natural analcime rock was determined with X-ray fluorescence (XRF) analysis. The test samples were in the form of fused beads. The analysis results are as in oxide form of chemical composition. The analyses were performed at Acme Analytical Laboratories (Bureau Veritas Commodities Canada Ltd., Vancouver, BC, Canada) using a Zetium WDXRF spectrometer (Malvern Pan-alytical B.V., Almelo, The Netherlands) operated with SuperQ software (version 5.0).

Prior to X-ray diffraction (XRD) analyses, both untreated and heat-treated analcime rock samples were ground. The atomic structure, crystal phases, and crystallographic properties of both untreated and heat treated analcime rock samples were examined with X-ray diffraction (XRD) analysis. It was performed using an X-ray diffractometer (Empyrean, Malvern PANalytical, Almelo, The Netherlands) operated with $\text{CuK}\alpha$ -radiation and Ni filter at 40 kV and 40 mA. The prepared samples were examined from $2\theta = 2^\circ$ to 45° , at a scanning speed of $2^\circ/\text{min}$.

Petrographic structure examinations were performed to determine the mineralogical and petrographic characteristics of the natural analcime rock samples in accordance with the EN 12407 [28]. For the investigations, blocks with dimensions of $30 \times 20 \times 10$ mm were extracted from each sample, and thin sections with a thickness of $30 \mu\text{m}$ were prepared using standard thin-sectioning techniques. The prepared thin sections were examined under a polarising microscope (DM2750 P, Leica Microsystems, Wetzlar, Germany) operated under both plane-polarized light (PPL) and cross-polarized light (XPL) modes. Within the scope of the examination, the mineral composition, mineral abundance, alteration degree, and crystal morphologies of the samples were determined. Additionally, photomicrographs were taken to document the characteristic microstructural features of the samples.

Additionally, to provide microstructure images and elemental analyses, SEM-EDX analysis was performed on powdered cubic samples. A scanning electron microscope (SEM; SU1510, Hitachi High-Tech Corp., Tokyo, Japan) integrated with energy-dispersive X-ray analysis (EDX; Oxford Instruments, Abingdon, UK) was utilized. Before being analyzed, the non-conductive samples were gold-coated to prevent charging effects.

The analcime rock samples were investigated using the ultrasonic pulse velocity (UPV) technique, which is classified as one of the non-destructive testing (NDT) methods in accordance with the ASTM D2845 standard [29]. The UPV measurements were performed with an ultrasonic device. To ensure effective acoustic coupling and no gaps between the transducer and the sample, an ultrasonic gel was applied. The pulse velocity (m/s) was calculated by dividing the path distance by the pulse transit time. Following the UPV tests, compressive strength tests were carried out on the same samples.

The mechanical performance of the analcime rock was evaluated by conducting both flexural and compressive strength tests using a computer-controlled (PROFI X6, Yüksel Kaya Machine, Ankara, Türkiye) mechanical testing machine. The uniaxial compressive strength of the natural analcime rock was determined in accordance with the EN 1926 standard [30]. In the tests, cubic samples with dimensions of $50 \times 50 \times 50$ mm were used. Prior to testing, the samples were dried in a ventilated oven at 70 ± 5 °C until they reached a constant mass. The compression tests were performed using a calibrated hydraulic testing machine with a capacity of 2000 kN. The load was applied continuously and monotonically at a constant stress rate of 0.5 MPa/s until failure occurred. The mean value of the three tested samples was reported as compressive strength. The flexural strength under concentrated load of the natural analcime rock was determined in accordance with the EN 12372 standard [31]. In the tests, prism samples with dimensions of $40 \times 40 \times 160$ mm were used. Prior to the testing, the samples were dried in a ventilated oven at 70 ± 5 °C until reaching a constant mass. The tests were performed using a three-point loading system on a calibrated testing machine with a supporting span (L) set to 120 mm. The load was applied continuously at a constant stress rate of 0.25 MPa/s until failure occurred. The mean value of tested three samples was reported as flexural strength.

In addition to observing both microstructure images and elemental analysis effects of heat treatment of the analcime rock samples, SEM–EDX analysis was utilized. The method regarding SEM-EDX analysis is the same as the test method applied to the natural analcime-bearing rock samples.

The thermal conductivity (λ) of the samples was measured using a heat flow meter (FOX 50, TA Instruments/LaserComp, New Castle, DE, USA) in accordance with the ASTM C518 standard [32]. Prior to the tests, the instrument calibration was verified using a standard reference material with known thermal conductivity. Disc-shaped samples with a diameter of 50 mm and a thickness of 28 mm were placed between the upper and lower plates. To minimize contact thermal resistance, a thin layer of thermal paste was applied to the sample surfaces. The measurements were conducted at a mean temperature of 20 °C established by setting the upper plate to 25 °C and the lower plate to 15 °C, thereby imposing a temperature gradient of 10 °C. To ensure highly accurate heat flux readings, the data were collected after the system reached the strict steady-state equilibrium. Each sample was tested in triplicate, and the mean thermal conductivity values were reported.

The specific heat capacity (C_p) analysis was systematically structured to maintain a clear distinction between the pre-testing macro-thermal exposure and the subsequent calorimetric measurement. Following the heat treatments conducted in the furnace at designated thresholds (300 °C, 600 °C, and 1000 °C) and subsequent slow cooling to ambient conditions, micro-specimens were extracted for testing. The specific heat capacity (C_p) of the post-treated materials was determined via Differential Scanning Calorimetry using a DSC apparatus (Q200, TA Instruments, New Castle, DE, USA).

The measurements were performed using the baseline-subtracted triple-curve method (baseline, sapphire reference, and sample) in strict accordance with the ASTM E1269 standard [33]. Approximately 10.0 mg of the sample was encapsulated in a Tzero aluminum pan. The scans were conducted under a continuous nitrogen (N_2) purge at a flow rate of 50 mL/min. The thermal profile consisted of an initial isothermal hold at 10 °C for 5 min, followed by heating to 55 °C at a constant rate of 10 °C/min, and a final isothermal hold for 5 min.

To ensure complete clarity and reproducibility against dynamic scanning intervals, each reported (C_p) value in this study represents the exact isothermal capacity determined at a specified DSC measurement temperature of 25 °C (room temperature), which lies within the continuous 10–55 °C evaluation window. The resulting heat flow data were

converted into capacity values using TA Universal Analysis software based on the sapphire calibration curve, with all units standardized to $\text{J} \cdot \text{g}^{-1} \cdot \text{K}^{-1}$ to maintain rigorous scientific consistency.

The rock samples were subjected to heat treatment ranging from 300 °C to 1000 °C with temperature increments of 100 °C (300 °C, 400 °C, 500 °C, 600 °C, 700 °C, 800 °C, 900 °C, and 1000 °C). Throughout this study, figures, and axis labels, the unheated reference samples are designated as ‘Untreated’ instead of 0 °C to avoid scientific ambiguity. The thermal treatments were conducted for three distinct holding durations (1, 2, and 3 h) inside a laboratory furnace under an ambient air atmosphere. To prevent thermal shock and explosive spalling of the porous rock samples prior to reaching the target temperatures, a controlled three-step heating schedule was implemented with a constant heating rate of 5 °C/min. The designated holding periods (1, 2, or 3 h) commenced strictly after the furnace internal temperature stabilized at the target threshold. Following the completion of the holding time, the furnace was turned off, and the samples were allowed to cool slowly to room temperature inside the closed furnace to mitigate post-cooling structural damage (Figure 7).



Figure 7. The oven interior layout of the natural analcime samples.

3. Results and Discussion

3.1. The Analysis of Natural Analcime-Bearing Rock

3.1.1. Physical and Chemical Analysis

The physical and chemical analysis results of natural analcime-bearing rock are displayed in Tables 2 and 3, respectively. The evaluated physical parameters clearly demonstrate that the analcime rock samples are characterized by a porous structure and low density inherent to the analcime samples. As seen in Table 3, the chemical composition of natural analcime-bearing rock confirms the hydrated sodium aluminosilicate structure of it.

Table 2. Physical properties of natural analcime-bearing rock.

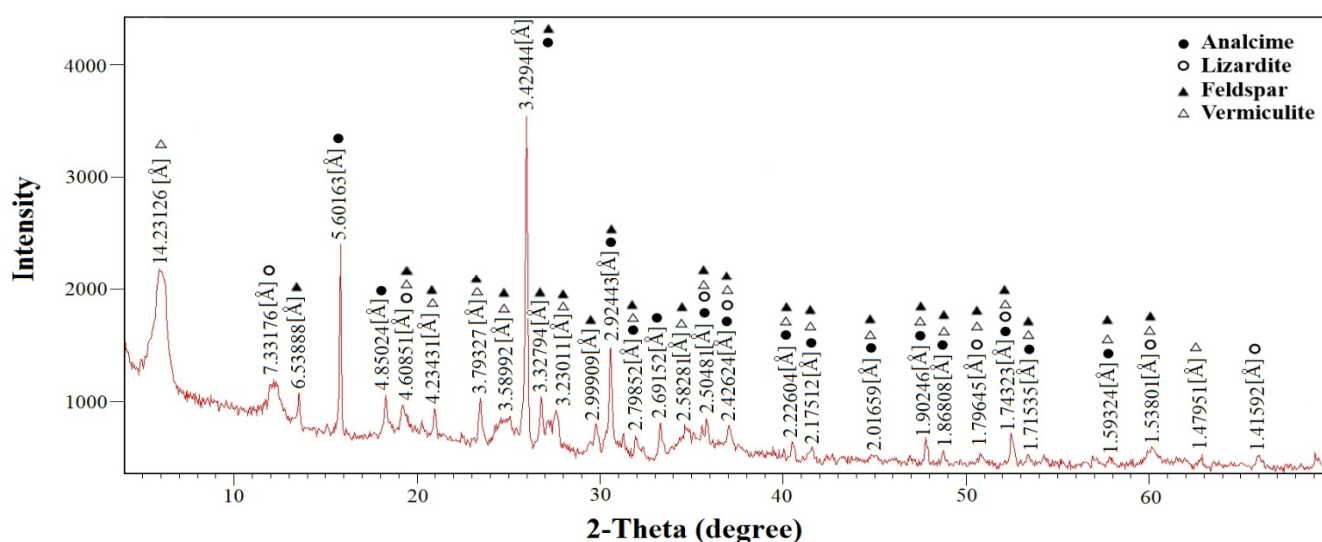
Physical Property					
Saturated Density (g/cm ³)	Natural Density (g/cm ³)	Dry Density (g/cm ³)	Void Ratio	Porosity (%)	Water Absorption (%)
2.27	2.16	2.10	0.20	16.65	7.85

Table 3. Chemical compositions of natural analcime-bearing rock.

Oxide Composition (wt.%)						
SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	Na ₂ O	K ₂ O
46.71	17.24	9.21	3.03	5.29	4.84	4.08

3.1.2. Mineralogical and Crystallographic Characterization (XRD Analysis)

The mineralogical composition and structural properties of the natural rock sample in the study were examined using the X-ray diffraction (XRD) analysis. The XRD patterns and resulting diffractogram of the analcime is presented in Figure 8.

**Figure 8.** X-ray diffraction (XRD) pattern of the natural analcime-bearing rock sample.

The qualitative phase analysis results indicate that the examined natural resource exhibits a complex mineralogical paragenesis, hosting both zeolite- and clay-group minerals within its structure. Detailed examination of the diffractogram reveals that the main matrix of the sample is composed of analcime, a mineral belonging to the zeolite group. The analcime phase exhibited highly sharp and intense characteristic peaks, particularly at d-spacings of $d = 5.59 \text{ \AA}$ ($2\theta \approx 15.8^\circ$) and $d = 3.42 \text{ \AA}$ ($2\theta \approx 26.0^\circ$). The symmetrical geometry and prominent intensity of the peak at $d = 5.59 \text{ \AA}$ confirm the high structural stability and degree of crystallinity of the analcime crystals within the rock framework. The prominent of this crystallinity evidenced by the XRD patterns also corroborates the presence of ordered tetrahedral Si-O-Al bond networks, which complies with the literature [34].

The most intense peak at $d = 3.42 \text{ \AA}$ occurred due to the overlapping of the analcime phase with the accompanying Feldspar phase, which is also consistent with the established literature [19,35]. Another remarkable component accompanying analcime in the rock matrix is Vermiculite, a clay mineral characterized by its distinct peak at a d-spacings of $d = 14.56 \text{ \AA}$ ($2\theta \approx 6.0^\circ$). The presence of vermiculite demonstrates that the natural rock

possesses a layered clay structure, which implies high porosity, as well as significant thermal and hydraulic retention capacities. Furthermore, the peaks detected at a d-spacings of $d = 7.34 \text{ \AA}$ ($2\theta \approx 12.06^\circ$) and $d = 2.42 \text{ \AA}$ ($2\theta \approx 37.15^\circ$) are attributed to the Lizardite phase, a magnesium-rich serpentine mineral, while the peak series around $d = 3.00 \text{ \AA}$ ($2\theta \approx 29.78^\circ$) represents the tectosilicate-based Feldspar minerals that support the mechanical skeleton of the rock. A slight background hump observed in the low-angle regions ($2\theta \approx 10\text{--}20^\circ$) of the diffractogram indicates that, in addition to the crystalline phases, volcanic amorphous (glassy) materials also remain as residues in the sample. This mineralogical association (Analcime + Vermiculite + Feldspar) is compatible with the alkali-hydrothermal alteration of Upper Cretaceous pyroclastic/volcanic materials typical of the Ordu-Perşembe region [20,22]. According to the semi-quantitative RIR evaluation of the baseline XRD pattern, the mineralogical mass fractions of the natural rock matrix consist of approximately 35%–40% feldspar, 30%–35% analcime, 15%–20% vermiculite, and 5%–10% lizardite.

3.1.3. Petrographic Analysis

The natural analcime-bearing rock examined mineralogically and petrographically is classified as vitric tuff (a pyroclastic rock). The alteration processes occurring in the rock are visible in the thin-section (petrographic) photographs of the analcime rock sample taken under a polarizing microscope. The component of the rock referred to as glass shards has widely transformed into zeolite and chlorite with alteration. Cryptocrystalline silica has been detected in the binding material of the rock. The crystalline components of the rock were observed to be fragmented pyroxene and trace amounts of biotite. The single-nicol image shows chlorite with the alteration of biotite and pyroxene minerals in the rock. Under crossed nicols, a relict clinopyroxene crystal proves that the rock is of original (primary) magmatic origin and has been preserved without undergoing complete alteration. The zeolitization observed in the same image is indicative of a typical alteration resulting from the interaction with low-temperature hydrothermal fluids of volcanic glass or feldspars. The rock contains less than 5% opaque minerals. Repeated examinations of representatively selected rock samples exhibited similar results. The polarizing microscope images of the analcime rock sample are given in Figure 9.

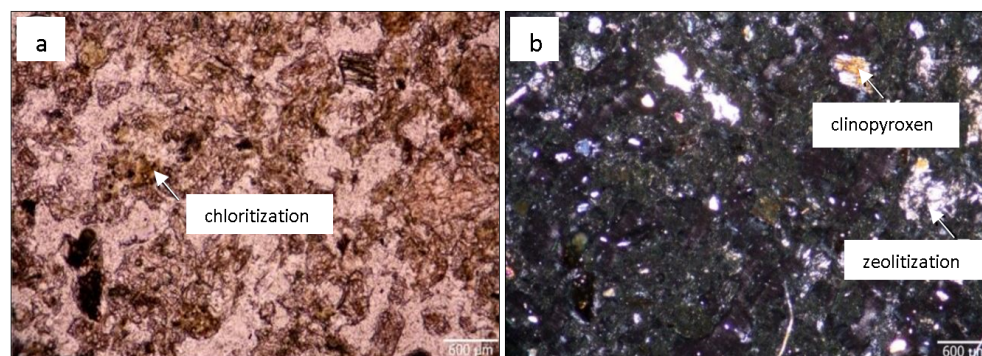


Figure 9. Polarizing microscope images of the analcime rock: (a) single nicol image and (b) crossed nicols.

3.1.4. SEM-EDX Analysis

SEM-EDX analysis was conducted on natural analcime-bearing rock samples. The micromorphology–textural characteristics and elemental compositions of analcime minerals were examined with the SEM-EDX. SEM images and elemental compositions obtained from SEM-EDX analysis are presented in Figure 10 and Table 4, respectively.

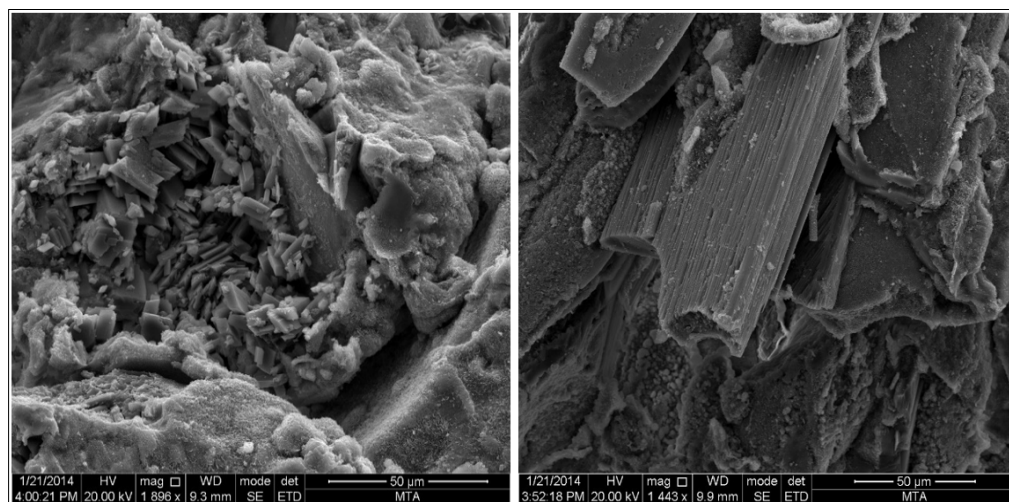


Figure 10. SEM images of natural analcime-bearing rock.

Table 4. Elemental composition (EDX) of natural analcime-bearing rock.

Elemental Composition								
Element	O	Na	Mg	Al	Si	Ca	Fe	K
Weight Percentage (wt.% element)	51.45	2.75	5.55	9.08	17.91	2.77	9.46	1.05
Atomic Percentage (at. %)	66.96	2.49	4.75	7.00	13.28	1.44	3.53	0.56

According to analysis findings undertaken to determine the general morphologic structure in the analcime rock sample, in the first image of the investigated analcime rock, slender, elongated, rod-like (prismatic/acicular) crystals—clustered as either parallel to one another or randomly within a micropore in the rock—are clearly visible at the center of the image. In zeolitic tuffs, this type of rod-like crystal morphology typically indicates a zeolite-group mineral [36]. The rock matrix is quite massive and dense, and a micro-cavity (pore) is located in the center. Within this cavity, the crystals—can be found to have unrestricted growth—have been developed retaining their forms. These microscopic pores and crystal fillings directly influence water absorption, porosity, freeze–thaw resistance and, consequently, the durability performance of rock. However, this preliminary study was limited to the evaluation of compressive–flexural strength and some physical properties to determine rock quality and structural performance. The lack of a comprehensive investigation into the environmental and time-dependent durability stands as a primary limitation of this study. The Author’s future studies will focus on evaluating how these microstructural features influence long-term durability. Furthermore, the fact that these pores are filled with minerals enhances the rock’s mechanical strength compared to leaving them empty. On the other hand, the amorphous, rough, and more massive structure covering the upper, right, and lower parts of the image constitutes the main matrix of the rock. The observed rough texture can be attributed to as a volcanic tuff texture. Based on the scale bar, the lengths and thicknesses of the rod-like crystals in the center were approximately in the range of 10–25 µm and 2–4 µm, respectively. In conclusion, this image shows zeolite crystals developing within a micropore in the rock sample under examination.

Although the second SEM image of the examined rock was obtained at a slightly lower magnification (1443×) compared to the first (1896×), morphological details and the overall topography can be clearly observed thanks to the use of the secondary electron detector.

This image details the fibrous and striated morphology of the analcime rock. At the center of the image, with a channel, a rod-like structure formed by the aggregation of fine fibers can be seen. In the literature, zeolites are defined as minerals due to their crystalline structure containing pores and channels [37]. Accordingly, the crystalline structure morphology containing pores and channels from the SEM image in is clearly seen in Figure 10 determined for the analcime rock sample. The fracture surfaces of the crystal tips demonstrate that this mineral is composed of fine, intertwined needle-like structures. Such a distinct fibrous and linear morphology in natural rocks is characteristic of the typical form of zeolite minerals. On the right side of the image, there are massive structures exhibiting angular and platy fracture surfaces. This positioning can explain that the distinct fibrous structure in the center developed by growing freely along its longitudinal axis within the spaces between these massive layers. It is observed that the fibrous main columns and the platy structures on the right side are covered with a very fine-grained microcrystalline coating. This suggests that surface alteration occurred due to the influence of hydrothermal fluids in the environment after the formation of the mineral. Based on the scale bar, the width of the main fiber bundle in the center is approximately in the range of 30–40 μm . This size value can be interpreted as a rather large and well-developed crystal form at the micro-scale. Owing to its porous and channeled structure, the natural analcime-bearing rock sample investigated in this study has a low density. This characteristic indicates that the analcime rock possesses good thermal insulation properties, with a measured thermal conductivity of $1 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$.

According to EDX analysis findings undertaken to determine the elemental composition in the analcime rock sample, it has an Al–Si–O-based zeolite structure with a low Si/Al ratio of approximately 1.9 as a percentage by atomic ratio (Table 4). The ideal atomic Si/Al ratio for analcime mineral is around 2.0 in terms of ion exchange capacity [15]. Based on the EDX results, due to the quietly close to the ideal Si/Al ratio (1.9) of the analcime-bearing rock in this study, it has a high ion exchange capacity. It is known that natural analcime minerals can be converted into more active ion exchangers for use in industry and wastewater treatment through acid or thermal modification [38]. The high Fe content (9.46 wt.% element) of analcime rock corresponds to impurities [39]. In addition, the elemental composition of the rock sample obtained from the EDX analysis (Table 4) reveals high concentrations of O (66.96%), Si (13.28%), and Al (7.00%), along with the presence of cations such as Na, Mg, Ca, and K. The elemental composition of the natural analcime-bearing rock is summarized in Table 4, revealing a characteristic Si/Al ratio of 1.9, which aligns with the theoretical structure of analcime.

3.2. The Analysis of the Heat-Treated Natural Analcime-Bearing Rock

3.2.1. SEM-EDX Analysis

Fully explaining the impact of thermal processes on rock mechanics requires SEM-EDX analysis to achieve high-resolution imaging of micro-fractures, and determining induced micro-morphological, mineralogical, textural, and elemental distribution changes. To provide a clearer interpretation of the heat-treated effects, the SEM-EDX findings of the analcime rock samples are presented collectively. Specifically, Figure 11 illustrates the SEM images of the samples subjected to various thermal treatments and exposure periods (1, 2, and 3 h). Concurrently, Table 5 details the corresponding elemental compositions across each specific temperature dynamic from 300 °C to 1000 °C.

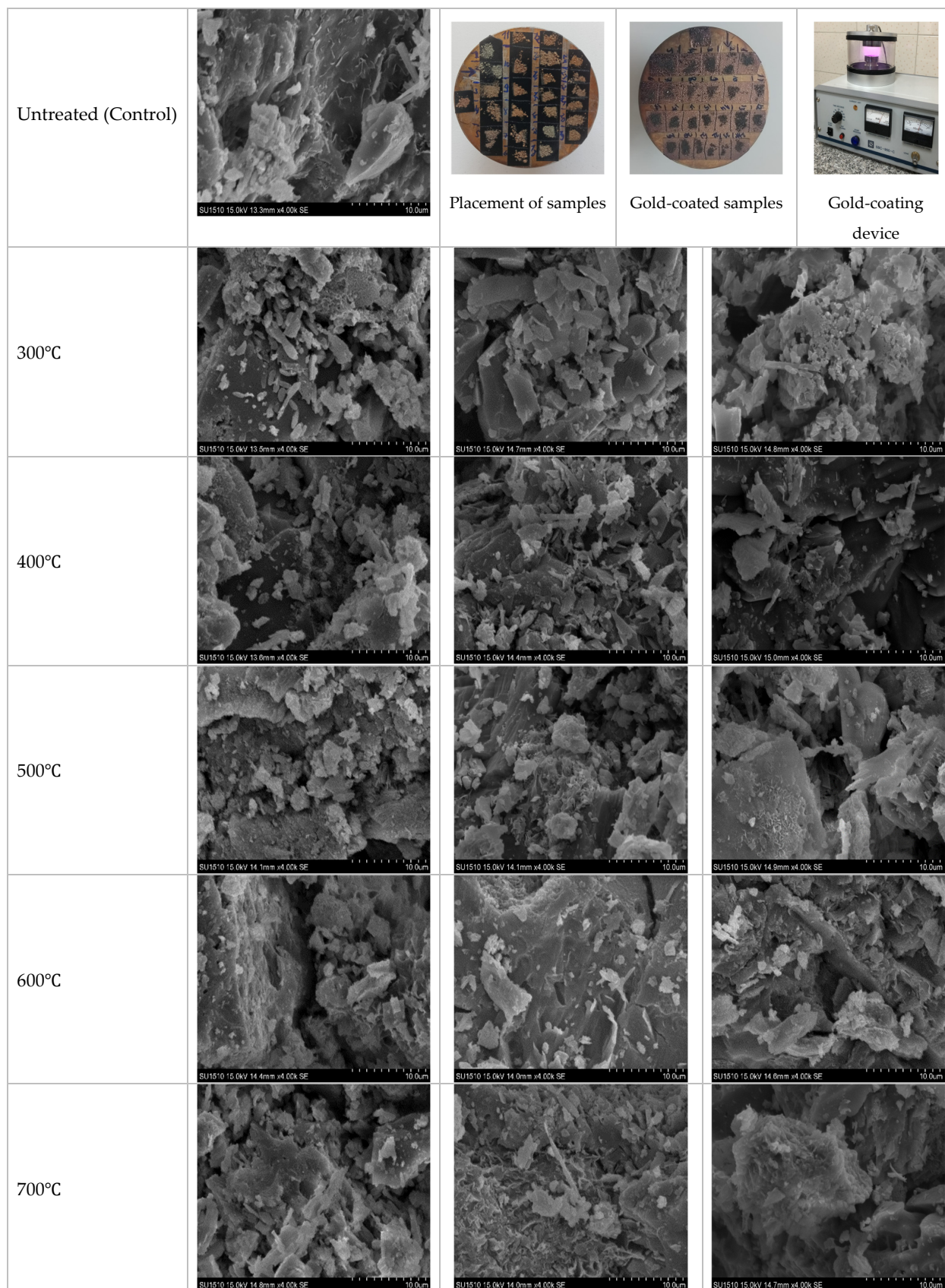


Figure 11. Cont.

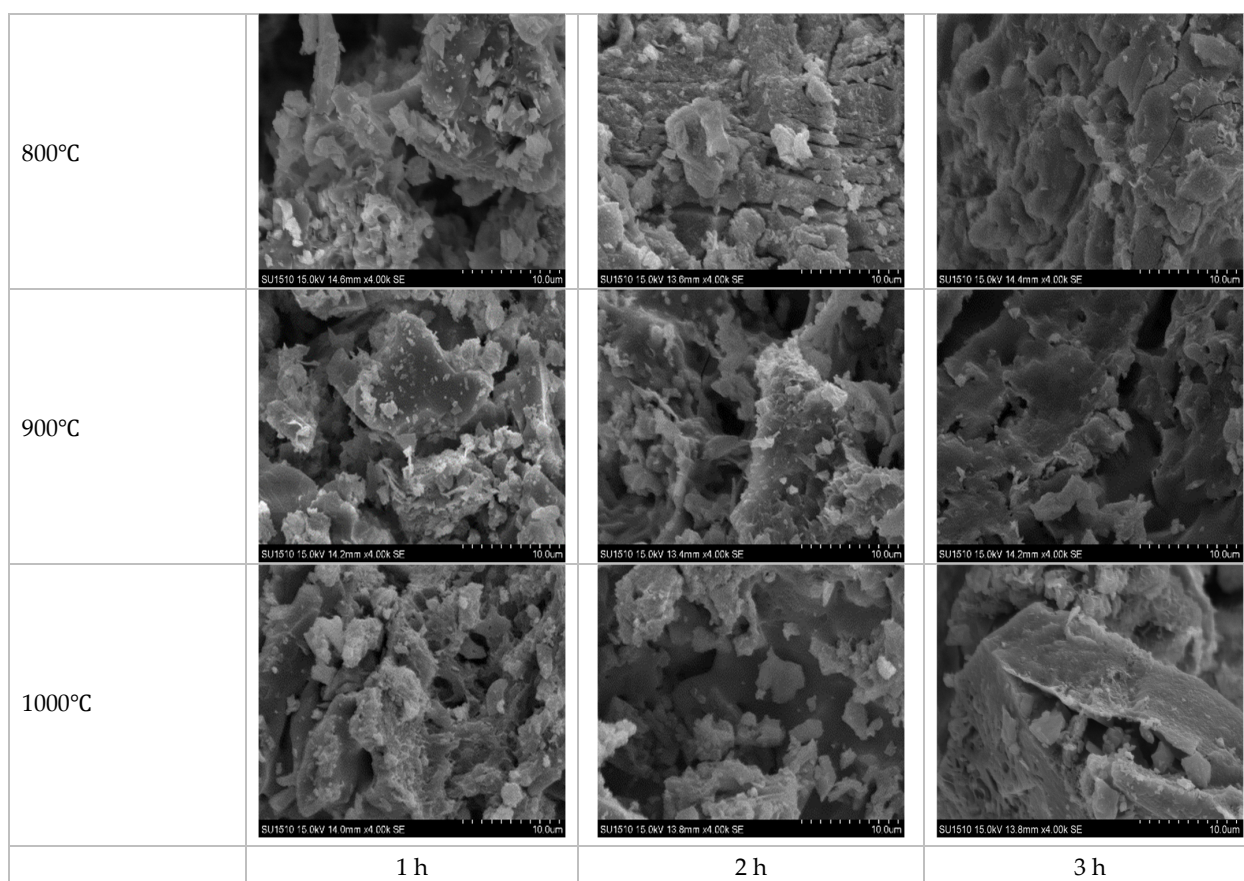


Figure 11. SEM images of untreated (control) and heat-treated natural analcime-bearing rocks for heat treatment temperature and duration.

Table 5. Elemental composition (at. %) of heat-treated natural analcime-bearing rocks obtained via wide-area EDX scanning.

Temperature (°C)	Duration (Hour)	O (%)	Si (%)	Al (%)	Fe (%)	Na (%)	Mg (%)	K (%)	Ca (%)
Untreated (Control)	-	66.96	13.28	7.00	3.53	2.49	4.75	0.56	1.44
300	1	66.34	13.63	7.06	3.49	2.98	4.31	0.71	1.48
	2	64.75	13.39	7.51	4.88	2.50	4.14	0.73	2.09
	3	65.69	13.74	7.38	3.85	2.76	3.41	0.73	2.44
400	1	65.08	13.94	7.28	4.20	2.82	3.86	0.73	2.09
	2	65.61	13.25	7.21	4.59	2.38	4.59	0.57	1.81
	3	64.45	13.61	7.59	4.58	2.48	3.85	0.93	2.53
500	1	64.49	14.06	7.90	3.76	2.76	4.25	0.55	2.23
	2	64.99	14.52	6.50	3.68	2.91	5.30	1.11	0.98
	3	63.41	14.55	8.36	3.82	3.32	3.44	0.53	2.57
600	1	63.34	15.64	6.68	4.29	3.35	4.56	1.26	0.87
	2	62.59	14.55	7.21	5.46	3.33	4.90	0.58	1.38
	3	64.33	13.90	6.74	4.81	2.12	5.70	0.85	1.54

Table 5. Cont.

Temperature (°C)	Duration (Hour)	O (%)	Si (%)	Al (%)	Fe (%)	Na (%)	Mg (%)	K (%)	Ca (%)
700	1	64.54	14.08	8.21	3.39	2.65	3.68	0.95	2.50
	2	62.91	14.60	7.86	4.49	2.57	4.45	0.90	2.21
	3	63.64	15.13	7.19	3.67	3.21	5.02	1.03	1.12
800	1	64.16	15.16	8.53	2.41	3.98	2.99	0.60	2.17
	2	61.38	13.58	7.23	6.84	3.71	5.23	0.47	1.54
	3	62.17	15.52	6.88	4.30	3.89	4.71	0.64	1.88
900	1	61.05	15.80	7.35	5.20	3.96	4.12	1.04	1.48
	2	64.22	15.03	4.04	3.56	1.89	5.81	0.45	5.01
	3	63.92	13.68	7.71	4.23	3.04	4.30	0.74	2.39
1000	1	63.29	14.95	7.21	3.77	3.20	4.18	1.26	2.14
	2	62.73	15.54	8.08	3.84	3.29	3.28	1.23	2.01
	3	62.45	16.41	7.60	3.30	3.22	3.48	1.91	1.63

The elemental composition presented for the untreated reference in Table 5 confirms that the investigated rock is a typical zeolite mineral in terms of its silicon and aluminum contents. Analcime minerals are specialized zeolites characterized by an aluminosilicate framework containing a high volume of structural channels and porous cavities. To account for the heterogeneous multiphase nature of the natural rock, the EDX data across all thermal conditions were collected utilizing wide-area matrix scanning (Map Sum Spectrum) over representative regions. This approach provides a normalized composition that reflects the collective behavior of the mineral matrix. The elemental data obtained from the EDX analysis explain the surface morphology, increased porosity, and mechanical behavior observed in the SEM images, all of which will be discussed in the subsequent section.

3.2.2. XRD Analysis

According to findings of the XRD analysis conducted on heat-treated natural analcime-bearing rock samples exposed to different temperatures (Untreated, 300 °C, 400 °C, 500 °C, 600 °C, 700 °C, 800 °C, 900 °C, 1000 °C) and durations (under a constant holding duration of 3 h), to provide a clearer interpretation of these heat-induced effects, Figure 12 presents a comprehensive evaluation of the sample phase analysis as a function of temperature.

The mineralogical transformations and structural evolution of the natural rock samples exposed to elevated temperatures were monitored via post-treatment XRD analysis (Figure 12). For the untreated reference sample, characteristic diffraction peaks of the analcime framework alongside primary feldspar reflections are clearly observed. Upon thermal treatment at 300 °C, a distinct and highly intense diffraction peak emerges immediately adjacent to the primary feldspar reflection. This prominent evolution is attributed to the intense dehydration of the analcime framework ($\text{NaAlSi}_2\text{O}_6 \cdot \text{H}_2\text{O}$), where the rapid removal of zeolitic water molecules induces a significant lattice contraction and structural rearrangement, corresponding to the formation of the dehydrated analcime phase. As the temperature is further elevated to 600 °C and beyond (600 °C, 800 °C, and 1000 °C), the characteristic reflections of the analcime framework completely disappear, signifying the progressive collapse of the zeolitic crystalline structure and its transformation into an amorphous phase.

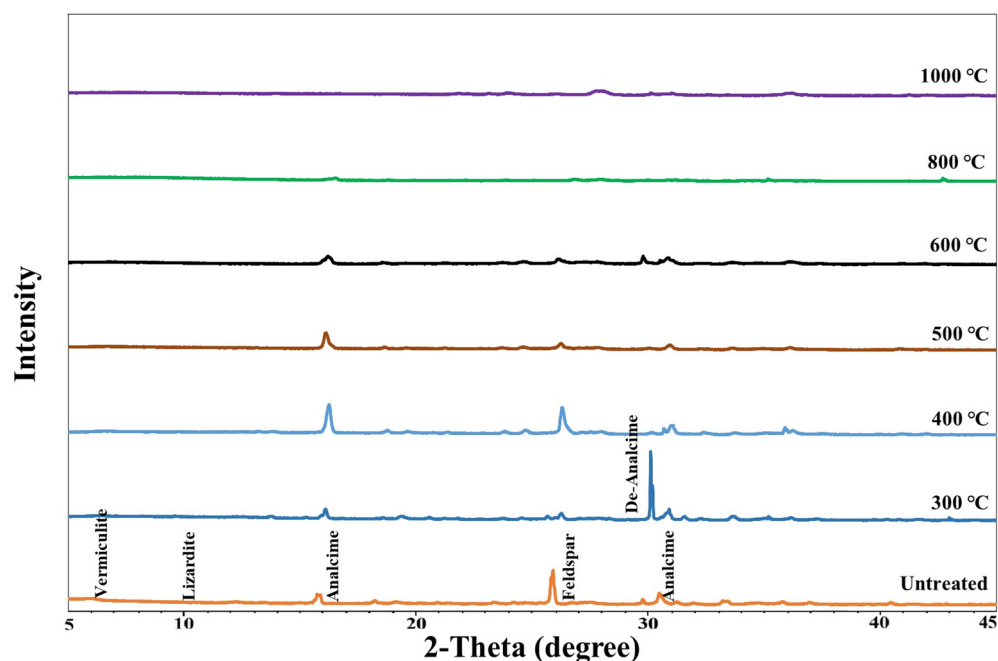


Figure 12. Comparative X-ray diffraction (XRD) patterns of untreated and heat-treated natural analcime-bearing rock samples under a constant holding duration of 3 h.

This crystallographic trend directly confirms that the interconnected aluminosilicate framework exhibits notable thermal stability and maintains its primary crystalline integrity during the initial heating stages. Although the continuous desorption of structurally bound zeolitic water occurs within this temperature window, the mineral skeleton avoids destabilization, facilitating the localized matrix consolidation (pore-closure effect) that supports the macro-mechanical strength optimization observed up to 600 °C. Conversely, a drastic structural divergence was recorded as the exposure threshold transitioned beyond 600 °C. In the XRD patterns of the specimens heat-treated at 800 °C and 1000 °C, a systematic flattening of the baseline and a near-complete disappearance of the primary analcime diffraction peaks were observed, accompanied by the emergence of a broad, amorphous halo. This structural shift provides direct mineralogical evidence of the complete thermal breakdown, lattice dehydroxylation, and subsequent phase amorphization of the analcime crystalline matrix. The total collapse of the aluminosilicate cages induces intense internal shrinkage stresses and volumetric instabilities, explicitly driving the extensive interconnected macro-cracking, apparent porosity increases, and severe loss in compressive and flexural strengths recorded at these extreme thermal boundaries.

3.2.3. Mechanical Analysis

Compressive Strength Test

Thermal processing duration and temperature increases significantly alter the degradation and enhancement mechanisms within the rock framework. According to findings of compressive strength tests conducted on natural analcime-bearing rock samples exposed to different temperatures (Untreated, 300 °C, 400 °C, 500 °C, 600 °C, 700 °C, 800 °C, 900 °C, 1000 °C) and different durations (1, 2 and 3 h), to provide a clearer interpretation of these heat-induced effects, Figure 13 presents a comprehensive evaluation of the sample compressive strength as a function of temperatures and durations.

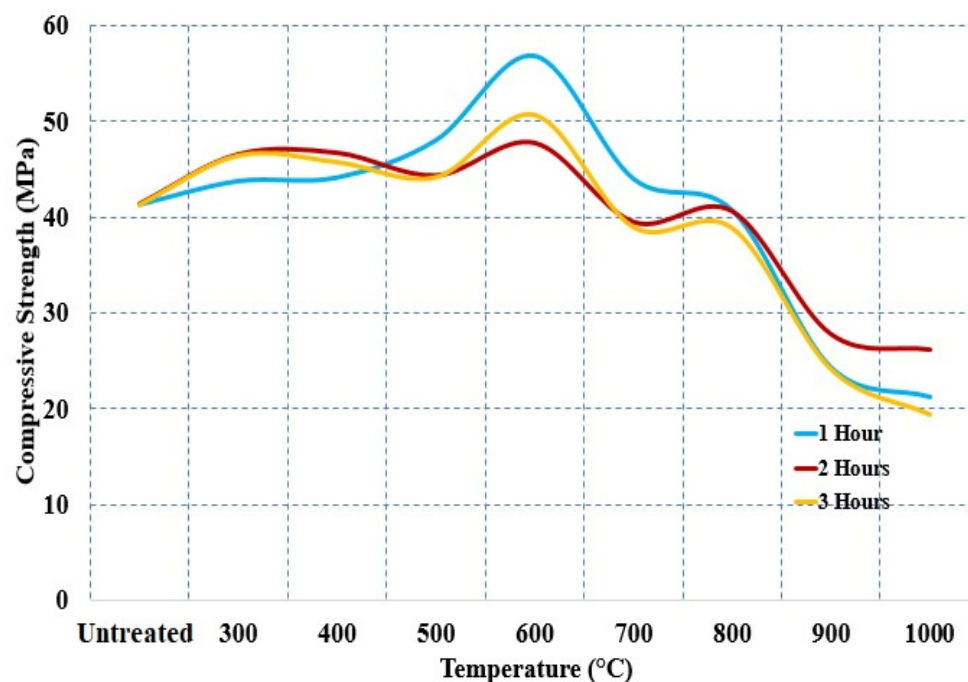


Figure 13. Comparative compressive strengths of the natural analcime-bearing rock as a function of heat treatment temperature and duration.

As illustrated in Figure 13, for 1 h, the compressive strength of the natural analcime rock sample stands at approximately 41 MPa. Elevating the temperature to 600 °C induces a 36% strength increase, peaking at 56 MPa compared to the untreated reference. Beyond 600 °C, the compressive strength decreases progressively, dropping to around 21 MPa at 1000 °C. Consequently, 600 °C is the optimum thermal threshold for maximizing the compressive strength of the 1 h heat-treated analcime stone. For 2 h, heat treatment up to 400 °C enhances the compressive strength of the natural analcime rock from 41 MPa to 46 MPa. Although a slightly reduction occurs at 500 °C, the optimum compressive strength of 47 MPa is attained at 600 °C, similar the behavior of the 1 h treated samples. Above this temperature, the material exhibits an overall declining trend despite minor fluctuations. Therefore, 600 °C is established as the optimum temperature for the 2 h heat-treated samples. The samples heat-treated for 3 h exhibit a thermal behavior similar to those treated for 1 and 2 h. Although a reduction in compressive strength occurs at 500 °C, the optimum compressive strength is again achieved at 600 °C. Beyond this 600 °C threshold, the compressive strength of the 3 h heat-treated sample follows a declining trend, ultimately dropping to approximately 19 MPa at 1000 °C. Despite this significant decrease at 1000 °C, the material still retains roughly 47% of the baseline compressive strength observed in the untreated natural rock sample (41 MPa); this preservation of nearly half its initial strength at such an extreme temperature underscores the thermal durability and structural integrity of the analcime framework under severe thermal conditions. In addition, based on the compressive strength of the natural analcime rock sample, the percentage increases in the compressive strength of samples heat treated at 600 °C for 1, 2, and 3 h are approximately 37%, 15%, and 22%, respectively.

The mechanical test results reveal a gradual decrease within certain limits in the strength values of the samples as the heat treatment temperature increases. Up to 600 °C, the samples maintain a relatively high strength, which is thought to be due to the orderly crystal framework of the rock (Figure 10) that contributes to its bulk compressive strength by redistributing external mechanical stresses across the crystalline lattice. Beyond 600 °C, however, this protective micro-structural integrity is disrupted, leading to a sharp reduction

in rock strength induced by elevated temperatures. This phenomenon, which serves as a direct indicator of thermal stress damage, is demonstrated with distinctly formation of micro cracks and increase in pores as macro observational findings of SEM images (Figure 11). In addition, this thermal mechanism is directly supported by the post-treatment XRD analysis presented in Figure 12. Up to 600 °C, the framework maintains its sharp crystalline peaks, confirming that the structural integrity is preserved during initial dehydration. However, beyond 600 °C (at 800 °C and 1000 °C), the complete collapse of the primary analcime peaks and the emergence of an amorphous halo directly confirm the thermal breakdown of the crystalline lattice, which explicitly accounts for the severe macro-cracking and loss in mechanical strength.

Flexural Strength Test

According to the findings of flexural strength tests conducted on analcime-bearing rock samples exposed to different temperatures and durations, to provide a clearer interpretation of these heat-induced effects, Figure 14 presents a comprehensive evaluation of the samples' flexural strength, illustrating the strength values across varying temperatures for the 1, 2, and 3 h heat-treated samples.

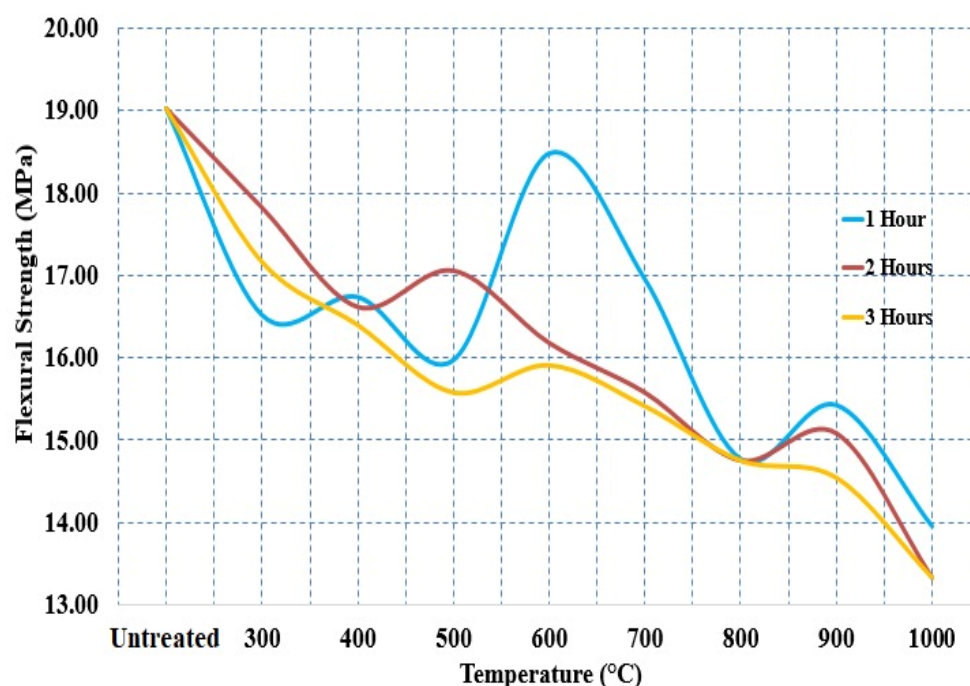


Figure 14. Comparative flexural strengths of the natural analcime-bearing rock as a function of heat treatment temperature and duration.

The experimental findings reveal that a single uniform optimum thermal threshold cannot be generalized for the flexural strength degradation pathways, as the response is highly governed by the duration of thermal exposure. For the short-term 1 h treatment series, the post-heating flexural strength exhibits a conventional consolidation peak near 600 °C (~18.5 MPa). However, prolonging the heating duration systematically shifts the optimal mechanical performance toward lower temperature windows due to the accelerated accumulation of micro-tensile damage along grain boundaries. Specifically, for the 2-h duration series, the absolute post-heating maximum is achieved at 500 °C (~17.0 MPa), beyond which a steady degradation commences. For the extended 3 h soaking series, the material demonstrates its highest post-baseline capacity at the lowest thermal exposure of 300 °C (~17.25 MPa); beyond this threshold, the flexural strength undergoes a contin-

uous reduction, with the 600 °C exposure registering merely as a minor local fluctuation (~15.95 MPa) that fails to recover the strength recorded at lower temperatures. Because flexural capacity is remarkably vulnerable to localized micro-cracking and volumetric expansion compared to bulk compressive matrices, these duration-dependent shifts highlight that extended thermal soaking significantly reduces the temperature threshold at which macro-structural degradation initiates [40].

The semi-quantitative element fluctuations observed via wide-area EDX scanning across the heat-treated samples provide preliminary indications of thermal alterations, which should be considered as tentative hypotheses rather than absolute molecular quantifications. The apparent relative reduction in normalized oxygen percentages at elevated temperatures is hypothesized to follow the macro-trends of thermal dehydration and the loss of structurally bound zeolitic water, a phenomenon widely reported in the thermal analyses of aluminosilicate frameworks. Similarly, the minor fluctuations and apparent relative increases in the localized iron content could tentatively point toward potential thermal oxidation trends or localized phase clustering of iron-bearing impurities within the rock matrix. However, since conventional EDX cannot evaluate hydrogen presence, directly quantify water fractions, or determine iron oxidation states, these elemental shifts remain preliminary. Instead, the actual bulk phase transformations and lattice collapses driving the material's structural performance are directly confirmed and validated via the post-treatment XRD patterns (Figure 12).

Statistical Analysis Using a Two-Way ANOVA

To evaluate the statistical meaningfulness of the recorded dataset and address the inherent heterogeneity of natural rocks, a comprehensive two-factor analysis of variance (two-way ANOVA) was conducted for both compressive and flexural strength across all heating permutations. The outputs have been documented in Tables 6 and 7.

Table 6. Two-way ANOVA results for the compressive strength of the natural analcime-bearing rock.

Source of Variation	SS	df	F	<i>p</i>	Significance
Temperature (T)	6603.54	7	23.06	<0.001	Highly Significant
Duration (d)	20.24	2	0.25	0.782	Not Significant
Interaction (T × d)	760.79	14	1.33	0.228	Not Significant
Residual (Error)	1881.42	46	—	—	—

Table 7. Two-way ANOVA results for the flexural strength of the natural analcime-bearing rock.

Source of Variation	SS	df	F	<i>p</i>	Significance
Temperature (T)	47.74	7	2.29	0.046	Significant (<i>p</i> < 0.05)
Duration (d)	1.32	2	0.22	0.802	Not Significant
Interaction (T × d)	33.60	14	0.81	0.656	Not Significant
Residual (Error)	118.91	40	—	—	—

The variance indices reveal that exposure temperature exerts a highly significant separate effect on both compressive strength ($F = 23.06$, $p < 0.001$) and flexural strength ($F = 2.29$, $p = 0.046$). Conversely, the holding duration and its immediate interaction with temperature did not reach separate statistical thresholds ($p > 0.05$), demonstrating that the fundamental mechanical limits of the analcime matrix are predominantly governed by

the target thermal limits. To display experimental variance without cluttering the visual clarity of the consolidated graphs, all numbers throughout the results text matrix have been updated to report the exact mean values $\pm$ standard deviations (mean $\pm$ SD), providing a mathematically verified dataset. The mean values $\pm$ standard deviations are presented in the Table 8. The standard deviations validate the reproducibility and reliability of the recorded datasets despite the heterogeneous matrix of the natural rock.

Table 8. Compressive–flexural strengths of the natural analcime-bearing rock under heat treatment temperatures and durations.

Temperature (°C)	Duration (Hour)	Compressive–Flexural Strength (MPa) (Mean $\pm$ Standard Deviation)	
		Compressive	Flexural
Untreated (Control)	-	41.35 $\pm$ 1.24	19.03 $\pm$ 1.32
300	1	43.80 $\pm$ 3.08	16.52 $\pm$ 0.18
	2	46.49 $\pm$ 7.94	17.83 $\pm$ 0.50
	3	46.47 $\pm$ 1.82	17.17 $\pm$ 0.76
400	1	44.17 $\pm$ 17.80	16.74 $\pm$ 0.46
	2	46.64 $\pm$ 11.20	16.62 $\pm$ 0.50
	3	45.80 $\pm$ 0.84	16.41 $\pm$ 0.93
500	1	48.08 $\pm$ 3.15	15.97 $\pm$ 0.68
	2	44.29 $\pm$ 0.99	17.06 $\pm$ 1.74
	3	44.22 $\pm$ 0.86	15.59 $\pm$ 0.23
600	1	56.90 $\pm$ 11.04	18.48 $\pm$ 5.32
	2	47.67 $\pm$ 4.62	16.19 $\pm$ 1.06
	3	50.73 $\pm$ 3.73	15.92 $\pm$ 0.23
700	1	44.03 $\pm$ 3.21	16.95 $\pm$ 3.85
	2	39.45 $\pm$ 3.69	15.59 $\pm$ 0.23
	3	57.27 $\pm$ 10.36	15.42 $\pm$ 0.26
800	1	40.72 $\pm$ 6.73	14.76 $\pm$ 0.33
	2	40.56 $\pm$ 4.23	15.42 $\pm$ 0.33
	3	38.89 $\pm$ 5.95	16.40 $\pm$ 2.85
900	1	24.28 $\pm$ 0.42	15.42 $\pm$ 0.66
	2	27.77 $\pm$ 1.45	15.09 $\pm$ 0.33
	3	24.13 $\pm$ 1.45	15.86 $\pm$ 0.69
1000	1	21.21 $\pm$ 2.98	13.95 $\pm$ 0.23
	2	26.18 $\pm$ 4.44	13.34 $\pm$ 0.38
	3	19.42 $\pm$ 0.54	15.86 $\pm$ 0.76

UPV Analysis

In this section, the relationship between Ultrasonic Pulse Velocity (UPV) data and compressive strengths is evaluated. The UPV values of the investigated rock samples are presented in Figure 15.

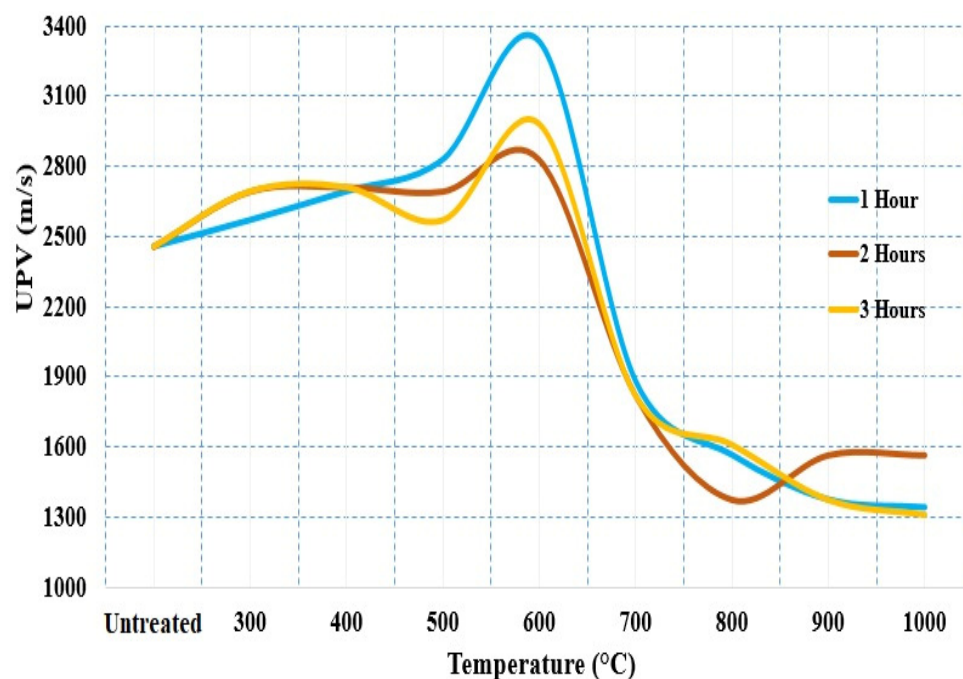


Figure 15. Comparative UPVs of the natural analcime-bearing rock as a function of heat treatment temperature and duration.

An examination of the test results reveals a clear two-stage variation trend in the Ultrasonic Pulse Velocity (UPV) values of the heat-treated rock samples as a function of temperature. Up to a certain threshold temperature, the incremental increase in heat treatment led to a stable, progressive rise in the UPV values. This initial phase can be attributed to the thermal expansion of mineral grains within the rock matrix, which causes volumetric expansion and consequently compresses and closes the pre-existing micro cracks and pores within the internal structure. This matrix compaction and the subsequent reduction in void volume facilitated faster propagation of acoustic waves through the rock medium, thereby positively influencing the UPV data [41]. The measured UPV values exhibited similar the variations determined in compressive strength test results. This consistency among the mechanical indicators confirms that the experimental findings mutually support one another. Such similar trends in velocity and strength parameters aligns with the literature [42]. Instead of remaining stable up to the highest exposures, the actual structural inflection range for the non-destructive readings was initiated between 600 °C and 700 °C, where a sharp and dramatic decline in UPV values commenced. This specific temperature interval marks the onset of progressive internal macro-void formation and intense interconnected micro cracking.

To quantitatively evaluate this mechanical degradation, a regression analysis was conducted to correlate the ultrasonic pulse velocity (UPV) directly with the compressive strength of the samples across all thermal conditions. As illustrated in Figure 16, a moderate determination coefficient ($R^2 = 0.6008$) was achieved utilizing the regression model. This moderate mathematical correlation demonstrates that while the velocity of ultrasonic waves through the internal matrix provides a reasonable trend for predicting the post-thermal mechanical capacity and microstructural integrity of the analcime-bearing rocks, its predictive reliability is somewhat limited. This moderate relationship is attributed to the inherent heterogeneities of natural rock samples, as well as the complex development of thermal microcracks, which introduce scatter into the non-destructive testing data.

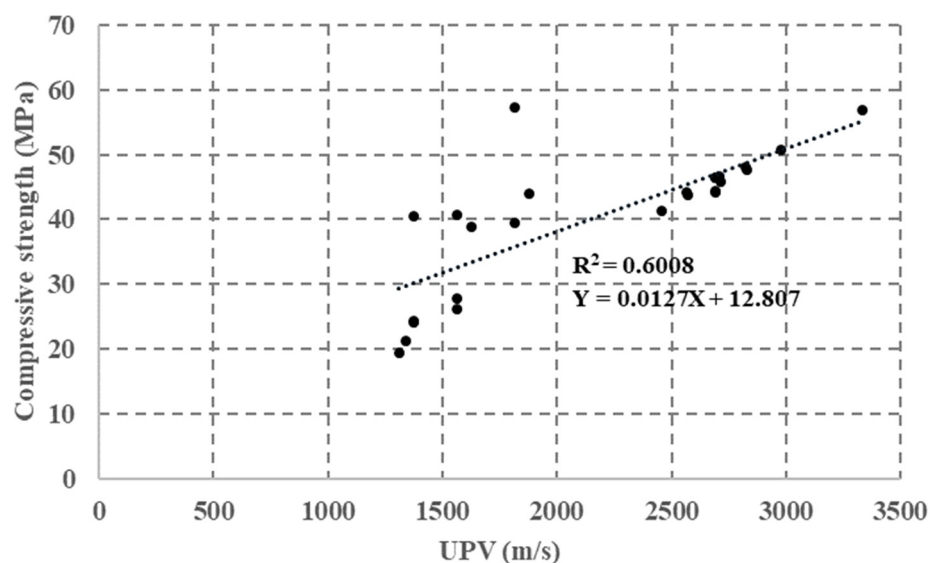


Figure 16. Linear regression correlation analysis between UPV and compressive strength of natural analcime-bearing rock.

3.2.4. Thermal Conductivity Test

Determining the thermal conductivity properties of rocks exposed to heat treatment is of critical importance for understanding the material's heat transfer capacity and its resistance to thermal stresses. Micro-fractures, pores and mineralogical changes induced by high temperatures directly disrupt heat propagation pathways, thereby significantly altering the thermal conductivity coefficient. Therefore, accurately establishing the thermal conductivity data of heat-treated samples is an essential requirement for both mapping the thermal behavior of rocks and correctly interpreting temperature-dependent mechanical degradation mechanisms.

According to the findings of thermal conductivity tests conducted on analcime-bearing rock samples exposed to different temperatures (in the range of 0–1000 °C) and different durations (1, 2 and 3 h), to provide a clearer interpretation of these heat-induced effects, the thermal conductivity coefficients of samples are summarized in Table 9.

Table 9. Thermal conductivity coefficients of the natural analcime-bearing rock under heat treatment temperatures and durations.

Temperature (°C)	Duration (Hour)	Thermal Conductivity Coefficient ($\text{W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$) (Mean $\pm$ Standard Deviation)
Untreated (Control)	-	1.000 $\pm$ 0.032
	1	0.695 $\pm$ 0.021
	2	0.648 $\pm$ 0.015
300	3	0.595 $\pm$ 0.012
	1	0.499 $\pm$ 0.014
	2	0.628 $\pm$ 0.028
600	3	0.597 $\pm$ 0.019
	1	0.442 $\pm$ 0.018
	2	0.569 $\pm$ 0.016
1000	3	0.551 $\pm$ 0.014

As summarized in Table 9, while the thermal conductivity of untreated analcime rock samples was $1 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$, following thermal exposure at 300°C , the thermal conductivity values of the natural rock samples were recorded as 0.695, 0.648, and $0.595 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$ for holding durations of 1, 2, and 3 h, respectively. Compared to the untreated reference sample ($1.000 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$), these shifts correspond to precise reductions of 30.5% for the 1 h duration, 35.2% for the 2 h duration, and 40.5% for the 3 h duration. This duration-dependent systematic decline highlights that prolonged thermal exposure continuously enhances the evacuation of structurally bound moisture, leading to a more pronounced reduction in heat transfer capacity even at lower thermal thresholds. As summarized in Table 9, while the thermal conductivity of the untreated analcime-bearing rock is $1.000 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$, the thermal conductivity values for the rock samples heat-treated at 600°C for 1, 2, and 3 h were determined to be $0.499 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$, $0.628 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$, and $0.597 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$, respectively. Specifically, the thermal conductivity of the sample exposed to 600°C for 1 h decreased by 50.1% relative to the untreated reference. Prolonging the duration to 2 h resulted in a structural fluctuation, where the thermal conductivity increased by 25.9% compared to the 1 h sample, followed by a subsequent decline of 4.9% for the 3 h condition. Similarly, as detailed in Table 9, the thermal conductivity values for the analcime rock samples heat-treated at 1000°C for 1, 2, and 3 h were measured as $0.442 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$, $0.569 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$, and $0.551 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$, respectively. These shifts correspond to specific reductions relative to the untreated control, showing a decrease of 55.8% for the 1 h duration, 43.1% for the 2 h duration, and 44.9% for the 3 h duration.

While the macro-trend of the thermal conductivity coefficient indicates a general reduction under thermal exposure, the profiles exhibit critical non-linear fluctuations, particularly visible in the prolonged 3 h series, which reject a simplistic monotonic model. Specifically, a localized increase in thermal conductivity was recorded at 500°C . This anomaly is associated with the localized framework contraction accompanying the final stages of major zeolitic water desorption [15]. The resulting structural shrinkage temporarily closes micro-pores and optimizes grain-to-grain contact boundaries, facilitating a temporary boost in heat transfer.

A more pronounced non-monotonic divergence occurs beyond the 800°C threshold, where the thermal conductivity values exhibit a notable upward trend. As confirmed by the post-treatment XRD tracking, exposure above 800°C triggers the total crystallographic collapse of the analcime cage lattice, leading to phase amorphization. Under these extreme thermal conditions, the multi-phase natural rock initiates localized sintering and partial vitrification. The generation of a liquid/glassy micro-phase flows into and partially seals the internal thermal microcracks and structural voids. By reducing the volume of heat-blocking air gaps and reconstructing a more continuous, fused amorphous matrix, this vitrification mechanism explicitly accounts for the recorded increase in thermal conductivity coefficients at 1000°C .

3.2.5. Specific Heat Test

In this experimental phase, which is very important for comprehensively understanding the thermal behavior of the rock, the precise determination of specific heat values constitutes a fundamental requirement for both the accuracy of subsequent thermal modeling and practical engineering design. To provide a clearer interpretation of these heat-induced effects in terms of specific heat, Figures 17 and 18 present a comprehensive evaluation of the rock sample specific heat as a function of temperature. Figure 17 shows the variation in the mean specific heat values of rock samples subjected to 3 h of heat treatment as a function of the test temperature, while Figure 18 displays these values as a function of heat-treated duration (1, 2, and 3 h) for 300°C , 600°C , and 1000°C . Additionally, the heat

storage capacity of the test sample that has the porous matrix was determined based on the endothermic desorption dynamics of the naturally trapped water within the crystal framework under controlled temperature gradients.

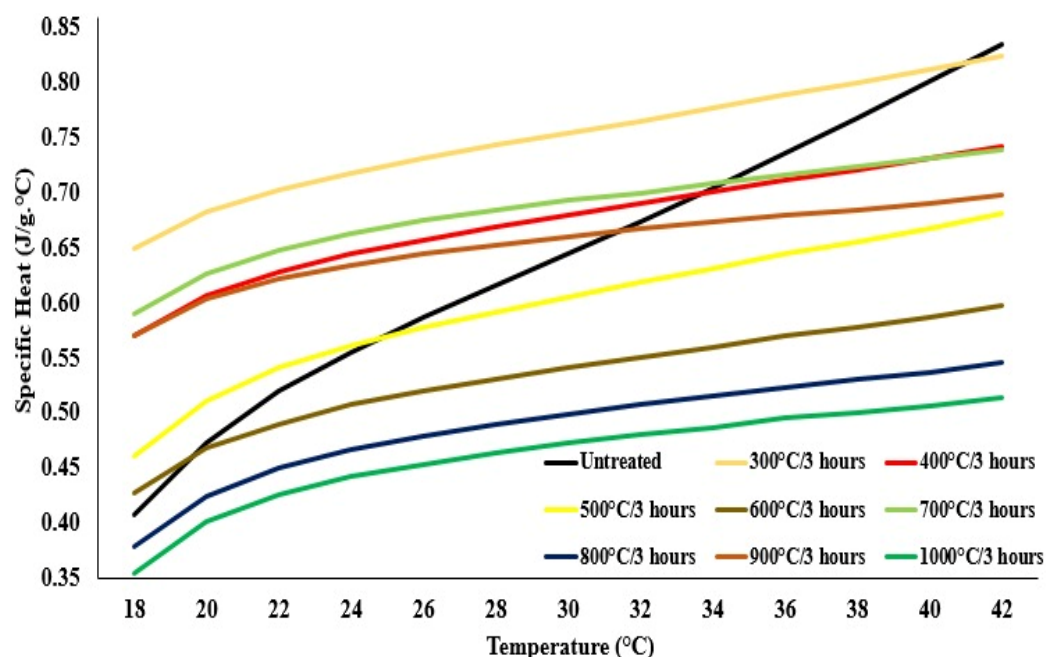
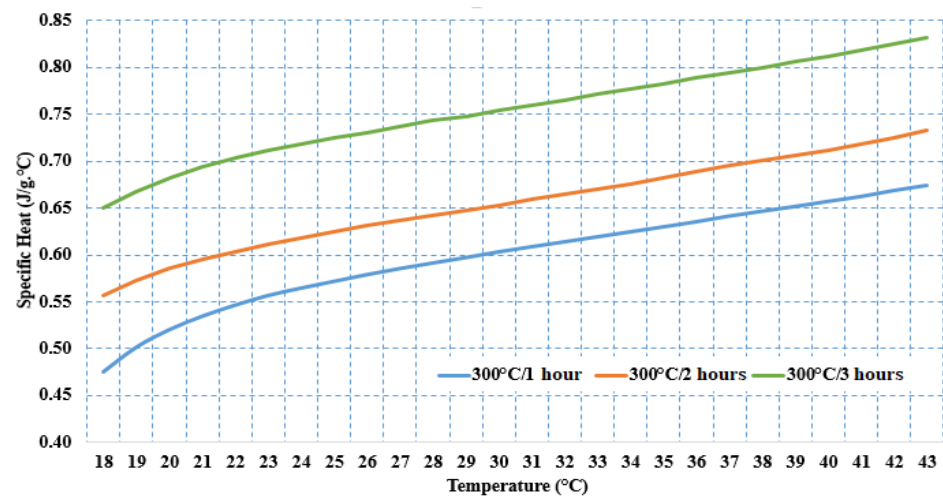


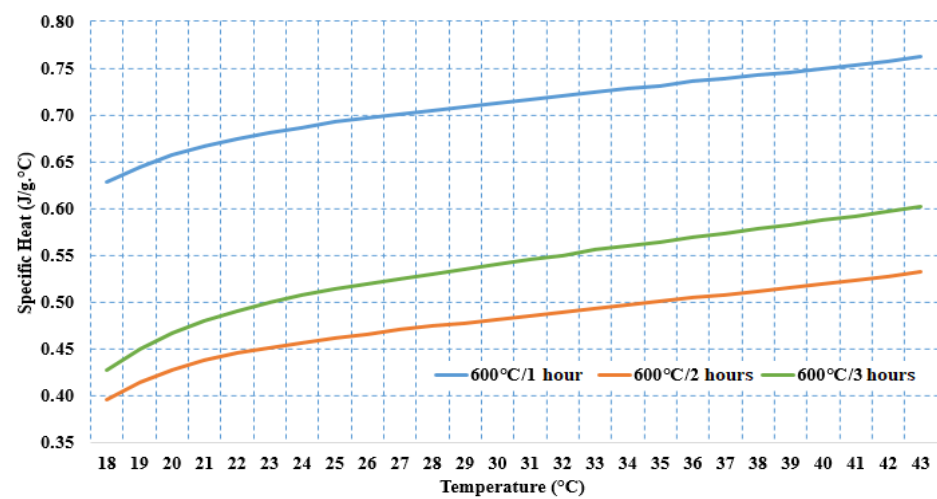
Figure 17. Comparative specific heat values of the natural analcime-bearing rock as a function of heat treatment temperature and duration (3 h).

As shown in Figure 17, the C_p values of the heat-treated samples increased. However, the C_p value of the untreated sample increased more significantly than that of the heat-treated samples. Additionally, Figure 18 illustrates the variations in C_p values for samples treated at 300 °C, 600 °C, and 1000 °C based on the treatment duration (1, 2, and 3 h). It was observed that while the C_p value of the untreated sample increased by approximately 110% with the increment in test temperature, the increase for the heat-treated samples was around 45%.

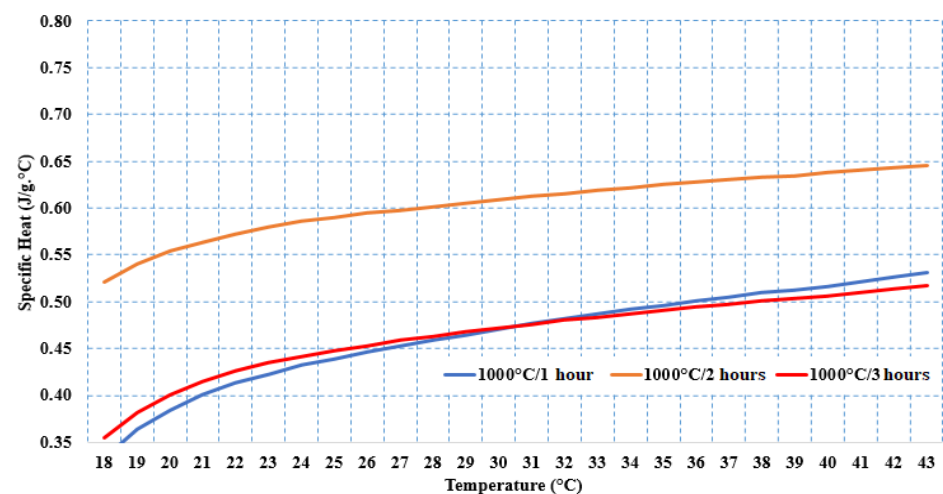
The interplay between the test temperature and heat-treatment duration was found to exert a profound influence on the C_p value of the rock sample. It was observed that while the C_p value of the untreated sample increased sharply by approximately 110% with the increment in test temperature, the corresponding increase for the heat-treated samples was restricted to around 45%. This distinct behavioral divergence indicates a substantial alteration in the rock sample's thermal sensitivity following the heat treatment process. The massive 110% surge in the untreated sample reflects a highly temperature-dependent atomic vibration and structural excitation within its initial, metastable state. In contrast, the significantly suppressed C_p increment (around 45%) in the heat-treated counterparts suggests that the prior exposure to elevated heat treatment temperatures and extended durations induced macro- and microstructural stabilization. Phenomena increase in pore structure based on heat treatment, along with potential phase transformations or grain growth, effectively stabilized the rock matrix. Consequently, the heat-treated samples developed a much higher thermal resistance and microstructural equilibrium, making their specific heat capacity notably less sensitive to subsequent test temperature fluctuations compared to the highly reactive (around 110%) untreated sample.



(a)



(b)



(c)

Figure 18. Comparative specific heat values of the natural analcime-bearing rock as a function of heat treatment temperature and duration. (a) 300 °C/1, 2, and 3 h; (b) 600 °C/1, 2, and 3 h; (c) 1000 °C/1, 2, and 3 h.

As shown in Figure 18a, the effect of heat treatment temperature and duration on the specific heat capacity of the samples was systematically investigated and correlated with

structural changes. For the samples heat-treated at 300 °C, the specific heat value exhibited a clear upward trend as the treatment duration increased, yielding a consistent incremental pattern across all samples and an overall average value of $0.70 \text{ J}\cdot\text{g}^{-1}\cdot\text{K}^{-1}$. Conversely, a prominent behavioral shift was observed at 600 °C; the specific heat value decreased with prolonged heat treatment duration, contrasting sharply with the trend recorded at 300 °C (Figure 18b). Despite this inverse behavior, the reduction pattern remained uniform among the 600 °C samples, resulting in a lower average specific heat value of $0.58 \text{ J}\cdot\text{g}^{-1}\cdot\text{K}^{-1}$. As presented in Figure 18c, when the heat treatment temperature was further elevated to 1000 °C, the specific heat capacity continued its declining trajectory, reaching a minimum average value of $0.51 \text{ J}\cdot\text{g}^{-1}\cdot\text{K}^{-1}$.

The shifts recorded in the thermal energy storage capacity under elevated temperatures point toward complex underlying physical–chemical alterations, which are tentatively discussed as plausible hypotheses rather than definitive causal certainties due to the lack of direct macro-porosity or grain boundary measurements. The potential increase in internal micro-void structures following initial dehydration is hypothesized to influence local thermal fields, thereby temporarily promoting alternative heat storage dynamics within the matrix.

Regarding the sub-microscopic structural modifications, the actual phase transformations driving these performance thresholds are directly validated by post-treatment XRD data (Figure 12). While crystalline framework preservation up to 600 °C supports baseline energy retention, the eventual amorphization at higher temperatures marks a clear mineral collapse. Other accompanying mechanisms, such as localized structural densification or potential grain growth alterations within the secondary mineral phases, are presented strictly as tentative structural hypotheses aligned with established zeolitic literature. This non-causal framing ensures that the interpretations remain fully supported by the verified crystal diffraction dataset [43].

4. Conclusions

This study investigated the mineralogical, mechanical, and thermal behaviors of natural analcime-bearing rocks exposed to heat treatments across a gradient from untreated to 1000 °C for durations of 1, 2, and 3 h obtained from the Ordu (Perşembe) region. The main conclusions drawn from the experimental results are summarized below:

- XRD analysis confirmed that the natural rock possesses a rare and valuable mineral combination consisting mainly of analcime and vermiculite, along with feldspar and lizardite. The co-existence of analcime, known for its highly porous framework, and vermiculite, which possesses exfoliation (expansion) capabilities upon heating, enables this natural rock to exhibit a low thermal conductivity coefficient.
- The micro-porous geometry of the analcime crystals combined with the layered gaps of vermiculite creates natural pockets that trap still air. This porous structure acts as a barrier against heat flow, resulting in a significantly low thermal conductivity coefficient ($\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$). The initial thermal conductivity of $1 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ for the natural analcime-bearing rock exhibited declines of 40.5% after 3 h of heat treatment at 300 °C, and reached a total reduction of approximately 44.9% when exposed to 1000 °C for 3 h.
- The specific heat values of the samples, evaluated strictly at an isothermal DSC measurement temperature of 25 °C, exhibited noticeable changes following thermal treatments. The untreated baseline sample possessed a specific heat value of $0.616 \text{ J}\cdot\text{g}^{-1}\cdot\text{K}^{-1}$. For the samples heat-treated from 300 °C to 1000 °C, the specific heat values altered to 0.754, 0.679, 0.605, 0.541, 0.693, 0.499, 0.660, and $0.472 \text{ J}\cdot\text{g}^{-1}\cdot\text{K}^{-1}$, respectively.

- Due to the ordered crystalline structure of the analcime mineral, bulk rock has a high compressive strength. The mechanical assessment identified 600 °C as the optimum thermal threshold for maximizing both compressive and flexural strengths, followed by a progressive decline in mechanical performance at higher temperatures. The samples maintained nearly half of their baseline strength even after exposure to 1000 °C, highlighting the thermal durability and structural resilience of the material. The optimal post-heating flexural strength systematically shifted toward lower temperature thresholds with increasing duration, peaking at 600 °C for 1 h, 500 °C for 2 h, and 300 °C for 3 h exposure due to accelerated micro-tensile damage.

In conclusion, this study evaluates the mechanical and thermal properties of natural analcime-bearing rocks exposed to various heat treatment durations and temperatures up to 1000 °C. The experimental findings demonstrate that the rock maintains its primary crystalline framework up to a critical thermal threshold of 600 °C, beyond which a significant decline in compressive–flexural strengths and microstructural integrity occurs due to crystal lattice amorphization. Crucially, the conclusions drawn from this research are strictly limited to the measured baseline physical, mechanical, and thermal parameters. While the recorded specific heat and thermal stability profiles indicate that this natural analcime-bearing rock possesses promising thermal characteristics, these properties describe the material behavior at a laboratory scale rather than establishing ready-to-use suitability for complex building systems. Therefore, the investigated rock should be considered a prospective precursor candidate for potential future applications in sensible thermal energy storage components or eco-efficient construction fabrics. Further comprehensive engineering evaluations, including post-thermal volumetric heat capacity mapping, dynamic long-term thermal durability cycling, and life-cycle sustainability assessments, remain strictly necessary in future research to fully validate these application fields.

Author Contributions: Conceptualization, Y.A., M.A. and E.T.; methodology, Y.A., M.A. and E.T.; validation, Y.A., M.A. and E.T.; formal analysis, Y.A., M.A., E.T. and M.C.A.; data curation, Y.A., M.A., E.T. and M.C.A.; writing—original draft preparation, Y.A., M.A., E.T. and M.C.A.; writing—review and editing, Y.A., M.A., E.T. and M.C.A.; supervision, M.A., E.T.; project administration, M.A. and E.T.; funding acquisition, M.A. and E.T. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Scientific Research Projects Coordination Department of Ordu University, Türkiye, grant numbers D-2501 and D-2503.

Data Availability Statement: The authors confirm that the data supporting the findings of this study are available within the article.

Acknowledgments: This study belongs to the Master of Science Thesis conducted in the Renewable Energy Department of Ordu University, Türkiye.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Metwally, W.M. Biomimicry and Green Architecture: Nature-Inspired Innovations for Sustainable Buildings. *Sustainability* **2025**, *17*, 7223. [\[CrossRef\]](#)
2. Stephen, S.; Aigbavboa, C.; Oke, A. Revolutionising Green Construction: Harnessing Zeolite and AI-Driven Initiatives for Net-Zero and Climate-Adaptive Buildings. *Buildings* **2025**, *15*, 885. [\[CrossRef\]](#)
3. Cuce, P.M. Sustainable Insulation Technologies for Low-Carbon Buildings: From Past to Present. *Sustainability* **2025**, *17*, 5176. [\[CrossRef\]](#)
4. Iştoan, R.; Tâmaş-Gavrea, D.R.; Manea, D.L. Experimental Investigations on the Performances of Composite Building Materials Based on Industrial Crops and Volcanic Rocks. *Crystals* **2020**, *10*, 102. [\[CrossRef\]](#)

5. Nikolaidis, P. Solar Energy Harnessing Technologies towards De-Carbonization: A Systematic Review of Processes and Systems. *Energies* **2023**, *16*, 6153. [CrossRef]
6. Podara, C.V.; Kartsonakis, I.A.; Charitidis, C.A. Towards Phase Change Materials for Thermal Energy Storage: Classification, Improvements and Applications in the Building Sector. *Appl. Sci.* **2021**, *11*, 1490. [CrossRef]
7. Al-Mazrouei, N.; Ahmed, W.; Al-Marzouqi, A.H. Characterization and Comparative Analysis of Natural, Sustainable Composite Material Properties Using Bio-Binder for Eco-Friendly Construction Applications. *Buildings* **2023**, *13*, 1324. [CrossRef]
8. Alotaibi, A.M. An Overview of Zeolites: From Historical Background to Diverse Applications. *Molecules* **2025**, *30*, 4036. [CrossRef] [PubMed]
9. Meenu, P.C.; Meena, B.; Smirniotis, P.G. A Review on the Applications of Various Zeolites and Molecular Sieve Catalysts for Different Gas Phase Reactions: Present Trends in Research and Future Directions. *Processes* **2026**, *14*, 132. [CrossRef]
10. Akgün, Y. Determination of Pozzolanic Activity for Using Natural Zeolite Analcime in Sustainability Additive Cement Products. *Period. Eng. Nat. Sci.* **2017**, *5*, 187–193. [CrossRef]
11. Mattioli, M.; Giordani, M. Post-Emplacement Zeolitization in Ignimbrites: Insights from Central Italy Volcanic Rocks. *Minerals* **2025**, *15*, 924. [CrossRef]
12. Akbelen, M. Investigation of Natural Analcime-Rich Zeolite Tuff From Turkey: A Combined XRD, XRF, FT-IR and SEM Study. *Eskişehir. Tech. Univ. J. Sci. Technol. B-Theor. Sci.* **2021**, *9*, 36–41. [CrossRef]
13. Radosavljević-Mihajlović, A.; Radulović, D.; Kasić, V.; Vuković, N.; Stojanović, J.; Radosavljević, S. Analcime-bearing tuffs from Bosnia and Herzegovina: Mineralogy and structure data. *Arab. J. Geosci.* **2023**, *16*, 543. [CrossRef]
14. Varol, E. Interpretation of the origin of analcimes with mineralogical, microtextural, and geochemical investigations: A case study from Aktepe region (NE of Kalecik, Ankara, Central Anatolia, Turkey). *Arab. J. Geosci.* **2020**, *13*, 343. [CrossRef]
15. Sakızcı, M. Investigation of Thermal and Structural Properties of Natural and Ion-Exchanged Analcime. *Anadolu Univ. J. Sci. Technol. A-Appl. Sci. Eng.* **2016**, *17*, 724–734. [CrossRef]
16. Akgün, Y.; Yamak, A.R. Mechanical and Thermal Characteristics of Foam Mortars: Effects of Analcime- and Clinoptilolite-Blended Cements. *Buildings* **2026**, *16*, 2657. [CrossRef]
17. Hofmeister, A.M.; Ke, R. Heat transport properties of feldspathoids and ANA zeolites as a function of temperature. *Phys. Chem. Miner.* **2015**, *42*, 693–706. [CrossRef]
18. Shushkov, D.A.; Simakova, Y.S. Porous Ceramic Materials Based on Analcime-Containing Rocks of Timan (Komi Republic). *Glass Ceram.* **2023**, *80*, 205–211. [CrossRef]
19. Karakaya, N.; Karakaya, M.C.; Temel, A. Mineralogical and chemical properties and the origin of two types of analcime in SW Ankara, Turkey. *Clays Clay Miner.* **2013**, *61*, 231–257. [CrossRef]
20. Yücel, C.; Temizel, R.; Abdioglu, E.; Arslan, M.; Yağcıoğlu, U.C. Origin of analcimes in the Tertiary volcanic rocks from the Eastern Pontides (NE Turkey): A textural, mineralogical and geochemical approach. *Neues Jahrb. Für Mineral.-Abh.* **2014**, *3*, 191. [CrossRef] [PubMed]
21. Abdioglu, E. Mineralogy and chemistry of zeolites and associated minerals in Tertiary alkaline volcanics from the Eastern Pontides, NE Turkey. *Neues Jahrb. Fur Mineral.-Abh.* **2012**, *189*, 35–47. [CrossRef] [PubMed]
22. Çelik, M.; Karakaya, N.; Temel, A. Clay minerals in hydrothermally altered volcanic rocks, Eastern Pontides, Turkey. *Clays Clay Miner.* **1999**, *47*, 6. [CrossRef]
23. Maden Teknik Arama (MTA). Türkiye Zeolit Yatakları Haritası. 2022. Available online: <https://e-madencilik.com/Maden-Rehber/Zeolit-yataklari-haritasi-585> (accessed on 6 February 2025).
24. Soylu, M.; Gökkuş, Ö. Türkiye'deki doğal zeolitler ve iyon değişimi uygulamaları. *Niğde Ömer Halisdemir Üniversitesi Mühendis. Bilim. Derg.* **2017**, *6*, 11–20. [CrossRef]
25. Temel, A.; Gündoğdu, M.N. Zeolite occurrences and the erionite-mesothelioma relationship in Cappadocia, central Anatolia, Turkey. *Miner. Depos.* **1996**, *31*, 539–547. [CrossRef]
26. CEN EN 1936; Natural Stone Test Methods—Determination of Real Density and Apparent Density, and of Total and Open Porosity. European Committee for Standardization: Brussels, Belgium, 2006.
27. CEN EN 13755; Natural Stone Test Methods—Determination of Water Absorption at Atmospheric Pressure. European Committee for Standardization: Brussels, Belgium, 2008.
28. CEN EN 12407; Natural Stone Test Methods—Petrographic Examination. European Committee for Standardization: Brussels, Belgium, 2019.
29. ASTM D2845; Standard Test Method for Laboratory Determination of Pulse Velocities and Ultrasonic Elastic Constants of Rock. ASTM International: West Con-shohocken, PA, USA, 2017. [CrossRef]
30. CEN EN 1926; Natural Stone Test Methods—Determination of Uniaxial Compressive Strength. European Committee for Standardization: Brussels, Belgium, 2006.
31. CEN EN 12372; Natural Stone Test Methods—Determination of Flexural Strength Under Concentrated Load. European Committee for Standardization: Brussels, Belgium, 2022.

32. ASTM C518-21; Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus. ASTM International: West Con-shohocken, PA, USA, 2021. [\[CrossRef\]](#)
33. ASTM E1269-11; Standard Test Method for Determining Specific Heat Capacity by Differential Scanning Calorimetry. ASTM International: West Con-shohocken, PA, USA, 2024. [\[CrossRef\]](#)
34. Neuhoﬀ, P.S.; Stebbins, J.F.; Bird, D.K. Si-Al disorder and solid solutions in analcime, chabazite, and wairakite. *Am. Mineral.* **2003**, *88*, 410–423. [\[CrossRef\]](#)
35. Sönmez, Ö.U.; Temel, A.; Karakaya, M.Ç.; Dogan-Kulahci, G.D. Mineralogy and Geochemistry of Upper Cretaceous-Pliocene Sedimentary Rocks in the Yahşihan Basin, Central Anatolia, Türkiye: Provenance and Tectonic Implications. *Minerals* **2025**, *15*, 92. [\[CrossRef\]](#)
36. Ercan, H.Ü.; Schroeder, P.A.; Korkmaz, G.G.; Ece, Ö.I.; Çiftçi, E. Multidisciplinary insights into zeolite and clay formation in hydrothermally altered volcanic rocks of Çubuk, Turkey. *Clays Clay Miner.* **2025**, *73*, e28. [\[CrossRef\]](#)
37. Breynaert, E.; Vandenabeele, D.; Yan, W.; Valtchev, V.; Sels, B.; Van Speybroeck, V.; Kirschhock, C. A reflection on ‘Flexibility versus rigidity: What determines the stability of zeolite frameworks? A case study. *Mater. Horiz.* **2025**, *12*, 8232–8239. [\[CrossRef\]](#)
38. Tsitsishvili, V.; Dolaberidze, N.; Nijaradze, M.; Mirdzveli, N.; Amiridze, Z. Natural analcime as a raw material for ion exchangers. In *Proceedings of the 2nd International Conference “Modern Technologies & Methods of Inorganic Materials Science”*; InterConf: Tbilisi, Georgia, 2021; pp. 188–192.
39. Abousif, A.; Masoud, A.; Abdullah, M.; Albaghdady, A.; Nasur, F. Mineral and Geochemical Approaches to Identify the Origin of Analcime in the Middle Carboniferous Dimbabah Formation, South-Western Libya. *J. Pure Appl. Sci.* **2025**, *24*, 129–138. [\[CrossRef\]](#)
40. Kruszewski, Ł.; Palchik, V.; Vapnik, Y.; Nowak, K.; Banasik, K.; Galuskina, I. Mineralogical, Geochemical, and Rock Mechanic Characteristics of Zeolite-Bearing Rocks of the Hatrurim Basin, Israel. *Minerals* **2021**, *11*, 1062. [\[CrossRef\]](#)
41. Yavuz, H.; Demirdag, S.; Caran, S. Thermal effect on the physical properties of carbonate rocks. *Int. J. Rock Mech. Min. Sci.* **2010**, *47*, 94–103. [\[CrossRef\]](#)
42. Vagnon, F.; Colombero, C.; Colombo, F.; Comina, C.; Ferrero, A.M.; Mandrone, G.; Vinciguerra, S.C. Effects of thermal treatment on physical and mechanical properties of Valdieri Marble-NW Italy. *Int. J. Rock Mech. Min. Sci.* **2019**, *116*, 75–86. [\[CrossRef\]](#)
43. Liu, H.; Zhao, X. Thermal Conductivity Analysis of High Porosity Structures with Open and Closed Pores. *Int. J. Heat Mass Transf.* **2022**, *183*, 122089. [\[CrossRef\]](#)

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.