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Research Article

Comparative study of physical and mechanical properties of limestone and sandstone at varying temperature condition

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Abstract: Limestone and sandstone are widely used in engineering, yet their behavior remains poorly constrained under combined thermal exposure and water saturation. We experimentally evaluate how temperature (22–750 °C) and saturation alter key physical and mechanical properties of these rocks using a consistent test matrix on 136 cores. Mass, density, and ultrasonic pulse velocity (UPV) were measured before and after heating; the strength was quantified by uniaxial compressive strength (UCS) and Brazilian tensile strength (BTS). Both rocks retained capacity up to ~450 °C, with limestone stronger than sandstone. Above this threshold, the strength and UPV declined markedly, reflecting thermal cracking; limestone showed pronounced density loss at high temperature, consistent with mineral decomposition. Saturation reduced strength in both lithologies, with a larger drop in limestone, and changes in density and UPV tracked these trends. The conceptual advance is a side-by-side, cross-property comparison that links thermal and hydraulic states to coupled changes in mass, density, UPV, UCS, and BTS for two common sedimentary rocks. These results provide practical bounds for designing and assessing rock materials and rock-hosted infrastructure exposed to heat and moisture, from tunnels and foundations to fire and geothermal scenarios.

Keywords: Limestone; Sandstone; High temperature; Water saturation; Density; Ultrasonic pulse velocity (UPV); Uniaxial compressive strength (UCS); Brazilian tensile strength (BTS)

1. Introduction

High temperatures present a considerable challenge to both natural geological processes and engineering applications, often leading to dramatic transformations in the performance of materials and structures. In the world of geology and engineering, understanding how rocks behave when exposed to intense heat is crucial, as high temperatures can weaken, alter, or even cause the failure of essential materials. From the geological perspective, rocks subjected to heat undergo changes in their mineral structure and porosity, which can lead to cracking, fragmentation, and loss of strength. In engineering, this is particularly crucial for materials used in construction, energy systems, and space exploration, where rocks and minerals must withstand extreme temperature without losing their integrity. Heat-induced damage can impact everything from the stability of buildings and infrastructure to the efficiency of geothermal energy systems, making it crucial to understand how these materials behave under such conditions. Limestone and Sandstone, for instance, are commonly used in construction and industrial applications, but their ability to endure high temperatures is not always assured. When heat disrupts their internal structure, materials can become more porous, brittle, and vulnerable to rapid degradation, threatening the safety and reliability of critical infrastructure.

These temperature-induced changes in rock properties are not just of academic interest but also have practical implications in a wide range of fields. Understanding the effects of heat on common construction materials like Limestone and Sandstone is crucial, as both rocks are frequently used in foundations, buildings, facades, and monuments. Their performance under heat can significantly impact the durability of structures, especially in regions prone to high temperatures or in applications involving high-heat environments such as power plants and industrial furnaces. For example, when limestone experiences thermal expansion from high temperatures, its calcite structure begins to degrade, leading to a weakening of the rock and a loss of its load-bearing capacity. In the case of sandstone, heat can change the mineral composition, especially destabilizing clay minerals like kaolinite and smectite, which are vital to the rock's structural integrity.

Several studies have investigated the behavior of these rocks under high-temperature conditions. For instance, Li and Zhang et.al [1] explored the thermal stability and mechanical properties of limestone, noting that temperatures exceeding 600°C lead to significant alterations in its calcite structure, resulting in degradation. Similarly, Vassallo et al. [2] examined sandstone and highlighted how its mineral composition influences its behavior under high heat, particularly focusing on the destabilization of clay minerals. Yilmaz et al. [3] contributed by analyzing the mechanical properties and microstructural transformations in both limestone and sandstone when exposed to fire, shedding light on the chemical and physical changes that occur under such conditions. Zhang et.al. [4] also provided valuable insights into how the mechanical properties, including fracture toughness and compressive strength, of sandstone change with temperature, emphasizing the role of grain size and mineral composition. Additionally, Savage et.al. [5] explored the innovative method of using dry ice cooling to enhance the porosity and permeability of high-temperature rocks, offering a unique approach to mitigating temperature-induced rock degradation.

Numerous other studies have also addressed the complex interaction between high temperature, mineralogy, and rock mechanics. For example, Heap et al. [6] investigated the influence of thermal cracking on the mechanical behavior of granites, while Zhang et al. [7] and Tian et al. [8] examined coupled thermal–hydraulic–mechanical effects on sandstones and limestones. Additionally, Wu et al. [9] explored microstructural evolution in limestones subjected to high temperatures, providing insights into the interplay between porosity development and strength degradation. These studies highlight that thermal effects on rocks are highly material-dependent and often involve combined physical and chemical processes. While these studies have made valuable contributions to the field, they primarily focus on individual aspects of thermal degradation, such as mineralogical changes or isolated temperature conditions. In contrast, the current research offers a more comprehensive analysis by examining the combined influence of water saturation and thermal exposure on the physical and mechanical properties of limestone and sandstone. This study involves three distinct groups: normal dry, water-saturated, and thermally stressed, with the heating group subjected to temperatures ranging from 150°C to 750°C. Notably, while the water-saturated group is not exposed to heat, the heating group undergoes incremental thermal loading to assess the rock's behavior under continuous temperature stress. The analysis focuses not only on the changes in mineral composition and porosity but also on the changes in fundamental mechanical properties such as density, ultrasonic wave velocity, mass loss, uniaxial compressive strength (UCS), and Brazilian tensile strength, comparing these results with the dry conditions.

This approach offers a deeper and more nuanced understanding of how these rocks behave under a combination of environmental factors, providing data that extends beyond conventional mineralogical studies. By combining a wide range of physical and mechanical properties with thermal and saturated conditions, this study expands the understanding of rock behavior under extreme environmental conditions. The findings will offer valuable insights for the design, selection, and performance evaluation of materials used in high-temperature environments, particularly in applications requiring long-term durability and stability.

2. Experimental tests

The laboratory tests were carried out on 136 cylindrical samples of limestone and sandstone. Each type of rock consisted of 68 samples (34 samples for the UCS Test +34 samples for the Brazilian Test). The average diameter of the specimens was 29.4 mm for limestone and 29mm for sandstone. The specimens were cut from core drillings and prepared for thermal treatment and subsequent laboratory measurements [10]. The thermal groups were created, one group at 22°C (room temperature, unaltered), one fully saturated in water, and the remaining groups at 150°C, 300°C, 450°C, 600°C, and 750°C, respectively. The thermal treatment was performed in a Carbolite ABA 7/35 electric oven.

The heating rate was set to 20°C/min to ensure a uniform thermal field, with the temperature gradually increasing to the target values: 150°C (5 minutes), 300°C (8 minutes), 450°C (20 minutes), 600°C (35 minutes), and 750°C (40 minutes). Each group was maintained at its respective temperature for 4 hours [11]. Following this period, the oven was turned off, and the cooling rate was set to 5°C/min until the samples returned to room temperature. Temperature-related changes in the samples were visible to the naked eye. The oven's built-in digital temperature gauge confirmed the heating and cooling rates, and the samples were tested at room temperature after cooling. First, all samples were tested under dry conditions to measure their mass, density, and ultrasonic wave velocity before heating. Next, the heating test was applied to each group until they reached their predetermined temperatures. Finally, after cooling, mass loss, density, and ultrasonic wave velocity (P-wave) were measured (Figure 1).

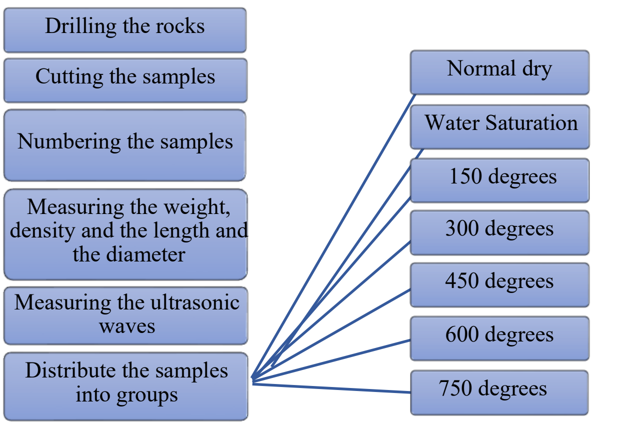

Figure 1. Experimental Methodology

2.1. Physical Properties

The mass loss of the samples was calculated using the following formula [12]:

$$\Delta m = \frac{m - m_T}{m} \quad (1)$$

where m is dry mass before high temperature, m_T is dry mass after high temperature.

The density was calculated using the tested weight and volume of the samples [13]:

$$\rho = \frac{m}{V} \quad (2)$$

where ρ is density of the sample, v is volume of the sample.

The ultrasonic wave velocity was measured by an *acoustic wave instrument type: RS-ST01C* these sound waves bounce back images, which reveal key characteristics of a material's properties. The images created by ultrasonic testing can indicate cracks, weld grooves, and fractures, as well as point out the material thickness and moving components [14]. The heating process was conducted in a Carbolite ABA 7/35 electric oven, with a temperature range from 25°C to 750°C, a heating rate of 20°C/min, and a cooling rate of 5°C/min, until room temperature was reached. Table 1 below shows the oven specifications [12].

Table1. The characteristics of the oven

Furnace type	Temperature range	Heating rate	Cooling rate
Carbolite ABA 7/35 electric oven	25-750 °C	20 °C/min	5 °C/min

2.2. Mechanical Properties

2.2.1. Uniaxial Compressive Strength Test

The UCS test was conducted using a single advanced testing machine that integrates both hydraulic and electronic components (Figure 2). This machine is capable of precisely applying uniaxial stress to rock samples while continuously measuring the resulting strain. It combines features such as load cells for accurate force measurement, displacement sensors for precise strain detection, and hydraulic control systems for maintaining consistent loading rates. Designed to meet industry standards, the machine ensures reliable and repeatable results, with regular calibration to minimize errors and ensure accurate readings during the test.

Figure 2. Uniaxial compressive test and Brazilian strength test

It is well established that the Brazilian test provides an indirect estimate of tensile strength, which may be higher than values obtained from direct tensile testing (Figure 2). This limitation has been widely discussed in the literature [16].

In the UCS test, cylindrical core specimens with a height of 60 mm and a diameter of 30 mm were used. For the Brazilian test, specimens with a height and diameter of 30 mm were employed. After heat treatment, the rock specimens were subjected to compression loading at a constant displacement rate of 0.1 mm/min. Once the sample failed, the machine was stopped, and the data were recorded and analyzed. The stress-strain curve generated during the UCS test indicated the maximum force each sample could withstand [11].

The formula for calculating uniaxial compressive strength (UCS) is:

$$\sigma_c = \frac{F}{A} \quad (3)$$

where σ_c is UCS strength of the sample, F is maximum force applied during the UCS test, A is area of the sample ($A = d^2/4$), d is diameter of the sample.

It is well established that the Brazilian test provides an indirect estimate of tensile strength, which may be higher than values obtained from direct tensile testing. This limitation has been widely discussed in the literature [16]. For the indirect tensile strength calculated after the Brazilian test, the following formula is used [15]:

$$\sigma_T = \frac{2P}{\pi D t} \quad (4)$$

where σ_T is indirect tensile strength of the specimen, P is maximum applied load during the test, D is diameter of the cylindrical specimen, t is thickness of the disc.

3. Results

3.1. Heating results

3.1.1. Mass loss

Figure 3 illustrate how high temperatures affect the weight of limestone and sandstone. Initially, as temperature rises, both rocks experience a slight weight gain. This is observed in sandstone up to 150°C and in limestone up to 300°C. The weight increase can be attributed to the evaporation of free water trapped within the rock pores. For sandstone, the weight rises from 85.1g to 85.27g, and for limestone, it increases from 101.82g to 102.77g.

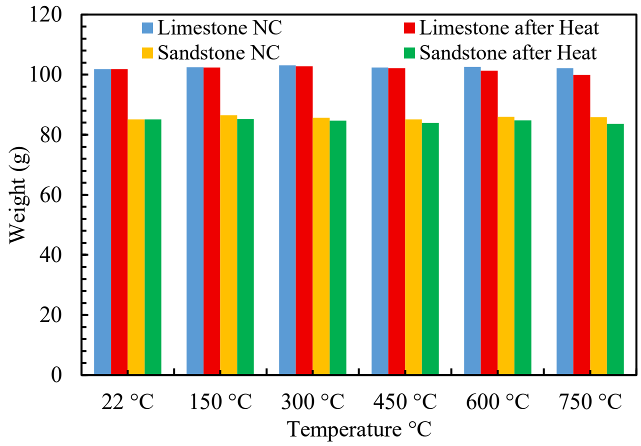

Figure 3. The effect of the temperature on the weight for limestone and sandstone rocks

Beyond these temperatures, however, the trend reverses. As the temperature continues to increase, the weight of the samples begins to drop, with a more pronounced decrease at higher temperatures, especially around 750°C. At this point, the average weight of sandstone decreases to 83.62 g, and limestone to 99.93 g. This reduction in weight is due to the complete evaporation of both free and bound water in the rocks. In sandstone, the porous structure allows significant water retention, and as the temperature rises, this water gradually evaporates, leading to a decrease in weight. In limestone, the weight loss is also due to the release of carbonation gases (CO_2) during the decarbonization process, which becomes more significant as temperatures exceed 600 °C. This release further reduces the rock's mass. Additionally, the rock structures undergo significant changes. After 300°C, micro-cracks begin to form due to the evaporation of pore water. These cracks expand as the temperature increases, evolving into larger fractures. This damage to the internal structure contributes further to the weight reduction, as the increased porosity allows more water to escape.

By 750 °C, both rocks show considerable structural alteration. The number of micro-cracks increases, leading to visible fragmentation in some cases. The rock's density decreases, especially in sandstone, where the space between grains becomes more pronounced. In limestone, the decarbonization process causes the loss of calcium carbonate ($CaCO_3$), weakening the rock's structure and contributing to the overall weight loss. These results are important for understanding the behavior of limestone and sandstone under extreme temperatures. The formation of cracks and the resulting weight loss can impact the rocks' strength and durability, especially in construction applications where temperature fluctuations are a concern.

3.1.2. Density and ultrasonic wave velocity

Figures 4 and 5 offer valuable insights into how high temperatures affect the density and ultrasonic wave velocity (USV) of limestone and sandstone. The density of limestone remains consistently higher than that of sandstone across all tested temperatures. This can be attributed to the composition of these rocks: limestone is primarily made of calcite or calcium carbonate ($CaCO_3$), which has a higher density than the quartz (SiO_2) and feldspar present in sandstone. Furthermore, limestone has fewer and smaller pores compared to sandstone, which is more porous and often filled with air or water. The higher porosity in sandstone contributes to a lower density compared to limestone, as the trapped air or water significantly reduces its overall mass per unit volume.

As the temperature increases, both rocks experience a slight decrease in density. However, this trend becomes more pronounced after 600°C, especially for limestone. The density of limestone drops dramatically from 2.61 t/m³ to 1.43 t/m³ at 750°C. This significant decrease can be explained by the chemical decomposition of calcium carbonate ($CaCO_3$) at elevated temperatures. At temperatures above 600°C, calcium carbonate decomposes into quicklime (CaO) and carbon dioxide (CO_2) gas.

This reaction results in a reduction in the solid volume of the rock because the gas (CO_2) is released, while the remaining solid—quicklime—has a lower volume than the original limestone. While the overall mass of the limestone remains unchanged, the release of gas causes the rock's volume to increase, leading to a decrease in density. Moreover, the crystal structure of quicklime differs from that of limestone, which further contributes to changes in the rock's density. In contrast, the minerals in sandstone, primarily quartz and feldspar, have high melting points and exceptional thermal stability. These minerals maintain their structure at high temperatures, which helps explain why the density of sandstone remains relatively stable even as temperature rises.

Turning to Figure 5, we observe the effect of temperature on ultrasonic wave velocity (USV) in both rocks. Initially, the USV remains nearly unchanged as the temperature increases from ambient to 300°C. This is consistent with the density behavior, as both the density and USV are closely linked—when the structural and bonding water migrates out of the rock, the internal structure remains relatively intact, so the USV stays stable. However, as the temperature surpasses 300°C, the water evaporates, and micro-cracks begin to form, creating channels between the pores. These micro-cracks disrupt the rock's structure and result in a decrease in USV. For limestone, the USV decreases notably at 450°C, dropping from 4.68 km/s to 3.96 km/s. This reduction is primarily due to thermal expansion, which induces internal stresses within the limestone. These stresses can cause microcracking, which alters the rock's elasticity and stiffness, affecting how ultrasonic waves propagate through it. The breakdown of limestone into quicklime also impacts the velocity, as the elastic properties of the material change, resulting in a further reduction in USV. In sandstone, the formation of cracks and changes in its pore structure, induced by high temperatures, similarly affect the USV. As the temperature rises, microcracking eventually leads to macro-cracks, which significantly disrupt the wave propagation, causing a noticeable drop in USV beyond 300°C.

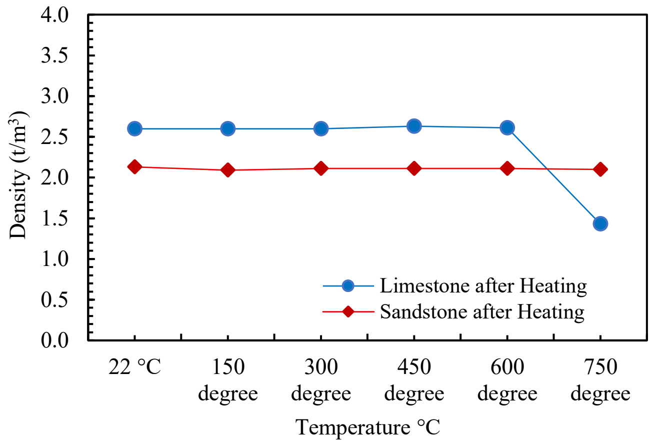

Figure 4. The effect of the temperature on the density for limestone and Sandstone rocks

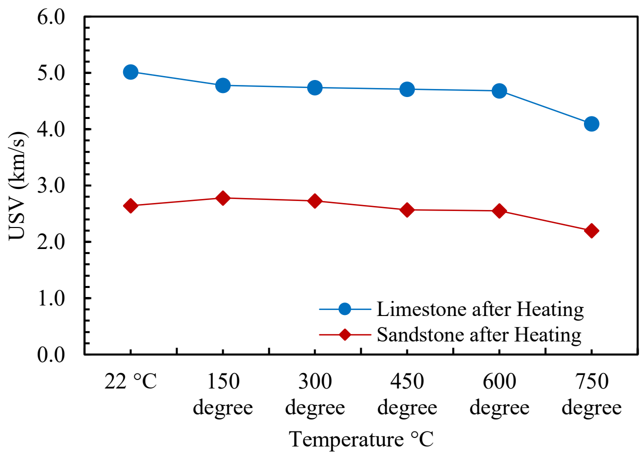

Figure 5. The effect of the temperature on the USV for Limestone and Sandstone rocks

In summary, the combined effects of high temperatures on density and ultrasonic wave velocity reveal the complex thermal behavior of these rocks. The density of limestone decreases sharply due to chemical decomposition, while sandstone maintains its structure until a higher temperature threshold, after which both the density and USV decrease as micro- and macro-cracks develop. These findings not only highlight the temperature-induced transformations in these rocks but also provide critical insights into their stability and potential applications under extreme conditions.

3.1.3. Uniaxial compressive strength and brazilian strength tests

Figures 6 and 7 illustrate the variation in uniaxial compressive strength (UCS) and indirect tensile strength (BTS) of limestone and sandstone with increasing temperature. The results provide insight into how these two common foundation and construction materials respond mechanically under thermally induced stress conditions. At room temperature (22 °C), limestone exhibits a UCS of 14.83 MPa, notably higher than sandstone (9.26 MPa). This difference reflects the denser microstructure and stronger cementation of limestone compared with the more porous and granular texture of sandstone. As the temperature rises to 150 °C and 300 °C, both rocks show a moderate increase in strength. This behavior is consistent with the drying and removal of pore water, which improves interparticle contact and reduces internal pore pressure, temporarily enhancing stiffness and strength. Such effects are often observed in engineering materials subjected to mild heating, particularly when the temperature remains below the threshold of mineral decomposition. A distinct strength peak is recorded at 450 °C, where limestone reaches its maximum UCS of 23.65 MPa. This can be attributed to the combined effects of thermal expansion and stress redistribution, which cause the closure of existing microcracks and densification of the rock matrix. For sandstone, the increase is less pronounced, reaching 7.83 MPa, owing to its higher porosity and weaker cementation. From a geotechnical perspective, this indicates that limestone can temporarily gain strength under moderate heating, whereas sandstone remains governed by its inherent fabric and pore structure. Beyond 450 °C, both materials show a clear degradation in compressive strength. At 600 °C, the UCS of limestone falls to 13.18 MPa and further declines to 10.05 MPa at 750 °C. This reduction is primarily driven by calcite decomposition ($CaCO_3 \rightarrow CaO+CO2$), This chemical breakdown weakens the limestone structure by disrupting the cohesive bonds between the mineral grains (Ibrahim, 2017) [17]. The resulting thermal stresses often exceed the rock's structural capacity, causing the initiation and propagation of microcracks. As these cracks spread through the rock, they further weaken its integrity, making it more prone to failure. In contrast, sandstone's strength is less affected by this temperature range, likely due to the more stable nature of its mineral constituents.

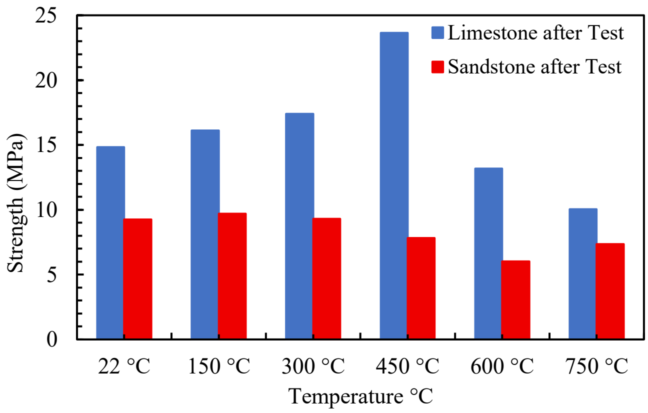

Figure 6. The effect of the temperature on UCS test

3.2. Saturation results

3.2.1. Mass loss

Figure 8 illustrates the impact of saturation on the weight of limestone and sandstone rocks. It is evident that the weight of the limestone experienced a slight increase from 102.73 to 103.07g after saturation. In contrast, the weight of the sandstone significantly increased from 84.62 to 88.44 g following saturation. This discrepancy in weight change can be attributed to the higher porosity of sandstone compared to limestone. Sandstone possesses greater pore space, and when saturated, these pores fill with water, resulting in a notable increase in weight. Conversely, limestone, with lower porosity, shows a relatively minor weight increase post-saturation. The increased weight of the sandstone reflects its ability to absorb and retain more water due to its porous nature, whereas the limited pore space in limestone restricts its water absorption capacity and subsequent weight gain. Additionally, factors such as grain size, mineral composition, and pore connectivity also contribute to the differential weight changes observed between the two rock types after saturation.

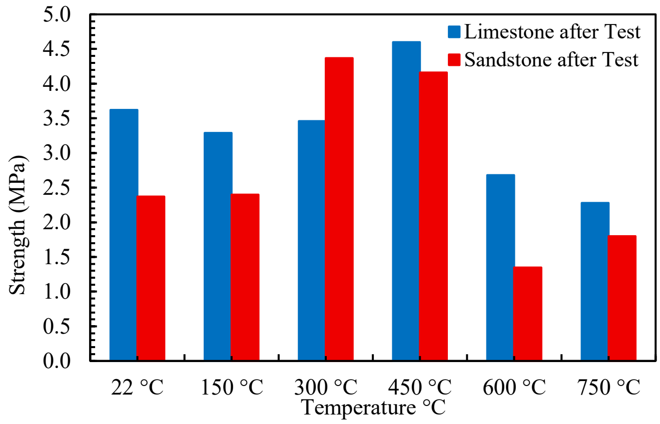

Figure 7. The effect of the temperature on tensile test

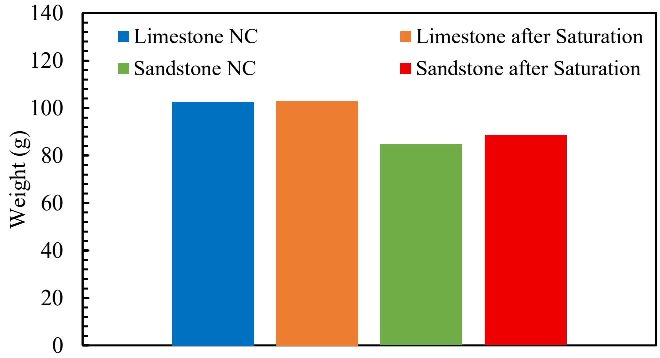

Figure 8. The effect of the saturation on the weight

3.2.2. Density and ultrasonic wave velocity

Figures 9 and 10 show us the effect of the density and the ultrasonic wave velocity after the saturation for limestone and sandstone rocks. The density and the ultrasonic wave velocity are proportional to each other, a higher density typically corresponds to stronger interatomic bonds and a stiffer material, resulting in faster transmission of ultrasonic waves. This relationship holds true in homogeneous materials with uniform density, where denser packing of atoms leads to higher ultrasonic velocities. However, the presence of porosity or structural irregularities can disrupt this proportional relationship by impeding the transmission of ultrasonic waves. As we can see in the figures 9 and 10, the density and the USV of the limestone increased strongly after the saturation 2.55to 2.80 t/m^3 and 4.75 to 5.39 km/s respectively. Limestone typically possesses a denser structure with fewer pore spaces compared to sandstone. When saturated with water, limestone can more effectively fill its remaining pore spaces, leading to a significant increase in density and stiffness. Additionally, limestone's mineral composition, primarily composed of high-density minerals like calcite or dolomite, contributes to its enhanced response to saturation. The cementation between mineral grains in limestone is often more pronounced than in sandstone, further reducing porosity and increasing material density. Conversely, sandstone, with its higher initial porosity and potentially less dense mineral composition, undergoes a comparatively smaller increase in density and ultrasonic wave velocity following saturation from 2.11 to 2.21 t/m^3 for the density and from 2.6 to 2.7 km/s for USV.

3.2.3. Uniaxial compressive strength and brazilian strength tests

Figures 11 show us the UCS strength for both rocks before and after the saturation, as we can see that after the saturation the strength decreased for both rocks from 14.83 to 7.67 MPa for limestone rock and from 9.26 to 7.54 Mpa for sandstone rock. The significant reduction in limestone strength following saturation can be attributed to a complex interaction of various factors. When water permeates the pore spaces of limestone during saturation, it disturbs the bonds between mineral grains, diminishing the cohesive forces. This infiltration not only raises pore pressure within the rock but also aids in the propagation of microcracks, further undermining the limestone's structural integrity.

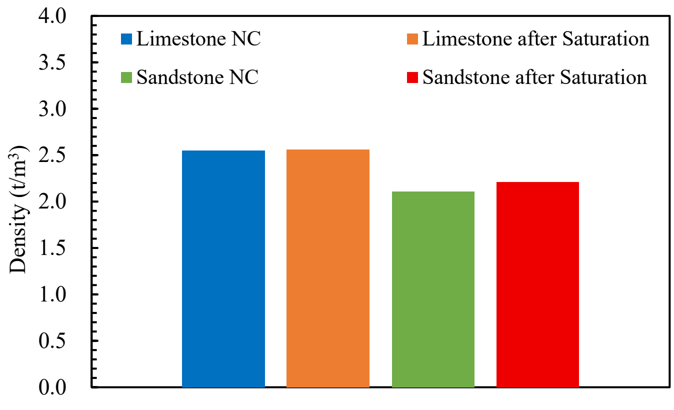

Figure 9. The effect of the saturation on the density

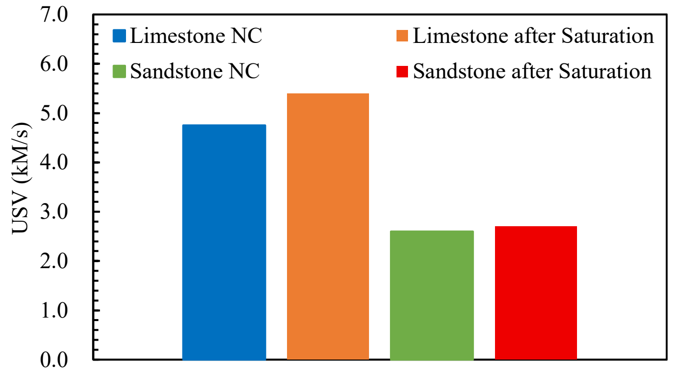

Figure 10. The effect of the saturation on the USV

Additionally, the presence of water alters the mechanical properties of the minerals in the rock, potentially leading to mineral dissolution or modification, which worsens the weakening effect. Furthermore, limestone's relatively limited porosity hampers effective drainage, resulting in water accumulation within its pore network, which exacerbates the adverse effects of saturation on its strength. In contrast, sandstone's response to saturation is characterized by a more nuanced interplay of factors. While water infiltration into sandstone pore spaces also weakens intergranular bonds and induces microcrack formation, the higher porosity of sandstone allows for more efficient drainage and limits water retention within the rock. This mitigates the extent of pore pressure buildup and reduces the severity of microcrack propagation, resulting in a milder decrease in strength compared to limestone. Furthermore, the mineral composition and cementation characteristics of sandstone play a significant role in its response to saturation. Sandstone may exhibit greater resilience against saturation-induced weakening due to the presence of cementing materials that enhance intergranular cohesion and resist water infiltration. Additionally, the water occupying sandstone pores may act as a supportive medium, providing additional mechanical stability and partially offsetting the strength loss.

In summary, the pronounced decrease in limestone strength after saturation is primarily attributed to its low porosity, limited drainage capacity, and susceptibility to water-induced microcracking and mineral alteration. Conversely, sandstone's higher porosity, effective drainage, and resilient mineral composition contribute to a comparatively milder decrease in strength following saturation. The complex interaction of these factors underscores the diverse responses of different rock types to saturation and highlights the importance of considering their inherent properties when assessing their behavior under environmental conditions such as saturation.

Figures 12 illustrate the effect of water saturation on the Brazilian strength of limestone and sandstone. Tensile strength is a critical mechanical property that governs a rock's ability to resist tensile stresses before failure. In natural conditions, most rocks exist in partially saturated states, and their mechanical behavior can significantly change when fully saturated. For limestone specimens, the indirect tensile strength in the dry state was recorded at 3.62 MPa. However, upon full saturation, the strength exhibited an unexpected increase to 4.60 MPa. This behavior can be attributed to the mineralogical composition and microstructural properties of limestone. Limestone, primarily composed of calcium carbonate (CaCO3), contains a relatively lower porosity compared to sandstone. During the saturation process, water molecules can penetrate the microstructure, potentially leading to slight dissolution and recrystallization effects that enhance intergranular cohesion. Additionally, capillary forces within the fine pore network may contribute to strengthening under tensile loading by increasing effective cohesion between mineral grains.

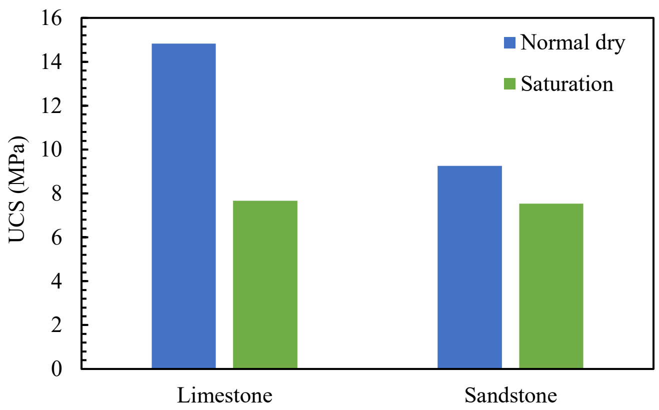

Figure 11. Changes in strength at from dry to saturation condition for limestone and sandstone

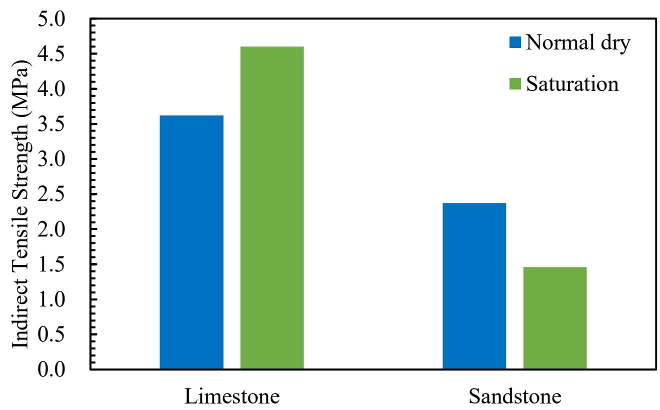

Figure 12. Changes in indirect strength at dry condition for limestone and sandstone

Conversely, sandstone demonstrated a more conventional weakening trend upon saturation. In the dry state, its indirect tensile strength measured 2.37 MPa, but after saturation, it declined to 1.64 MPa—a reduction of approximately 30%. This decrease is primarily linked to the sandstone's higher porosity and permeability, which facilitate water infiltration into its pore spaces. When water fills the voids, it reduces interparticle friction and weakens grain contacts, leading to a decrease in overall cohesion. Furthermore, water pressure within the pores can contribute to microcrack propagation under tensile loading, accelerating failure. This behavior aligns with the well-documented softening effect of water on sedimentary rocks with granular structures.

The contrasting responses of limestone and sandstone to saturation highlight the importance of microstructural characteristics in determining mechanical strength. While limestone may exhibit a slight strength enhancement due to pore fluid interactions and recrystallization, sandstone's higher porosity and granular texture make it more vulnerable to weakening upon water absorption. These findings are essential for understanding rock stability in engineering applications, particularly in construction, tunneling, and reservoir engineering, where water-rock interactions play a crucial role in long-term durability and structural integrity.

4. Discussion

The results of this study clearly highlight the contrasting thermal and hydraulic behavior of limestone and sandstone, reflecting their distinct mineralogical compositions and microstructural frameworks. Both rocks exhibited stable mechanical performance up to approximately 300–450 °C, after which a pronounced degradation occurred. Limestone showed a notable increase in uniaxial compressive strength (UCS) up to 450 °C (23.65 MPa), followed by a sharp reduction beyond 600 °C, whereas sandstone displayed a gradual decline across the entire temperature range. These differences stem from the thermal reactivity of calcite in limestone compared with the relative stability of quartz in sandstone.

Above 600 °C, limestone experienced rapid deterioration due to calcite decomposition ($CaCO_3 \rightarrow CaO + CO_2$), resulting in gas release, increased porosity, and weakened intergranular bonding. This transformation led to a significant drop in both density and ultrasonic pulse velocity (UPV), confirming that UPV is an effective non-destructive parameter for identifying thermally induced damage. In contrast, sandstone maintained structural stability up to the α–β quartz transition (~573 °C), where thermal expansion and differential strain initiated new microcracks. While this transition reduced stiffness and UCS, the damage progression remained more gradual than in limestone, reflecting the superior thermal resilience of quartz-rich frameworks.

At moderate temperatures (≤450 °C), both rocks exhibited a temporary improvement in mechanical strength. This enhancement can be attributed to the evaporation of pore water and the closure of pre-existing microcracks, which improve intergranular contact and stiffness. However, as temperature increases further, the accumulation of microcracks and internal stresses surpasses the rock's tensile limit, leading to a reduction in strength and ultrasonic velocity. The correlation between decreasing UPV and UCS beyond this point highlights the coupled deterioration of physical and mechanical properties under elevated temperature.

The saturation experiments further reveal distinct hydromechanical responses between the two rocks. Both limestone and sandstone experienced a reduction in UCS following full saturation, but the decrease was more severe in limestone (from 14.83 MPa to 7.67 MPa) than in sandstone (from 9.26 MPa to 7.54 MPa). The difference is attributed to limestone's finer pore network and stronger capillary retention, which promote water-induced microcracking and pore pressure buildup. In contrast, sandstone's higher porosity allows better drainage, mitigating internal stress concentration. Interestingly, limestone showed a slight increase in Brazilian tensile strength (BTS) after saturation, likely due to capillary bonding and limited recrystallization effects within fine pores. Sandstone, however, exhibited a decrease in BTS, consistent with reduced interparticle friction and cohesion under wet conditions.

From an engineering perspective, these findings underscore the importance of considering both thermal and hydraulic factors in rock design and assessment. Limestone, while initially stronger, is highly sensitive to high-temperature exposure and moisture infiltration, making it less reliable in fire-prone or water-saturated environments. Sandstone, though weaker at ambient conditions, retains more stable residual strength and demonstrates better thermal endurance. For geotechnical applications such as tunneling, underground storage, or geothermal systems, incorporating temperature- and moisture-dependent strength reduction factors is essential. Post-fire or heat-affected rock assessments should prioritize UPV and density measurements to evaluate the extent of internal damage and residual integrity.

In summary, limestone exhibits greater initial mechanical capacity but undergoes abrupt degradation after thermal decomposition and water saturation, whereas sandstone degrades more gradually yet consistently under similar conditions. The integrated analysis of density, UPV, UCS, and BTS presented here provides valuable diagnostic indicators for evaluating the stability of thermally or hydrologically altered rock masses, contributing to safer and more reliable engineering design under extreme environmental conditions.

5. Conclusions

This study provides valuable insights into how high temperatures and saturation influence the mechanical properties of limestone and sandstone, shedding light on their structural behavior under extreme conditions. The results demonstrate that while both rocks undergo initial minor weight changes, their responses diverge significantly at elevated temperatures. Beyond 600°C, limestone experiences a sharp decline in density due to calcite decomposition, whereas sandstone remains more structurally stable due to the α-β quartz phase transition. This distinction is crucial for understanding material degradation in fire-prone environments and high-temperature applications.

The effect of water saturation further reveals key differences between the two rock types. While limestone exhibits a moderate reduction in tensile strength, sandstone shows a more severe decline due to its higher porosity and weaker intergranular bonding. These findings emphasize the role of rock microstructure in determining durability in moisture-rich environments, which is particularly relevant for underground engineering and infrastructure exposed to fluctuating humidity.

By addressing both thermal and saturation effects, this study contributes essential data for predicting rock behavior in challenging environments. The results provide a more refined understanding of material deterioration, enabling engineers to make informed decisions when assessing the long-term stability of structures subjected to heat and water exposure.

Author contributions

Conceptualization, A.M; methodology, B.A; validation, B.A, formal analysis, B.A; investigation, B.A; data curation, B.A; writing — original draft preparation, B.A; writing — review and editing, E.A; visualization, E.A; supervision, A.M and H.B.A; project administration, A.M and H.B.A. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

All the authors claim that the manuscript is completely original. The authors also declare no conflict of interest.

Data availability

All relevant data related to this manuscript are available and can be provided upon reasonable request.

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