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Thermal effects on the mechanical properties of marble, travertine and concrete cores under direct tensile test

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ABSTRACT: Fire and high temperatures are the most destructive accidental loads that a structure can be subjected to. There are numerous kinds of research concentrated on the effect of high temperature on physical and mechanical properties of rocks and concrete while there are a few inadequate investigations on marble and limestones. This work presents direct tensile tests results obtained under high temperatures on marble, travertine and concrete samples, previously heated at a namely temperature (350°C), were tested. Destructive tests of direct tensile tests and uniaxial compressive tests were performed on the samples. Furthermore, tests were carried out under air-cooled conditions to minimize the effect of the fire-off method and then physio-mechanical properties of thermally treated, and the reference samples at room temperature were discovered. The results show that direct tensile strength, and tensile modulus decrease as the temperature rises for the tested range of temperatures. After thermal treatment, the measured direct tensile strength is found to show a decrease up to 44%, 45%, 16.71% for Marble, travertine, and concrete samples respectively. Regarding Young's modulus, a fall over 42% , 22% and 33% in air-cooled is observed.

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1. INTRODUCTION

Natural stones, such as Marble and travertine are extensively utilized in each area of our lives, and it can be respected as the prominent building substance throughout the history of architecture and civil works. Marble has many unique properties that make it an invaluable rock in many different industries. Therefore, it was used extensively throughout the Taj-Mahal building, including the marble domes and towers. The Romans mined deposits of travertine for building temples, aqueducts, monuments, bath complexes, and amphitheaters. However, the stone is always regarded as an "everlasting" element, it is known widely that building stone undergoes many processes of deterioration so exact characteristics, such as uniaxial compressive strength, tensile strength, and durability of the natural stones must be known [1]. External forces such as that originate from water, wind-flow, and fire exposes structural deterioration, which causes weakening or loosening stone and concrete particles internally. As a result, stone and concrete as structural members in buildings have to satisfy certain fire safety requirements specified in building codes. Owing to material deterioration, it is important to know strength mechanisms. Compressive behavior of rocks and concrete in the fire has been studied by many researchers. Until now, the thermal effect on tensile strength is still unknown [2, 3]

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Various mechanical properties of concrete including compressive, tensile and flexural strength have been studied by many researchers [4, 5]. Researchers mention that the exact tensile strength of concrete may be found only by a direct method[6]. Tensile strength estimations must be used for preparatory design purposes due to extensive disperse in the available data for evaluating tensile strength from indirect tests [7]. In spite of the influence of the tensile capacity in controlling many failure processes, tensile strength measurement is often neglected in engineering practice because of complications with achieving valid results [7]. Diederichs and Kaiser (1999) claimed that tensile strength determination is crucial for underground openings stability [8].It is important to note that researchers encounter great difficulties for direct tensile strength specimen preparation. As a result, indirect tensile strength, like the Brazilian tensile strength Testing allows them to avoid the above-mentioned difficulties [9]. Tensile strength is sharply associated with the fracture initiation stress threshold in compression [7].

That is also substantial to predict the performance of natural stones, which are located at high temperature and heat sources, against the temperature to take certain preservation measures with determining the demolition [10]. Yavus et al investigated the heating temperature effect on various rock characteristics such as bulk density, porosity, pressure wave velocity. They found that an increase in temperature up to

500°C causes new micro crack occurrence [11]. Yin et al show that there is an inverse relationship between temperature and longitudinal wave velocity, and elastic modulus. Whereas the relationship between peak strain of coal rocks and temperature is direct [12]. It is also found that pressure and temperature have an effect on the thermal conductivity of rocks. Rock structure and mineralogy composition tend to be very important on thermal treatments [13]. It is also important to mention that a drastic drop was observed when uniaxial compressive strength and indirect tensile strength of granite were investigated under various high temperature by Török [14]. It is also deducted that porosity increases when the concrete and andesite samples are exposed to heat. On the other hand tensile strength decreased [15]. Researchers also examined fracture toughness under 150°C and ambient temperatures. The results verified that fracture displays temperature dependence [16]. Researchers also revealed that thermal damages are mainly because of the impact of the macro-properties of rocks [17]. The effect of high temperature on concrete samples under various types of loadings has been investigated by Sadrmomtazi and Tahmouresi. A decrease in strength properties was detected due to increasing the temperature [18].

The Azar Shahr's marble and Hajiabadd's travertine, studied in this paper, have been extensively used in buildings from different cities of Iran. It is essential to comprehend the behavior of this kind of rock upon distinct destructive factors. Temperature changes are one of the main factors affecting the inherent characteristics of rocks. It can alter the rock dilation by varying the coefficients of thermal expansion [17]. This investigation is centered on the effect of high temperatures (as obtainable calamitous fires) on remarkable physical and mechanical properties of rocks and concretes. Several investigations on the thermal effect on compressive strength of different kind of rocks and concrete have been reported, but little is grasped about the effect of temperature on thermal degradation on their direct tensile strength properties, which is considered in this research [17, 19, 20].

2. MATERIAL AND METHODS

2.1. Description of rock specimens

In this study, the purpose is to determine the variations of the properties of the natural stones against the temperature, which are usually accessible in Iran. Block samples were taken from Hajiabad mine, located at the West of the urban area of Mahallat, Markazi province, Iran and the Azarshahr East Azerbaijan Province, Iran. These materials were chosen regarding their repetition, abundance, and regional significance of application as building elements. The specimens scrutinized in this research were obtained from rock blocks. The rock blocks were picked up quickly after the excavation and conveyed to the laboratory, where the specimens were cored by drilling then they were cut with a circular saw to the sought dimensions. The surface was then carefully smoothed. To avoid anisotropy impact, the orientation of stratification planes in the blocks was taken into account. The physical properties of investigated marble and travertine samples such as dry unit weight were determined according to the ASTM standard D2216-98 with adequate repetitions for each material[21]. The studied rocks present a dry unit weight of 2453.5 kg/m^3 and 2574.5 kg/m^3 for marble and travertine samples respectively. For this study, 51 cylindrical specimens of 54, 65 and 75 mm in diameter with height to diameter ratio of 2, and 2.5 were prepared. These tests were conducted to convince their appropriateness according to relevant standards[22]. Evaluation of samples perpendicularity, cylindricity, parallelism as well as the flatness of the base were considered according to the guidelines. In this research, the authors conducted a series of uniaxial compressive strength for concrete, marble, and travertine (Fig.1 to Fig.3). Furthermore, to discover the effect of temperature, specimens which were not exposed to heat were segregated from the ones exposed to heat. Selected specimens were then exposed to heat up to $350°C$ with a heating device furnace and later compared with reference specimens at room temperature.

2.2. Concrete mixture composition and sample preparation

Different kinds of coarse and fine aggregates (without admixtures) and ordinary Portland cement were used for concrete specimens. The preparation of standard concrete test specimens is according to ASTM C192 specifications[23]. Aggregates were sieved using standard sieves and separated into seven groups consisting of No. #4,#8, #16, #30, #50, #100, and #200. And Cylinder samples with 58 mm diameter and height to diameter ratio 2 and 2.5, were cast. For the next step, the vibration table was used for compaction. The specimens were kept at $25°C$ $25°C$ and 100% relative humidity in a curing chamber until testing. The specimen uniaxial compressive strengths of the concrete are presented in Fig.1 to Fig.3. Moreover, mixtures developed 30 MPa compressive strength and Young's modulus 5 GPa at 28 days, varied from 2% to 3%.

2.3. Heating process

Rock and concrete samples heating process were performed in an oven from $25°C$ to touch the target temperature. Once the target temperature of $350°C$ was reached for different samples with a heating rate of $5°C$ per min to ensure thermal equilibrium of the samples, the temperature was kept constant for one hour and then air cooled to the laboratory temperature to avoid specimen cracking if abruptly are cooled. It is important to note that samples heated up to $350°C$ were cooled in a free from moisture atmosphere at room temperature. Subsequently, the specimens were kept dry until the completion of consequent tests. Alongside, a collection of samples were kept at $25°C$ to act as reference samples.

2.4. Uniaxial compressive strength

Although the aim of this study is to evaluate fire and heat effect on the tensile strength, several uniaxial compressive strength tests were also performed on concrete and rock samples to find a correlation between UCS and DTS. The result of uniaxial compression tests carried out on 9 rocks and

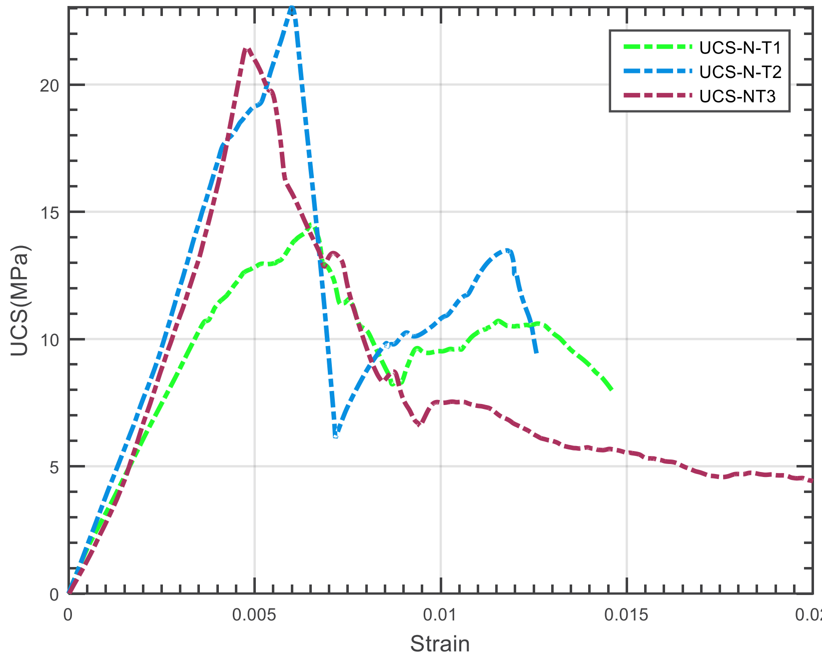

Fig. 1. UCS - 25°C temperature – Travertine

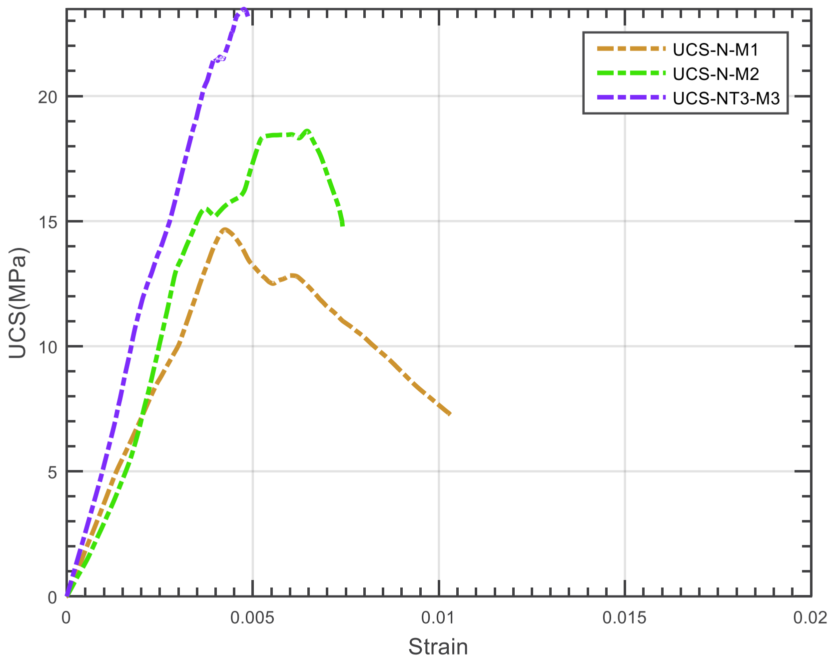

Fig. 2. UCS - 25°C temperature – Marble

concrete specimens presented in Fig.1 to Fig.3. The results reported that the UCS value is 28.67, 20.63, 22.85 MPa for concrete, Marble and Travertine respectively. Based on the average results for the specimens, the UCS value of tested rocks was evaluated as weak rocks [24]. Literature supporting reports, apparently claims for a correlation factor between UCS and DTS (known as strength ratio) from 2.7 to 50.The UCS value for most rocks is approximately ten times greater than the tensile strength [25, 26].

2.5. Direct tensile strength

The direct tensile test has scarcely been employed in rock mechanics laboratories due to the difficulty to perform correctly. A number of researchers have described a variety of research studies that have used appropriate configuration for direct tensile samples such as dog-bone or non-dog bone

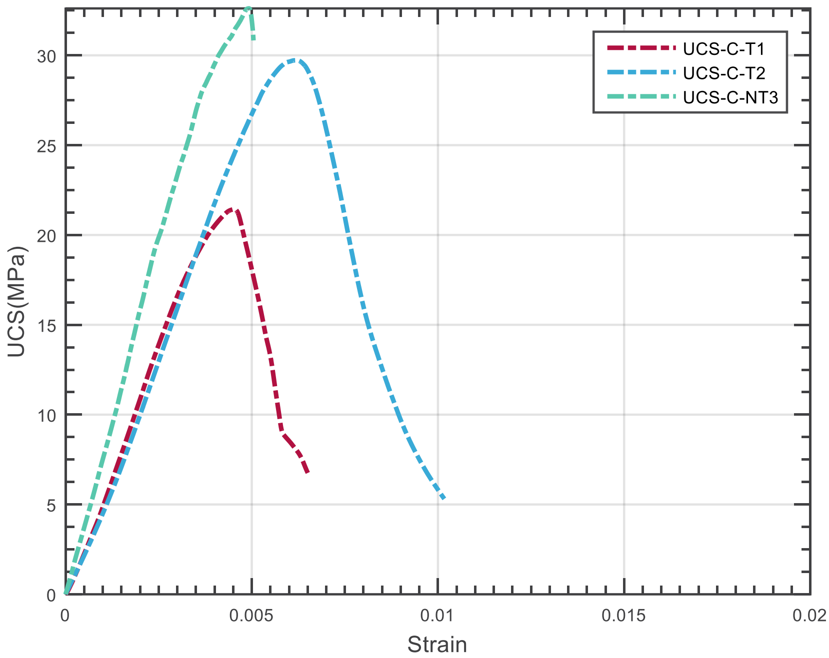

Fig. 3. UCS - 25°C temperature – Concrete

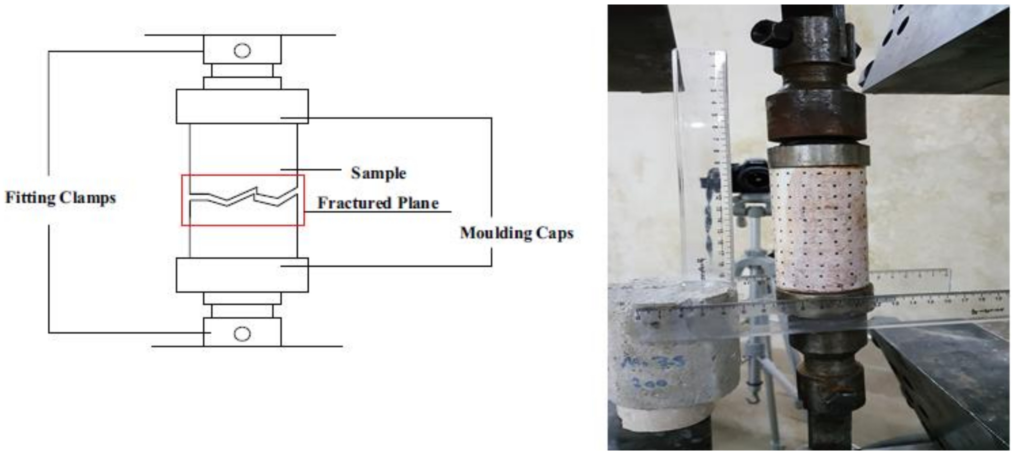

Fig. 4. Experimental setup

shape [25, 27]. Reliable direct tensile test results in failure are at the midpoint of the specimen. In the present work, such as the method introduced by Fairhurst, the concentration of stress was diminished by directly gluing end caps of the equal diameter to the specimen ends[28]. The designed caps overcome load transferred by twisting, as shown in Fig.4.The tensile strength of the specimens was measured using direct tensile strength tests, DTS test was performed according to ISRM suggested methods[22]. In this test, a cylindrical specimen is vertically loaded, Fig.4. shows that the specimen glued to specially-fabricated molding caps and subjected to direct tension. Special care was needed when gluing the samples to the molding caps to warrant precise alignment between the sample and caps axis. The DARTEC 9600 Servo-controlled Testing Machine was employed to test the samples.

According to preceding researches, it was found that the loading rate of 0.001 mm/s produced the more appropriate direct tensile failure [29-31]. Similar strain loading rate was also selected for use in this investigation. The Direct Tensile Strength (DTS) was computed using Eq. (1).

$$DTS = \frac{P_{max}}{\pi r^2} \quad (1)$$

Where, DTS is in MPa; P_{max} refers to the maximum load of each stress-elongation curve and r is the radius of each specimen in mm.

2.6. The results and discussion

Laboratory tests carried out on rock and concrete specimens heated at $350°C$ temperature after being air diagrams of the tensile tests for any thermal treatment and rock type are displayed in Figs.5. to 10. Results show that average thermally treated specimen's tensile strength is lower than the target specimens.

As shown in Fig.5 to .10, ideally, the test results which their stress-strain curves originate from zero are acceptable. As a result, some test results categorized as invalid (such as; DTS-H-T4) and eliminated from data processing.

The group of rocks and concrete tested at ambient temperature showed the highest tensile strength and tensile elastic modulus. The rock groups with high temperature, marble, and travertine at $350°C$, showed lower tensile strength and Young's modulus with a declining trend as the temperature raised (Table .1).

Furthermore, the ultimate strain variations is higher for marble and travertine at $25°C$ (Fig.6. and Fig.8.). The variations of ultimate strain with the thermal treatments are within the experimental scattering for reference samples but manage to decrease for samples when the temperature rises (Fig.7. and Fig.8.).

This behavior indicates that reference samples, marble, and travertine at $25°C$, have a significantly greater strength and are more brittle than the thermally treated specimens.The

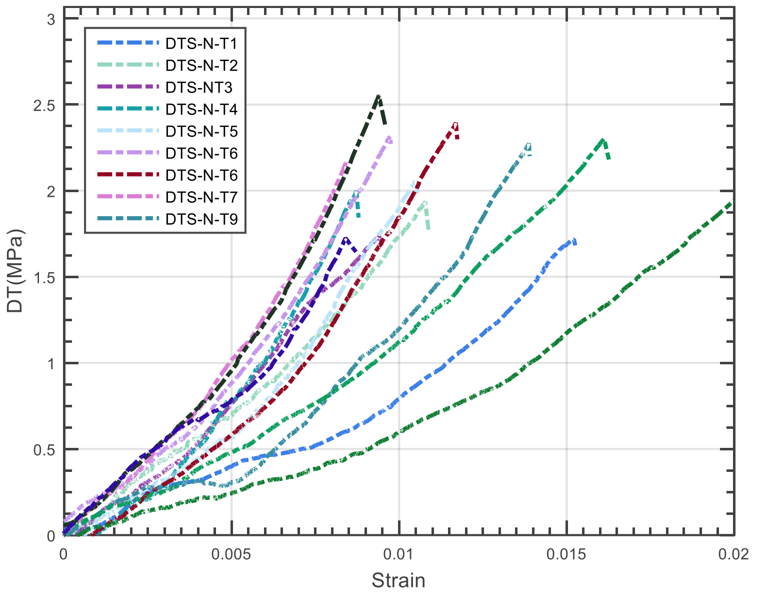

Fig. 5. Direct tensile strength change related to 25°C temperature – Marble

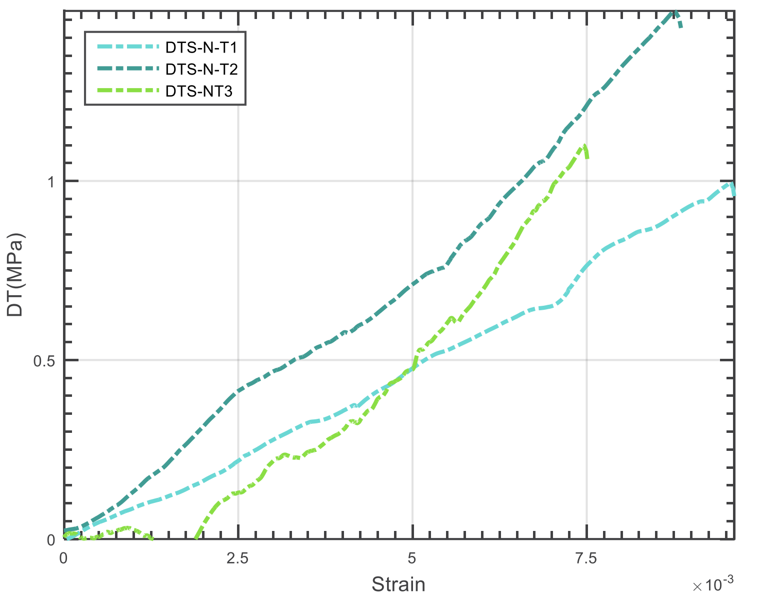

Fig. 6. Direct tensile strength change related to 350°C temperature – Marble

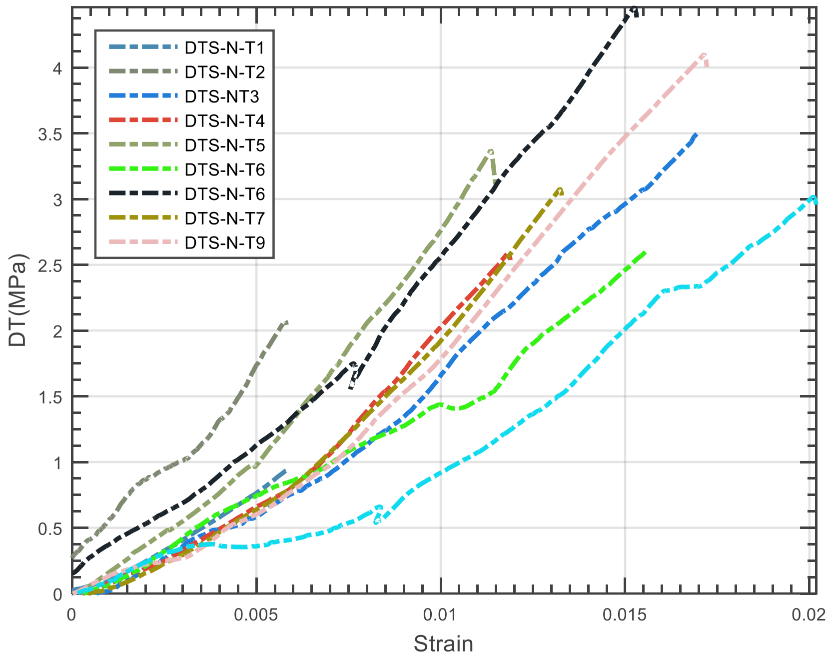

Fig. 7. Direct tensile strength change related to 25°C temperature – Travertine

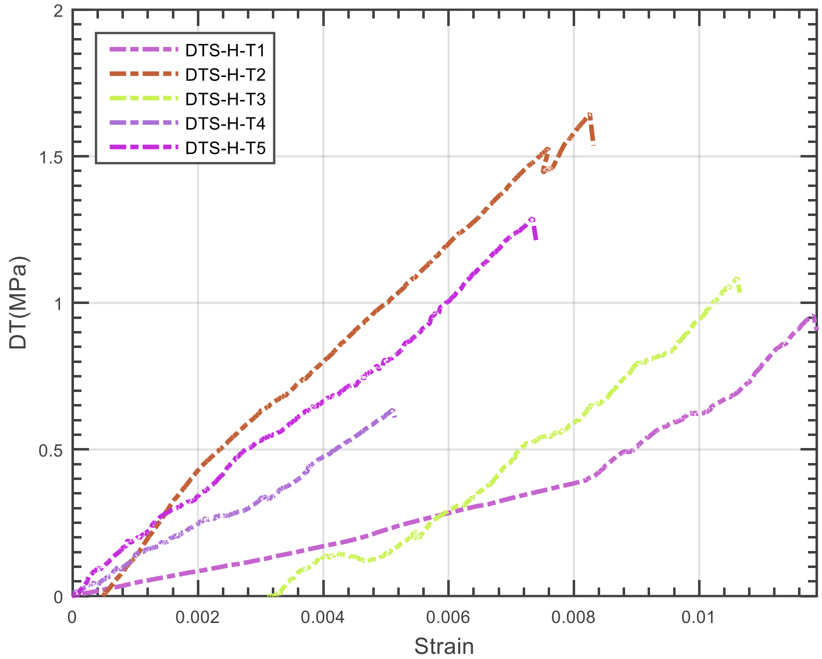

Fig. 8. Direct tensile strength change related to 350°C temperature – Travertine

cooled. From these variables next parameters were obtained include, Young's modulus (tensile modulus), and direct tensile strength. To understand tensile strength results, a series of uniaxial strength tests were also conducted to help the authors estimate the tensile strength range and strength ratio. It is important to note that the tensile modulus of elasticity is the slope of the stress-strain diagram at the half ultimate stress. Firstly, the tests were conducted on the samples at $25°C$ $25°C$ to obliterate temperature effect. These specimens were affirmed as target samples and presented the reference values. Moreover, the test was conducted on a number of 51 specimens which were beforehand classified into nine unequal groups. For each collection, the previously noted characteristics were investigated before and after the heating process. Next subsections explicate the obtained results for the different tested rock samples. Representative stress-strain

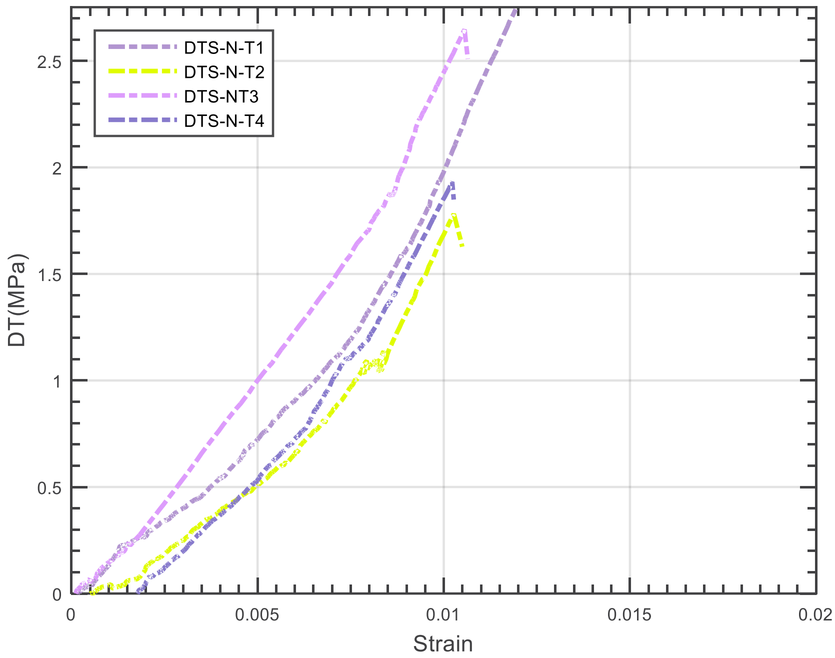

Fig. 9. Direct tensile strength change related to temperature –for concrete mixture design

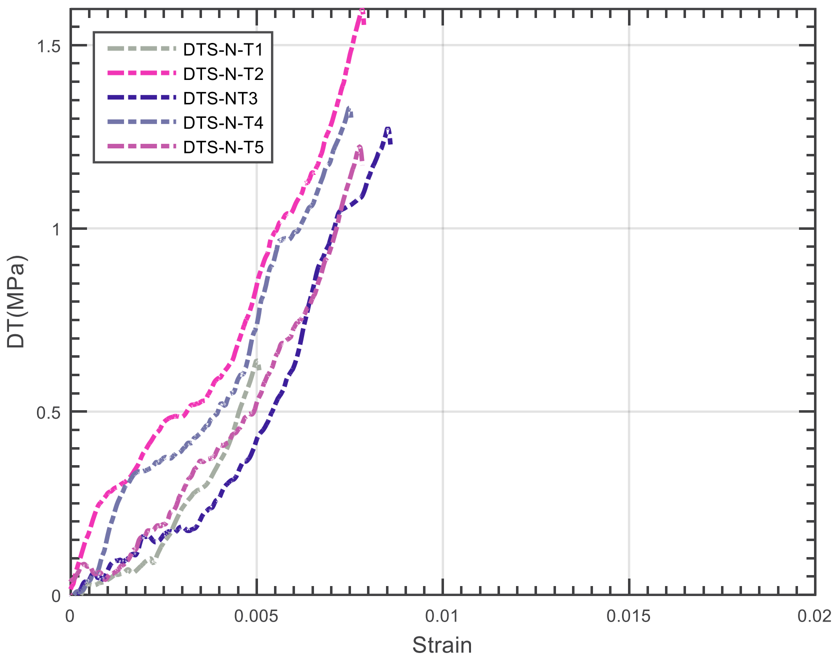

Fig. 10. Direct tensile strength change related to 350°C temperature –for concrete mixture design

mean value of tensile strength without thermal treatment is 2.51, 2.39, and 2.5 MPa and with thermal treatment is 1.39, 1.3, and 2.08 for marble, travertine, and concrete, respectively. Due to the uniaxial compressive strength and direct tensile strength, the correlation equations between uniaxial compressive strength and direct tensile strength for thermally treatment groups and without thermally treatment groups are given below as Eq. (2).

$$UCS = k.DTS \tag{2}$$

In which UCS is the uniaxial compressive strength (MPa), DTS is the direct tensile strength (MPa) and k varies ranges between [8-11.5] for samples tested at ambient temperature and [14-17.5] for thermally damaged samples.

Moreover, the mean value of tensile modulus of elasticity

Table 1. Values of DTS, UCS, and Elasticity modulus

Material	UCS 25 C (MPa)	DTS 25 C (MPa)	DTS 350 C (MPa)	Tensile strength reduction	E Compressive 25 C (GPa)	E Tensile 25 C (GPa)	E Tensile 350 C (GPa)	Tensile strength reduction
Marble	20.63$^{(3)}$	2.51$^{(9)}$	1.39$^{(3)}$	44%	5	1.5	0.86	42%
Travertine	22.85$^{(3)}$	2.39$^{(9)}$	1.30$^{(5)}$	45%	4.69	1.19	0.92	22%
Concrete	28.67$^{(5)}$	2.50$^{(4)}$	2.08$^{(6)}$	16.71%	5.05	1.56	1.04	33%
Upper case numbers presents the number of conducted valid tests.								

Table 2. Summary of statistical results

Material	CV[1](%)
$Marble_{\mathrm{DTS}}^{(25)}$	25
$Marble_{\mathrm{DTS}}^{(350)}$	29
$Concrete_{\mathrm{DT}}^{(25)}$	15
$Concrete_{\mathrm{DTS}}^{(350)}$	19
$Travertine_{\mathrm{DT}}^{(25)}$	21
$Travertine_{\mathrm{DT\,S}}^{(350)}$	29
$Marble_{\mathrm{UCS}}^{(25)}$	14
$Travertine_{\mathrm{UCS}}^{(25)}$	12
$Concrete_{\mathrm{UCS}}^{(25)}$	15

is 0.86, 0.92, and 1.04 or the specimens exposed to the heat and 1.5, 1.19, and 1.56 for non-exposed specimens. In other words, the tensile elastic modulus (E) at $25°C$, is also expressively higher for the more brittle rocks (reference samples) than for thermally treated cases. For marble, and in less proportion for travertine, there is a trend of decreasing E as temperature increases. As it can be inferred from the results tensile strength decreases with the increase in temperature may be regarded linearly. Sudden changes were not perceived at any of the temperatures. It may be implied that building stones must be used by admitting particular attention at places which are expected to reach catastrophic temperatures. Due to statistical analysis results of uniaxial compressive strength tests and tensile strength tests at ambient and 350°C, the coefficient of variation indicates that data distributions are considered to be low-variance, which shows the results are in acceptable ranges (Table 2.).

The direct tensile strength test achieved by mechanical tests displays a linear decrease with temperature, up to 36% in dry-cooled specimens. Admittedly, among all the parameters analyzed in this work, travertine uniaxial tensile strength is the most sensitive to the thermal effect, whereas marble Young modulus is the most sensitive to thermal treatment. The direct tensile strength and tensile elastic modulus were affected by temperature in the concrete and rock samples. The computed tensile strength before and after thermal treatment is concluded in the Table 1.

As it can be noticed, uniaxial tensile strength and Young's modulus reduction reaches 44%,45%, and 16.71% at $350°C$, in dry-cooled for DTS, and a fall over 42% and 22% and 33% for E, for Marble, travertine and concretes samples respectively. It is believed that heat expansion causes micro-cracks[31]. And because the direct tensile strength is very susceptible to rock samples micro-cracks, the results indicate that thermal damages produce new micro cracks which leads to strength reduction. The results show good agreement with the literature review.

Due to stress-strain curves, it is apparent that thermal damages cause a reduction in maximum and peak strain for all samples (Fig. 5 to .10). The samples failure modes seem to be connected to rock specimens mineralogy without thermal treatment. It is also proved that thermal damage has a very strong impression on failure mode as a result of micro-cracks.

3. CONCLUSION

The following final results were achieved in this study by performing tests on specimens of different rocks and concrete under the impact of high temperature to determine the changes in their physio-mechanical properties facing fire and heat.

- Increase in temperature causes regularly decreases in the direct tensile strength. By interpreting the tensile strength of all specimens, the influence of temperature changes with the likewise tendency was ascertained.
- It is concluded that temperature increasing, decreases Young's modulus of the natural stones and concrete.
- It is concluded that rising temperature induce variations in strain results of all specimens.
- Temperature variations of rocks are affecting the tensile strength values. Particularly, the strength values of the samples at 350 °C and above. Accordingly, using the natural stones as a carrier in buildings is not acceptable in cases which it may encounter catastrophic temperature.
- Temperatures which are approaching 350 °C and above cause destructive damage to stones. Hence, a high amount of abrasion can damage the building structure and increase the renovation expenses.
- As thermal micro-cracks appear within the specimen structures, maximum and peak strain reduces.
- The UCS was found to be correlated with DTS through a linear relationship having an average slope of 10 and

15.5 without and with thermally treated specimens, respectively.

4. NOMENCLATURE

UCS Uniaxial compressive strength, MPa
DTS Uniaxial tensile strength, MPa
k Correlation factor
P_{max} Maximum load, MPa
r specimen radius, mm

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