



ORIGINAL PAPER

**THERMAL AND FREEZE-THAW-INDUCED DEGRADATION OF LIMESTONE:
A COMPREHENSIVE STUDY ON PHYSICO-MECHANICAL PROPERTIES**

Abid NAWAZ^{1)*}, **Muhammad SAJID**^{2,3)}, **Waqas AHMED**¹⁾, **Abdul Rahim ASIF**^{1,4)},
Fahad ALSHEHRI⁵⁾, **Sattam ALMADANI**⁵⁾, **Muhammad SHAHAB**^{5)*},
Muhammad AMIN⁶⁾ and **Muhammad Ahmad AFZAL**⁷⁾

¹⁾ National Centre of Excellence in Geology, University of Peshawar, Peshawar 25120, Pakistan

²⁾ Department of Geology, University of Peshawar, Peshawar, 25120, Pakistan

³⁾ Helmholtz Centre Potsdam - German Research Centre for Geosciences (GFZ), Telegrafenberg, 14473 Potsdam, Brandenburg, Germany

⁴⁾ Department of Geology, FATA University, FR Kohat, Pakistan

⁵⁾ Abdullah Alrushaid Chair for Earth Science Remote Sensing Research, Geology and Geophysics Department, King Saud University, P.O. Box 2455, 11451 Riyadh, Saudi Arabia

⁶⁾ Department of Earth Sciences, The University of Haripur, Haripur, 22620, Pakistan

⁷⁾ Department of Civil Engineering, Ghulam Ishaq Khan Institute of Engineering Sciences and Technology, Swabi, 23640, Pakistan

*Corresponding author's e-mail: abidgeo88@uop.edu.pk; shahabgeo07@gmail.com

ARTICLE INFO	ABSTRACT
Article history: Received 27 February 2025 Accepted 2 May 2025 Available online 14 May 2025	This manuscript thoroughly investigates the effects of temperature variations on the physico-mechanical properties of limestone taken from the Nowshera formation in northwestern Pakistan. The rock samples were subjected to heat treatment at various temperatures, ranging from 150 °C to 600 °C for 24 hours. Additionally, the samples underwent freeze-thaw cycles, alternating between room temperature and -40 °C, with each cycle lasting 8 hours (4 hours of freezing followed by 4 hours of thawing). Both destructive tests (uniaxial compressive strength, point load index) and non-destructive tests (specific gravity, ultrasonic pulse wave velocity, porosity, and water absorption) were performed to evaluate the rocks' responses to these temperature variations. The density of induced fractures was calculated at the investigated temperatures and after 50 and 100 freeze-thaw cycles. The results indicate reductions in uniaxial compressive strength (UCS), specific gravity, ultrasonic pulse velocity (UPV), and point load (PL) strength with increasing temperature or number of freeze-thaw cycles. After thermal treatment at 600 °C, UCS decreased by 71 %, point load strength by 74 %, UPV by 49 %, and specific gravity by 7.8 %. Similarly, after 100 freeze-thaw cycles, these properties decreased by 23 %, 19 %, 15 %, and 2.6 %, respectively. Conversely, fracture density, porosity, and water absorption increased with elevated temperatures and freeze-thaw cycles. At 600 °C, increases of 2.51 % in fracture density, 66.5 % in porosity, and 67 % in water absorption were observed. Additionally, after 100 freeze-thaw cycles, these properties increased by 1.44 %, 10 %, and 12.8 %, respectively. Significant changes in all properties were noted when the temperature exceeded 300 °C or the number of freeze-thaw cycles surpassed 50. These findings highlight the degradation of rocks and alterations in their physico-mechanical properties due to thermal variations, which have important implications for industries such as mining and construction.
Keywords: Physico-mechanical Thermal treatment Freeze-thaw Destructive and non-destructive tests Fracture density Thermal damage	

1. INTRODUCTION

Rocks are widely utilized in construction, both as crushed stone and dimension stone, among other applications. They can be used in their natural state or combined with cement, water, and sand to produce concrete (Bell, 2007). Composed of minerals, a binding matrix, and various pores and fractures, rocks exhibit specific physical and mechanical properties. These properties are influenced by factors such as the mineral composition, texture, and the geometry and density of pores and fractures (Bubeck et al., 2017). When selecting rocks for construction purposes, these physical and mechanical properties are crucial considerations, as they determine the rock's suitability for engineering applications (Asif et al., 2022, 2024).

Temperature variations have a significant impact on the structural integrity and physical characteristics

of rocks. Previous studies have shown that temperature-induced changes in rocks lead to the formation of new fractures and microcracks, altering the microstructure of the rock and increasing the volume of voids (Chaki et al., 2008). This transformation can affect the rock's strength and durability, which is particularly relevant in regions subjected to extreme temperature fluctuations. Thus, it is essential to understand the effects of both high and low temperatures on the development of microcracks and the resulting changes in the rock's physical properties. A number of studies have examined the impact of temperature fluctuations on the microstructure of rocks, yet the specific effects of freeze-thaw cycles, in particular, remain underexplored in certain rock types, such as limestone.

Limestones, which are primarily composed of calcium carbonate (CaCO₃) in the form of calcite or

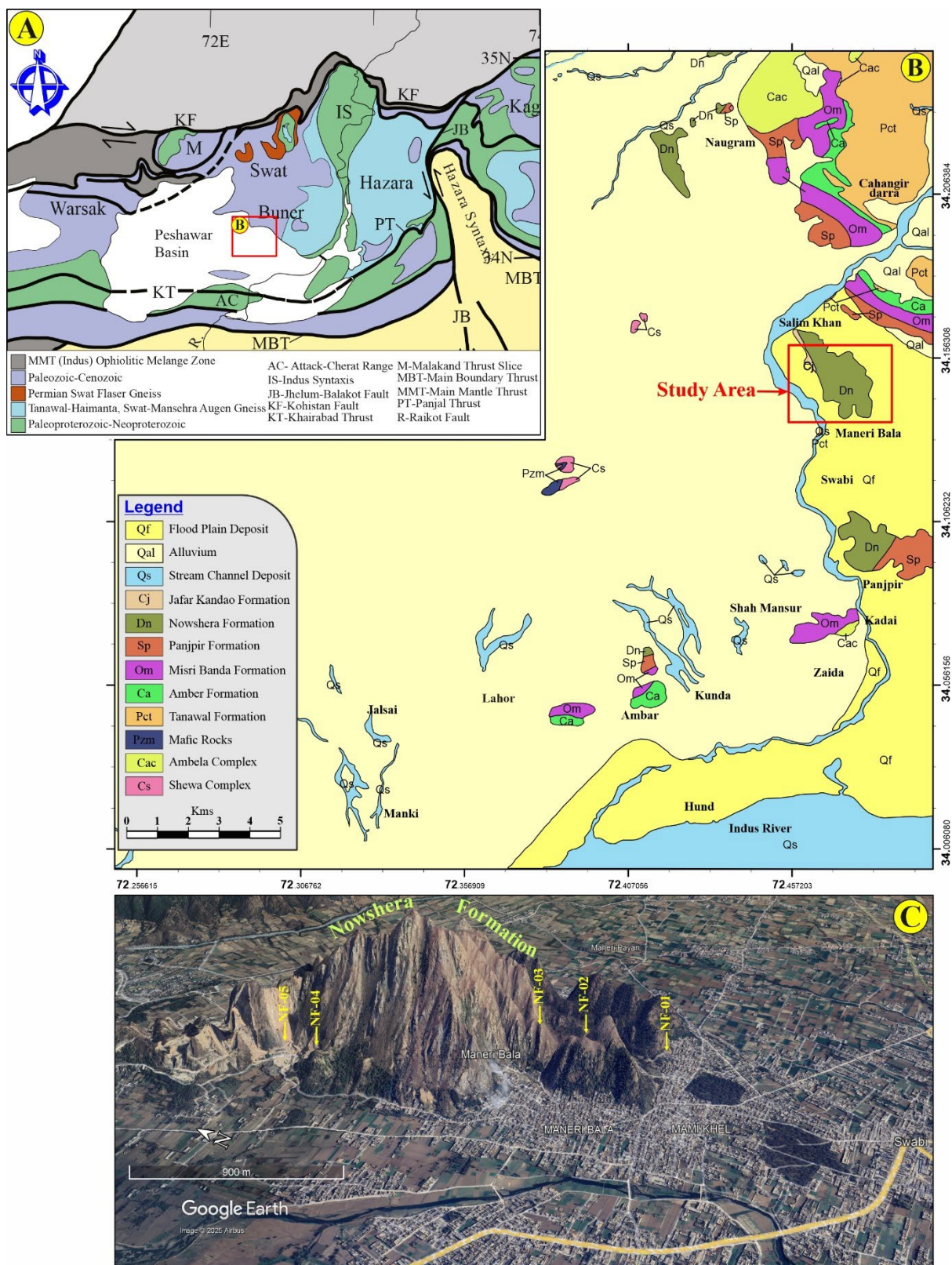


Fig. 1 A) Regional geologic map of the western Himalayas, Pakistan showing the location of the Peshawar Basin and its structural boundaries with an inset showing the current study area (modified after DiPietro et al., 2021). B) Geological map of the northeastern Peshawar basin showing the location of the study area (modified from Pogue et al., 1992). C) A Google satellite image showing the sampling location of the Nowshera Formation, Maneri Section.

aragonite, are commonly used in construction due to their strength and durability. Previous research has demonstrated that the physical, mechanical, and chemical characteristics of limestone play a crucial role in determining its suitability for construction applications (Asif et al., 2021; Mofteh et al., 2022). Studies have also shown that calcareous rocks, including limestone, experience significant degradation when subjected to thermal treatments and freeze-thaw cycles. For example, research by Chaki et al. (2008) highlighted the detrimental effects of thermal cycles on limestone's structural integrity, such as increased porosity and decreased strength. However, while these studies contribute to the understanding of limestone's behavior under temperature stress, they do not specifically address the effects of such treatments on Nowshera limestone, which is the focus of this study.

The Nowshera Formation, consisting of fossiliferous limestone, calcareous and dolomitic quartzite, argillites, and sandy dolomite, has been well-documented in terms of its geological composition (Ahmad et al., 2023). However, to date, no study has specifically investigated the effects of thermal treatment and freeze-thaw cycles on its physical and mechanical properties. This research aims to address this gap by examining the changes in the mechanical and physical characteristics of Nowshera limestone subjected to both heat treatment and freeze-thaw cycles. The limestone samples were exposed to a range of temperatures, from -40°C (below freezing) to 600°C (high temperature), and the resulting changes in their properties were evaluated. This study builds on previous research by providing experimental data on how both freeze-thaw cycles and thermal treatments affect Nowshera limestone, which is essential for understanding the rock's behavior in engineering applications, particularly in regions with extreme temperature variations.

Furthermore, the results of this study offer valuable insights into the damage mechanisms of limestone at both low and high temperatures. By comparing the behavior of Nowshera limestone to other calcareous rocks studied in prior works, this study makes a significant contribution to the existing body of knowledge. It also provides experimental references for rock engineering projects where temperature variations could potentially impact material integrity.

2. GEOLOGICAL SETTINGS

This study focuses on the limestone of the Nowshera Formation, which is located in the northeastern Peshawar basin in the Maneri village region, district Swabi (Fig. 1). The research region is located between longitudes $72^{\circ}15'00''\text{E}$ and $72^{\circ}30'00''\text{E}$ and latitudes $34^{\circ}00'00''\text{N}$ and $34^{\circ}15'00''\text{N}$. There are many different rock types and formations in this region's geological background, but the Nowshera Formation is of special importance for its sedimentary limestone deposits.

3. EXPERIMENTAL CAMPAIGN

A comprehensive field investigation was conducted in the Peshawar Basin to sample the Nowshera Formation at the Maneri Section, located between latitudes $34^{\circ}00'00''\text{N}$ – $34^{\circ}15'00''\text{N}$ and longitudes $72^{\circ}15'00''\text{E}$ – $72^{\circ}30'00''\text{E}$ (Fig. 1). Outcrop characteristics such as texture, thickness, and color were documented in detail. Samples were carefully selected based on freshness, absence of fractures, and homogeneity to ensure isotropy and consistency in testing.

To obtain representative bulk limestone samples, multiple techniques were employed. Fresh outcrop surfaces were prioritized, and where necessary, core drilling, chiseling, and trenching were used to access unweathered rock. Large blocks were also extracted from selected sites. All samples were sealed and stored properly to preserve their integrity, ensuring they accurately reflect in-situ geological and mechanical properties.

3.1. THERMAL TREATMENT

Bulk samples from the Nowshera Formation were taken during fieldwork in northern Pakistan (Fig. 1). These samples were cut into $2 \times 2 \times 2$ -inch cubes at the National Centre of Excellence in Geology (NCEG), University of Peshawar. Following that, two cubic specimens from each sample were heated to a range of temperatures, including room temperature, 150°C , 300°C , and 600°C . The objective of this method was to examine and assess the physico-mechanical alterations brought about by these temperature variations. The samples were allowed to progressively cool in the air at room temperature after being exposed to the designated temperature ranges. Thin sections of the samples treated at all temperatures were made to analyse the changes that occurred during thermal treatment. The thermal treatment of the samples was carried out in the Geochemistry Laboratory of the National Centre of Excellence in Geology, University of Peshawar.

3.2. FREEZE-THAW TESTING

The cube specimens were subjected to a sequence of freeze-thaw cycles, with a duration of eight hours per cycle. The samples were subjected to -40°C for four hours during each cycle, followed by four hours of room temperature (25°C) thawing. The samples went through 50 and 100 cycles as part of the investigation. Thin sections of the samples were produced to examine changes in their physico-mechanical characteristics following the freeze-thaw treatments. In addition, a single sample of every type of rock was kept at room temperature for future study and comparison. The freeze-thaw experiments were conducted at the Sulaiman Bin Abdullah Aba Al-Khail Centre for Interdisciplinary Research in Basic Science (SA-CIRBS), International Islamic University, Islamabad, Pakistan.

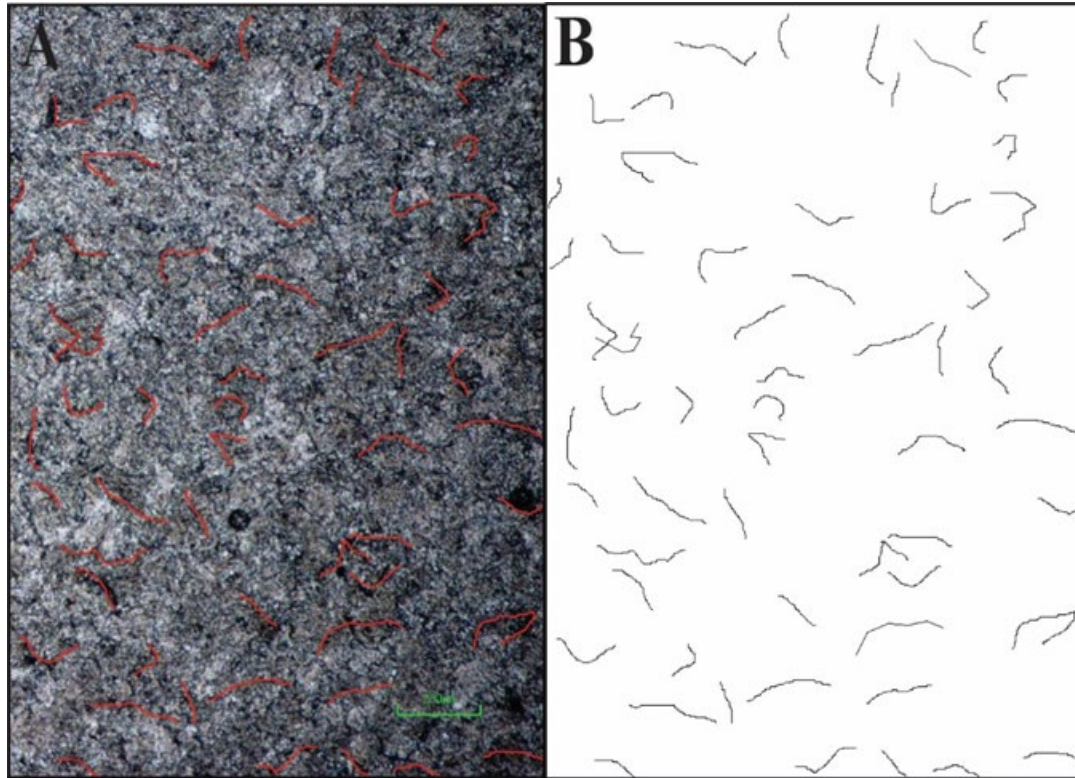


Fig. 2 Fractures pointed out after 50 freeze-thaw cycles in Nowshera limestone.

4. FRACTURE DEMARCATION

To enable a thorough analysis of the samples' internal structures and changes, thin sections of the samples were made at ambient temperature as well as at each treatment temperature. These thin sections were photomicrographed to provide visual records for analysis. The photomicrographs of treated samples were compared to the photomicrographs of untreated samples (at room temperature) using ImageJ software to locate and delineate individual fractures. Every fracture that was apparent in the photomicrographs was measured exactly in terms of both area and extent. The entire area of the rock specimen that was put on the thin section was also calculated. Next, the following formula was used to get the fracture density.

$$\text{Fracture density} = 100\% - (\text{Area of thin section} - \text{Area of Fractures}) / \text{Area of thin section} \times 100$$

Several important factors were taken into consideration when analysing thin sections to find induced fractures. First, different fracture patterns, such as straight or curved lines that cross or pass through the rock matrix, were seen in the treated samples. In the thin section, these fractures could show up as black isotropic lines or discontinuities. The existence of iron leaching around the fractures, which results in obvious colour changes or staining patterns after therapy, was another important indication. These fractures can be distinguished from other kinds of discontinuities or cleavages by their frequent irregular and jagged patterns. After 50 freeze-thaw cycles, the

photomicrograph of limestone is shown in Figure 2A, and the fracture analysis produced by ImageJ software is shown in Figure 2B.

5. RESULTS

5.1. FRACTURING

5.1.1. THERMALLY INDUCED FRACTURING

As the temperature rises, the study shows that the examined samples have an increase in fracture density, as shown in Figures 3 and 4. The image below shows how increasing temperatures cause fracture densities in rock samples. Limestone has a fracture density of 0.73 at 150 °C and 2.51 % at 600 °C temperature. Moreover, the rock starts deteriorating above 600 °C.

The results revealed significant mineralogical transformations in limestone when subjected to varying temperatures. At temperatures exceeding 600 °C, the calcite in the limestone underwent calcination, converting into powdered lime (CaO) and releasing carbon dioxide (CO₂). This transformation led to a noticeable degradation in the limestone's structure, as evidenced by increased porosity and a reduction in strength. Additionally, at around 300 °C, the limestone samples showed the development of microcracks, which further contributed to the deterioration of the rock's mechanical properties. These findings highlight the thermal behavior of limestone and provide a detailed understanding of how temperature influences its mineralogical composition and overall structural integrity.

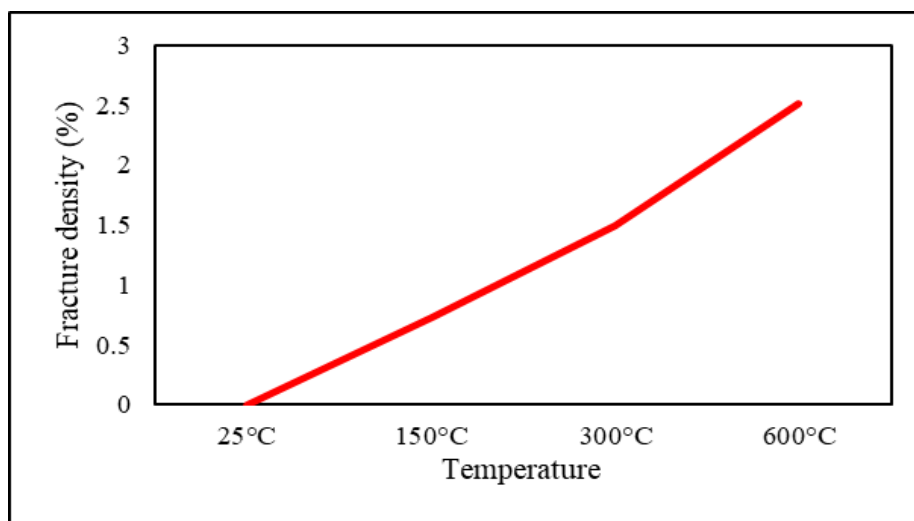


Fig. 3 Fracture density of limestone across different temperatures.

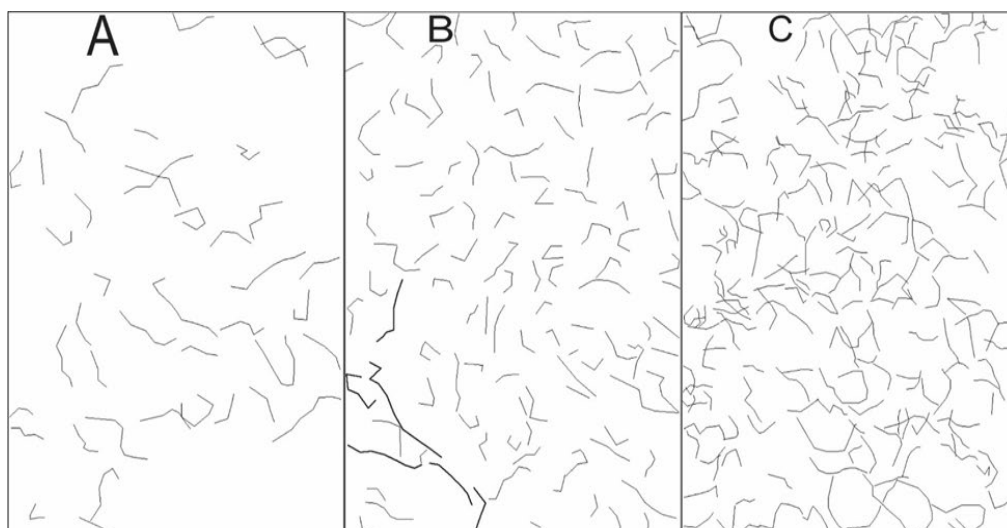


Fig. 4 Fracture distribution in Nowshera limestone across different temperatures: (A) 150 °C; (B) 300 °C; (C) 600 °C.

5.1.2. FREEZE-THAW-INDUCED FRACTURING

Based on the number of freeze-thaw cycles, the fracture density of the samples under investigation increased (Figs. 5, 6). The limestone's fracture density increased to 0.88 % following fifty cycles. After 100 freeze-thaw cycles, the fracture density reached 1.44 %. The extent and intensity of the fractures increased as the number of cycles increased. This demonstrates that limestone is extremely prone to fragmentation during freeze-thaw process.

5.2. PHYSICO-MECHANICAL TESTING

Rock samples treated at each temperature were put through destructive and nondestructive tests following treatment in order to assess the physico-mechanical behaviour. Physical tests like specific gravity, water absorption, porosity, and ultrasonic pulse velocity (UPV) were conducted in addition to mechanical tests like point load (PL) testing and

uniaxial compressive strength (UCS) testing. In compliance with the American Society for Testing and Materials (ASTM) guidelines, these tests were carried out.

The UPV of each specimen was measured using a pitch-catch approach with two transducers (transmitter and receiver) (ASTM-D-2845-08). The samples were weighed in air, water, an oven, and a water-saturated state lasting 24 hours. The following formulas were then used to calculate the bulk porosity, bulk saturated specific gravity (DC97/C97M-18), and bulk water absorption:

$$\text{Water absorption} = \frac{(\text{Water saturated weight} - \text{Dry weight})}{\text{Dry weight}}$$

$$\text{Specific gravity} = \frac{\text{Saturated weigh}}{(\text{Saturated weight} - \text{Weight in water})}$$

$$\text{Porosity} = \frac{(\text{Weight in air} - \text{Dry weight})}{(\text{weight in air} - \text{weight in water})}$$

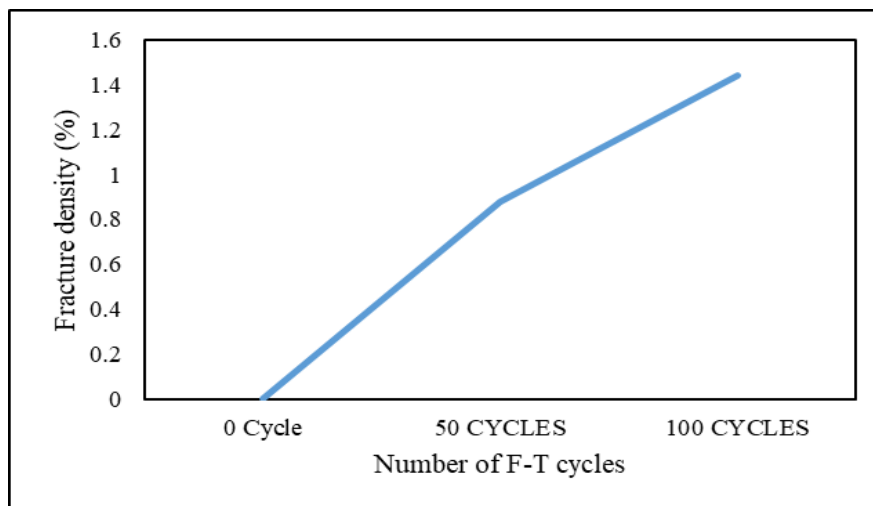


Fig. 5 Fracture density of limestone after various F-T cycles.

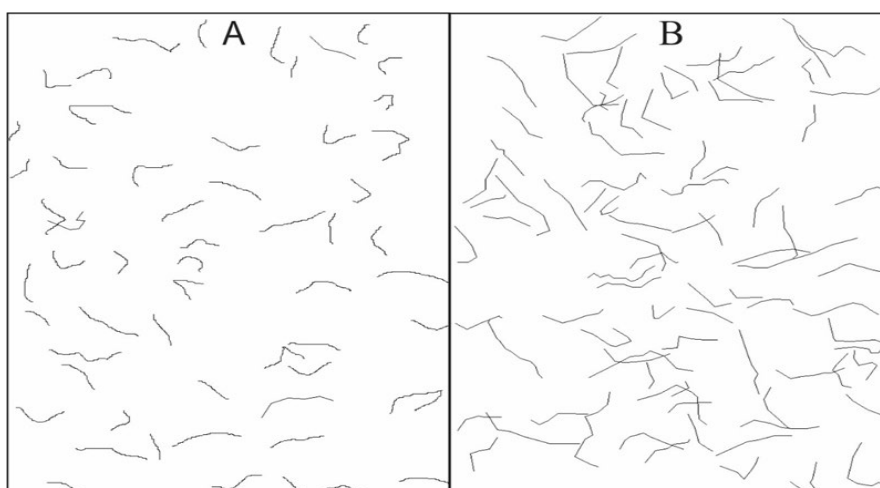


Fig. 6 The distribution of fractures in rocks with an increasing number of freeze-thaw cycles: (A) 50 (B) 100 cycles.

Table 1 UCS, Point load, UPV, and Fracture density results for limestone.

Temperature	Properties			
	UCS(MPa)	Point load (MPa)	UPV (m/s)	Fracture density (%)
25°C	56	31	3537	0
150°C	48	27	3157	0.73
300°C	42	22	2709	1.5
600°C	16	8	1792	2.51
FT 50 Cycles	51	29	3350	0.88
FT 100 Cycles	43	25	3010	1.44

The unconfined compressive strength (ASTM D7012–14e1) and point load testing (ASTM D5731) were also performed on the treated samples.

5.2.1. UNIAXIAL COMPRESSIVE STRENGTH (UCS)

As temperature rises and freeze-thaw cycles proceed, there is a general decrease in UCS. To be more precise, during these experiments, limestone gradually loses its strength. As shown in Figures 7 and

8, the UCS values obtained at room temperature, at higher temperatures, and following 50 and 100 freeze-thaw cycles are compiled in Table 1. Beyond 600 °C, the limestone disintegrates, with its UCS dropping to 71 % of its initial value (Fig. 7A and Table 1). Likewise, the UCS of limestone dropped by 9 % after 50 freeze-thaw cycles and by 23 % after 100 freeze-thaw cycles (Fig. 8A and Table 1).

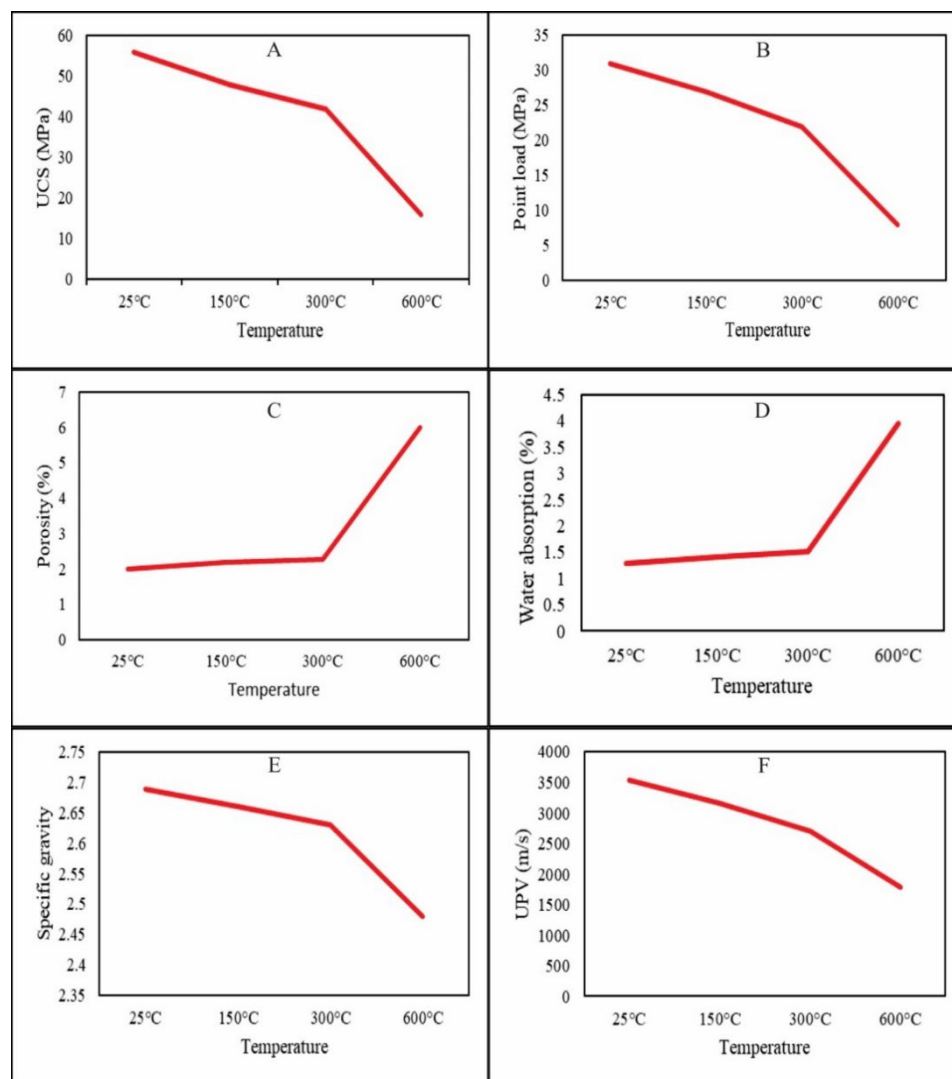


Fig. 7 Influence of temperature on physico-mechanical properties of limestone: (A) UCS; (B) Point load; (C) Porosity; (D) Water absorption; (E) Specific gravity; (F) UPV.

5.2.2. POINT LOAD

The experimental findings show that the point load strength of the limestone samples is significantly impacted by temperature and the cycle of freeze-thaw. The point load strength initially decreases slightly as the temperature rises from room temperature to 150 °C. A comparable pattern is noted in the freeze-thaw cycle as temperature rises. The point load strength of the limestone decreases by 74 % at 600 °C (Fig. 7B and Table 1) and by 19 % following 100 cycles of freeze-thaw (Fig. 8B and Table 1).

5.2.3. POROSITY, WATER ABSORPTION AND SPECIFIC GRAVITY

With increasing temperature, the porosity of limestone generally increased. Furthermore, the total porosity increased following the freeze-thaw cycles, most likely as a result of the increased fracture density. The findings from porosity tests carried out at different temperatures are shown in Figures 7 and 8 as well as

Table 2. In particular, Figure 7C and Table 2 show that at 600 °C, limestone's porosity increased by 67 %. According to Figure 8C and Table 2, limestone's porosity increased by 10 % following 100 freeze-thaw cycles. When thermal and freeze-thaw procedures were used, a commensurate increase in water absorption values was also noted. According to Figure 7D and Table 2, limestone's water absorption rose by 67 % at 600 °C. The water absorption of limestone increased to 13 % during 100 cycles of freeze-thaw (Fig. 8D and Table 2).

However, specific gravity decreases noticeably when temperature and the frequency of freeze-thaw cycles increase. As seen by Figures 7 and 8 and Table 2, the test results reveal that temperature variations have an impact on specific gravity. In particular, at 600 °C, limestone's specific gravity dropped by as much as 7.8 % (Fig. 7E). Furthermore, the rock's specific gravity dropped by 2.6 % following 100 freeze-thaw cycles (Fig. 8E).

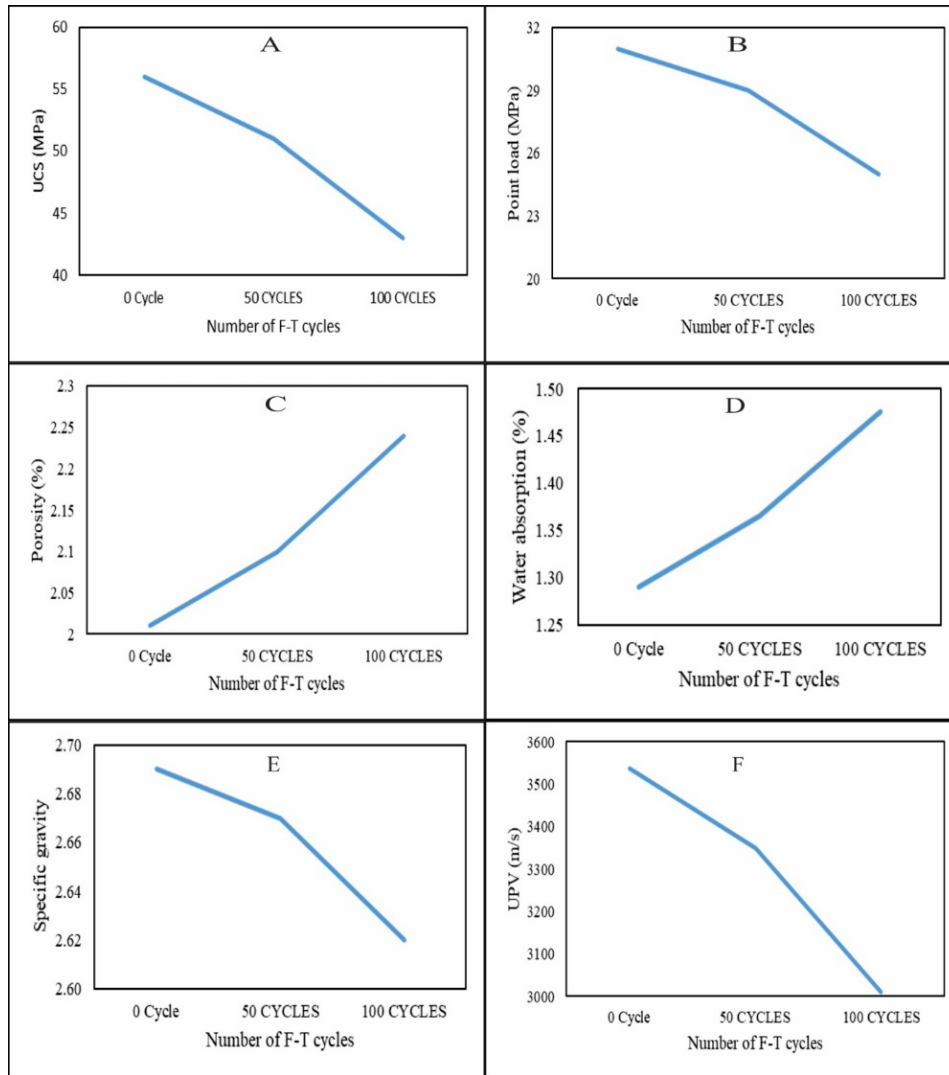


Fig. 8 Influence of freeze thaw on physico-mechanical properties of limestone: (A) UCS; (B) Point load; (C) Porosity; (D) Water absorption; (E) Specific gravity; (F) UPV.

Table 2 Results of Porosity, Water absorption, and Specific gravity of studied rocks.

Temperature	Properties		
	Porosity	Water absorption	Specific gravity
25 °C	2.01	1.29	2.69
150 °C	2.18	1.41	2.66
300 °C	2.28	1.51	2.63
600 °C	6.01	3.95	2.48
FT 50 cycles	2.1	1.37	2.67
FT 100 cycles	2.24	1.48	2.62

5.2.4. ULTRASONIC PULSE VELOCITY (UPV)

As temperature rises, the UPV consistently decreases, according to experimental results. When temperatures rose above a particular threshold, there was a significant drop in UPV, which was initially just slightly variable. The limestone's UPV dropped by 49 % at 600 °C (Fig. 7F and Table 1). Moreover, UPV values for limestone decreased by 15 % following 100 freeze-thaw cycles (Fig. 8F and Table 1). The effects of heat treatment and freeze-thaw cycles on characteristics including porosity, specific gravity,

UPV, and water absorption are highlighted by these findings. It also highlights how crucial it is to take temperature changes into account when evaluating the mechanical qualities and integrity of rocks.

6. DISCUSSION

The physico-mechanical characteristics of rocks are influenced by various elements, including their composition, textural relationships, individual mineral behaviour, and the type of fractures and deformations present. These factors also determine how heat

treatment and freeze-thaw processes affect these qualities. The number of freeze-thaw cycles the samples underwent and particular temperature ranges were used to evaluate the physico-mechanical properties.

6.1. FRACTURING

6.1.1. THERMALLY INDUCED FRACTURING

Rocks' mineralogical properties can be altered by high temperatures. Such temperature variations can cause new microcracks to emerge, which can severely damage rocks (Dong et al., 2024; Jin et al., 2024). Furthermore, temperature variations cause fracture-related damage that further reduces the strength of the rock (Yin et al., 2021; Hou et al., 2024).

Empirical models have been established in recent research to assess thermal damage in rocks that are exposed to different temperatures (Sirdesai et al., 2018; Liu et al., 2020; Khan et al., 2022; Lu et al., 2024). To identify the threshold for thermal damage, these tests usually required subjecting rocks to temperatures as high as 1000 °C. Fractures appeared in the current experiment soon after thermal treatment started and became more noticeable at increasing temperatures.

Thermal fracturing starts when the temperature rises and its density rises with higher temperatures. At room temperature, thermally induced fracture density is 0 %, rises to 0.73 % at 150 °C, reaches 1.5 % at 300 °C, and peaks at 2.51 % at 600 °C (see Figs. 3 and 4 as well as Table 1). The limestone disintegrates at temperatures higher than 600 °C.

6.1.2. FREEZE-THAW-INDUCED FRACTURES

A freeze-thaw cycle is a process when the temperature swings between high and low (below freezing) and then rises again (above freezing) (Abdolghanizadeh et al., 2020). The freeze-thaw effect extends beyond severely cold climes to areas where temperatures periodically fall below freezing, particularly at night (Park et al., 2020; Lin et al., 2020; Chen et al., 2021). In these types of environments, regular freeze-thaw cycles may cause fractures that could allow water to enter (Liu et al., 2024). When water freezes, it can expand by up to 9 %, increasing the pressure inside the rock's pores (Gong et al., 2022; Zhou et al., 2024). As the pressure gets closer to the rock's tensile limit, the rock gets damaged and loses strength. Additionally, it causes pre-existing microfractures and causes new ones to form. The density of fractures in the limestone increases with the number of cycles of freeze-thaw. In particular, the limestone's fracture density rose by 0.88 % after 50 cycles and by 1.44 % after 100 cycles (Figs. 5 and 6, and Table 1).

6.2. DAMAGE CALCULATION

When subjected to temperature variations, rocks suffer physico-mechanical degradation, mostly from internal fracturing. Using data from thermally and

freeze-thaw tested rock samples, the damage to each type of rock has been assessed using UCS, UPV and PL. The thermal damage has been calculated mathematically by using a formula (Ersoy et al., 2019).

The mathematical analysis shows that mechanical and physical deterioration in rocks is caused by both heat and freeze-thaw processes. Internal damage gets more extensive as these processes continue. In contrast to rocks with lesser mechanical strength, those with higher UCS and PL values typically exhibit less physico-mechanical damage.

6.2.1. CALCULATION OF THERMAL DAMAGE (DT)

The degradation of the uniaxial compressive strength (UCS), point load strength (PL), and ultrasonic pulse velocity (UPV) is primarily driven by structural changes in the rock due to thermal treatment and freeze-thaw cycles. During thermal treatment, the application of heat causes differential expansion of the rock's minerals. This thermal expansion induces internal stresses, leading to the formation of microcracks and fractures within the rock. As the temperature increases, these microcracks propagate, reducing the overall integrity of the rock matrix. The weakening of the bond between mineral grains, along with the development of additional fractures, compromises the rock's ability to resist compressive and point load stresses, resulting in a decrease in UCS and PL. Additionally, the increase in porosity due to thermal cracking reduces the rock's overall density and alters the acoustic properties, leading to a lower UPV. The reduction in UPV reflects the increased fracture density and porosity, as the ultrasonic waves travel slower through the more fragmented material.

Rocks that are exposed to greater temperatures experience considerable reductions in mechanical strength as a result of internal thermal damage followed by fracturing. The UCS, UPV, and Point Load data from thermally tested rock samples have been used to compute the thermal damage (DT) for Nowshera limestone. The calculation is performed using the formula provided by Ersoy et al. (2019).

$$(DT) \text{ UCS} = 1 - \text{UCS}_{(T)} / \text{UCS}_{(0)} \quad (1)$$

$$(DT) \text{ UPV} = 1 - \text{UPV}_{(T)} / \text{UPV}_{(0)} \quad (2)$$

$$(DT) \text{ PL} = 1 - \text{PL}_{(T)} / \text{PL}_{(0)} \quad (3)$$

where DT is thermal damage, $\text{UCS}_{(T)}$ is the UCS of the sample exposed to T °C, $\text{UCS}_{(0)}$ is the UCS of the samples at room temperature, $\text{UPV}_{(T)}$ is the UPV of the sample exposed to T °C, $\text{UPV}_{(0)}$ is the UPV of samples at room temperature, $\text{PL}_{(T)}$ is the point load at specific temperature, while $\text{PL}_{(0)}$ is point load at room temperature.

Table 3 displays the thermal damage (DT) corresponding to UCS, PL, and UPV for limestone at

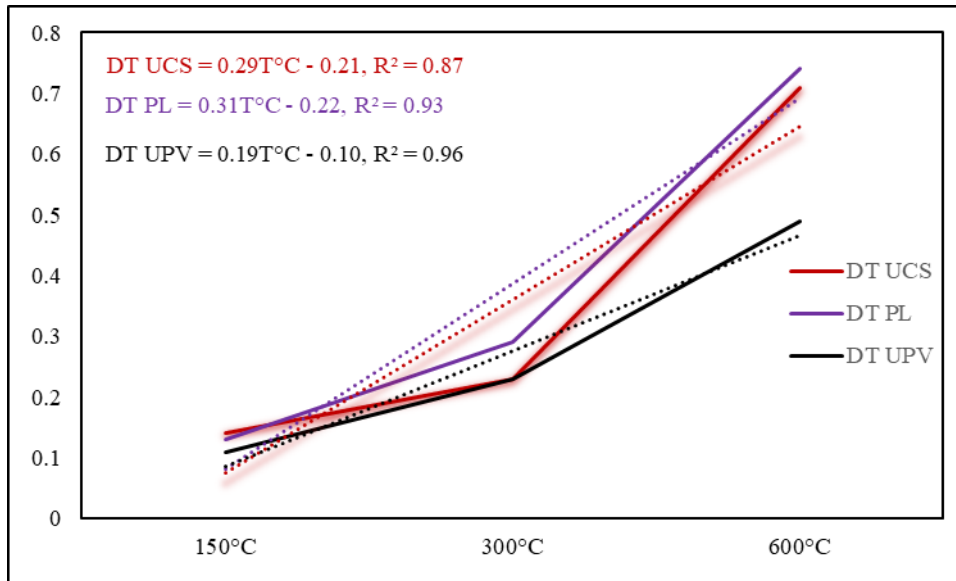


Fig. 9 Thermal damage parameters in rock samples of Nowshera limestone across varied temperature ranges.

Table 3 Thermal Damage (DT) values were calculated using UCS, UPV, and PL results.

Temp	PROPERTIES		
	DT UCS	DT PL	DT UPV
150°C	0.14	0.13	0.11
300°C	0.23	0.29	0.23
600°C	0.71	0.74	0.49
Number of cycles	DFT UCS	DFT PL	DFT UPV
50 F-T cycles	0.09	0.06	0.05
100 F-T cycles	0.23	0.19	0.15

different temperatures. At 150 °C, the UCS (DTUCS) thermal damage increases from 0 to 0.18, and at 600 °C, it rises to 0.71. In the same way, higher temperatures are associated with an increasing trend in DTPL and DTUPV. These values have been subsequently plotted against respective temperatures in Figure 9. These corresponding linear equations for each rock have been combined with eq. 1, 2 and 3, and subsequently, new equations have been acquired for the prediction of UCS, UPV, and PL values at any designated temperature.

$$\text{UCS}(T) = \text{UCS}_{(0)} [1 - (0.29 \times T^{\circ}\text{C} - 0.21)] \quad (4)$$

$$\text{UPV}(T) = \text{UPV}_{(0)} [1 - (0.19 \times T^{\circ}\text{C} - 0.10)] \quad (5)$$

$$\text{PL}(T) = \text{PL}_{(0)} [1 - (0.31 \times T^{\circ}\text{C} - 0.22)] \quad (6)$$

This study suggests the use of these equations for the estimation of UCS, UPV, and point load of the rocks at elevated temperatures. However, variations may occur depending on the extent of rock alteration.

6.2.2. CALCULATION OF FREEZE-THAW DAMAGE (DFT)

Freeze-thaw cycles cause significant degradation of rock strength parameters, such as UCS, PL, and UPV, by introducing mechanical stresses that

gradually weaken the rock. During the freezing phase, water within the rock's pore spaces expands as it turns to ice, exerting pressure on the rock matrix and widening existing fractures. This expansion causes microcracks to grow and new cracks to form, reducing the rock's structural integrity. Upon thawing, the ice melts, and the water re-enters the fractures, increasing the stress on the rock as it rehydrates the already weakened material. The cyclic nature of freezing and thawing accelerates the damage, as the repeated expansion and contraction of water continually enlarges fractures and increases porosity. Over multiple cycles, this process leads to a progressive weakening of the rock, as the material becomes more porous, fractured, and less cohesive. The increased fracture density and porosity directly contribute to a decrease in UCS, PL, and UPV, as the rock's ability to resist compressive, point load, and ultrasonic wave propagation is significantly impaired by the extensive internal damage.

When rocks are subjected to freeze-thaw cycles, internal damage from fracture causes their strength to decline. The freeze-thaw damage (DFT) for each rock type has been calculated using the UCS, UPV, and PL results from freeze-thaw tested rock samples, applying the formula provided by Ersoy et al. (2019).

$$(\text{DFT}) \text{ UCS} = 1 - \text{UCS}_{(\text{FT})} / \text{UCS}_{(0)} \quad (7)$$

$$(\text{DFT}) \text{ UPV} = 1 - \text{UPV}_{(\text{FT})} / \text{UPV}_{(0)} \quad (8)$$

$$(\text{DFT}) \text{ PL} = 1 - \text{PL}_{(\text{FT})} / \text{PL}_{(0)} \quad (9)$$

where DFT is thermal damage, $\text{UCS}_{(\text{FT})}$ is the UCS of the sample exposed to various numbers of FT cycles, $\text{UCS}_{(0)}$ is the UCS of the samples at room temperature, $\text{UPV}_{(\text{FT})}$ is the UPV of the sample exposed to FT, $\text{UPV}_{(0)}$ is the UPV of samples at room temperature, $\text{PL}_{(\text{FT})}$ is Point Load after specific FT cycles, while $\text{PL}_{(0)}$ is the Point Load at room temperature.

The freeze-thaw damage corresponding to UCS, PL, and UPV for limestone at the examined temperatures is shown in Table 3 and has been displayed against the number of cycles in Figures 8A, 8B and 8F, respectively. The freeze-thaw damage was determined from the preceding equation. As the number of freeze-thaw cycles rises, DFT values also rise. For example, DFT PL values increase from 0 to 0.10 after 50 F-T cycles, and after 100 F-T cycles, they reach 0.29. Increased DFT values signify damage from freezing to thawing, and vice versa.

6.3. EFFECTS OF TEMPERATURE AND FREEZE-THAW ON PHYSICO-MECHANICAL PROPERTIES OF ROCKS

Through petrographic observations and the tracking of changes in physico-mechanical characteristics following treatment at varying temperatures and freeze-thaw cycles, this study examined the impact of thermal treatment and freeze-thaw cycles on a variety of rocks. Research has shown that heat treatment causes new microcracks to grow, which drastically lowers the strength of the rock (Wong et al., 2021; Xu et al., 2023; Zhao et al., 2024). When subjected to temperatures above 500–600 °C, rocks usually lose roughly half of their initial strength; the amount of this loss varies according to the mineral composition and texture of the rocks (Ashrafi et al., 2020; Ahmed et al., 2022; Dong et al., 2024). Similarly, cycles of freeze-thaw constitute an important physical weathering agent that can quickly change the mechanical characteristics of rocks, influencing their durability (Momeni et al., 2016; Mei et al., 2021; Chen et al., 2021; He et al., 2023). Freeze-thaw cycles are found to be the most harmful physical processes influencing rock durability and disintegration, whereas heating-cooling cycles have little effect on the rocks (Hosseini and Khodayari, 2019; Mousavi et al., 2019). As the frequency of freeze-thaw (F-T) cycles increases, rocks lose a considerable amount of their mechanical strength (Chen et al., 2023; Wu et al., 2023).

From room temperature to 300 °C, there is a gradual drop in the UCS. On the other hand, UCS sharply decreases at 300 °C. According to Figures 7A, 8A, and Table 1, the UCS curve analysis clearly shows that the rocks' response to heat treatment is unstable within the 300 °C to 600 °C temperature range. On the

other hand, limestone experiences no sudden decreases in UCS during the freeze-thaw process; rather, it gradually loses mechanical strength. Throughout the investigated rocks, the point load strength exhibits a tendency that is comparable to UCS and reflects steady patterns of reduction (Figs. 7B, 8B, and Table 1).

The porosity of rocks is greatly impacted by both heat treatment and freeze-thaw cycles, with an overall increase seen as these processes progress (Figs. 7C, 8C, and Table 2). Likewise, there is a strong significant link between temperature and freeze-thaw processes, and water absorption in rock samples (Figs. 7C, 8C, and Table 2). Up to 300 °C, the sintering effect of heat treatment leads to a stabilization of porosity and water absorption. This process causes particles to bond, reducing the number of available pores. However, above 300 °C, the thermal expansion and initiation of microcracks result in a notable increase in both porosity and water absorption. The formation of these thermal cracks is primarily due to differential thermal expansion between mineral grains and matrix materials, which causes internal stresses and crack propagation. This is further supported by fracture density measurements obtained at each temperature under investigation, which suggest a significant increase in crack development beyond the critical threshold of 300 °C. In addition, the influence of freeze-thaw cycles on porosity and water absorption can be explained by the expansion of water during freezing, which leads to the opening and widening of pre-existing microfractures. During thawing, the water infiltrates further into the rock matrix, increasing the void space and promoting additional fracture development. This process, compounded by the cyclic nature of freeze-thaw actions, results in the maximum values of porosity and water absorption being recorded after the freeze-thaw cycles, as observed in our experimental analysis.

As the temperature rises, specific gravity and UPV both decrease (Figs. 7, 8, and Table 2). Like the other properties investigated, a significant shift in UPV and specific gravity is seen at 300 °C. These results show that heat treatment above 300 °C significantly changes the behavior of minerals. Furthermore, during freeze-thaw cycles, the expansion and freezing of water causes a decrease in the density of the rock, which is represented by reduced specific gravity. These results demonstrate how freeze-thaw cycles affect the mechanical and physical properties of rocks by lowering their specific gravity and decreasing their UPV.

7. CONCLUSIONS

This work examined in detail how thermal treatment and freeze-thaw process affect the physico-mechanical characteristics of rocks, such as their water absorption capacity, porosity, specific gravity, and UPV. At different phases of treatment, the properties of Nowshera limestone were assessed by exposing it

to a range of temperatures and several freeze-thaw cycles. The findings demonstrated that the mechanical behavior of rocks varies with temperature, highlighting the significance of considering temperature effects when formulating recommendations for geological and engineering applications. The major outcomes can be summarized as:

- It was found that when temperature and the number of freeze-thaw cycles increased, UPV, point load strength, specific gravity, and uniaxial compressive strength decreased. Conversely, there was a positive trend observed in the porosity and water absorption values.
- Fracture density increased significantly with both thermal treatment and freeze-thaw cycles, leading to the disintegration of the rocks.
- When temperatures rise above 300 °C during heat treatment, a notable shift in the physico-mechanical properties of limestone is seen. This can be recommended of as the critical temperature at which limestone become unstable.
- The equations obtained from the physico-mechanical results of the investigation can be used to estimate the corresponding property at any expected temperature. However, variations may arise due to changes in the rock's alteration grade.

ENGINEERING IMPLICATIONS AND RECOMMENDATIONS

The results of this study have direct implications for construction and mining operations involving limestone or similar carbonate rocks in thermally active or cold-climate regions. In construction, materials subjected to elevated temperatures (e.g., near fire-prone areas or industrial zones) or repetitive freeze-thaw cycles (e.g., high-altitude or temperate climates) may experience substantial loss in strength and durability. Thus, it is recommended to avoid using limestone that has been exposed to temperatures above 300 °C or subjected to numerous freeze-thaw cycles without prior treatment or reinforcement. In mining, understanding these degradation patterns can aid in designing safer excavation plans and support systems, particularly for slopes and underground workings in regions with thermal fluctuations.

LIMITATIONS

While this study provides valuable insight into the degradation of limestone under thermal and freeze-thaw stresses, it is limited to a single lithology from a specific location. Variations in mineral composition, grain size, and natural weathering among different carbonate rocks may influence their response to environmental stresses. Furthermore, field conditions such as moisture availability, chemical weathering, and complex stress regimes were not simulated and should be addressed in future studies.

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AUTHOR CONTRIBUTION

Abid Nawaz, contributed to conceptualization, methodology, field investigation, data curation, and writing—original draft; Muhammad Sajid, Waqas Ahmed, Fahad Alshehri and Sattam Almadani contributed to reviewing and editing, supervision, and funding acquisition; and Abdul Rahim Asif, Muhammad Shahab, Muhammad Amin, and Muhammad Ahmad Afzal contributed to field investigation, laboratory work, and data support.

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DATA AVAILABILITY

All data are included in the manuscript.

DECLARATION

CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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