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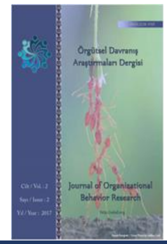

A LABORATORY STUDY OF CONCRETE BEHAVIOR AT HIGH TEMPERATURES UNDER CYCLIC LOADS

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ABSTRACT

High temperatures are considered one of the causes of damage to reinforced concrete structures, which placing the concrete in such conditions accompanied by reducing the mechanical properties of concrete. The simultaneous effect of both factors on the reinforced concrete structures is examined. For this aim, several concrete samples were made, and they were exposed to temperatures of 28, 100, 150, 200, 250, 250, 300, 400, 600, 700, and 800 °C. The samples were immediately exposed to compressive and loading steps. The modulus of elasticity and fracture energy of the samples were compared at different temperatures to examine the results more accurately. It was found that as the test temperature increases, the amount of compressive stress of concrete decreases, and the corresponding stress strains have an upward trend in maximum monotonic and cyclic loads, accordingly. Comparing the vertical strain and transverse strain at 800 °C with ambient temperature indicated an increase of 84% and 122%, respectively.

It was found that as the test temperature increases, the elasticity modulus in all loading steps decreases, which the significant damage to concrete is at temperatures above 500 °C. Besides, as the load cycles increase from 1 to 22, the elasticity modulus is almost constant, and no significant changes were observed. In the loading mode, the energy change process is similar to that of the load energy, and as the test temperature and loading steps increase, the number of energy increases.

Keywords: *High temperature, Cyclic loading, Vertical strain, Transverse strain, Concrete, Energy.*

INTRODUCTION

According to studies conducted after September 11, changing the properties of the building materials used in these buildings, such as reduced strength and stiffness, is considered one of the essential factors in destroying world trade buildings. Following this event, researchers paid more attention to the impact of fires on the behavior of building materials and structures in recent years. The performance of structures against fire has recently been investigated. Generally, the structural behavior of individual elements such as beams and columns under fire is investigated with prescriptive approaches or standardized fire tests (Moghadam and Izadifard, 2019). Most building materials show high vulnerability against rising temperatures. Concrete and steel are no exception to this rule, so that reduced strength and scaling phenomenon occurs in the concrete. As a result, it is essential to study the mechanical properties of concrete in these conditions (Karatas *et al.*, 2017).

Literature

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In 1964, the first qualitative and quantitative studies of the stress-strain relationships of concrete in cyclic loading were performed. These tests were based on cylindrical tests with a compressive strength of about 20 to 28 megapascals (Sinaie *et al.*, 2015). In 1969, a more detailed study of loading in the compression range was performed, and a precise definition of stability was provided accordingly]. One-dimensional and multi-piece models simulate concrete behavior in cyclic loading based on geometric characteristics in 1989. Cycle loading affects both stress and deformation. Both loading and unloading parts are better at the same speed. These loading speeds are usually "static or dynamic"(Sinaie *et al.*, 2015).

An experimental study was performed to investigate cyclic loading on self-compacting concrete. For this purpose, several cylindrical and cubic samples were tested. It was found that heated concrete has a lower compressive strength (Abiodun and Nalbantoglu, 2015; Al-Bared and Marto, 2017). Heated concrete shows more strains in cyclic loading. Cracks' growth is different in the heated and unheated samples under cyclic loading. It was found that: 1. High-temperature SCC behavior is similar to that of standard concrete in similar conditions, i.e., as temperature increases, the compressive strength of SCC and modulus of elasticity decreases. 2. Cyclic loading affects the heated concrete SCC (before the maximum point), which decreases the compressive strength and increases the maximum strain point from the stress-strain diagram (Farzadnia, 2019). These changes were appeared by cyclic loading after heating the samples. 3. The combined effect of thermal and cyclic loading leads to a further reduction in SCC compressive strength. 4. Increasing the temperature affects the cyclic loading test results and SCC samples, such as ordinary concrete, operating at low compressive strengths under a cyclic load at 23°C (Firmo *et al.*, 2015).

The research conducted on concrete joints was varied and consisted of scattered experiments with various parameters (Thomas and Gupta, 2015). Therefore, there is a need for an almost comprehensive study on how different design parameters affect connections' behavior. 29 samples of reinforced concrete bonds under cyclic loading through laboratory data of the network was trained to achieve this purpose using an artificial neural network (Jia *et al.*, 2018). The parameters considered in this study are the percentage of the column's longitudinal steel, the percentage of the volumetric reinforcement of the connection, the axial stress of the column, the compressive strength of the concrete, and the geometric dimensions of the beam and column (Sinaie *et al.*, 2015). The results included the role and effect of each mentioned parameters on the load capacity of the connections under cyclic loading which finally, the proposed model, such as the curves and equations for calculating the bearing capacity of the above concrete joints, were introduced through the results of the artificial neural network on these useful parameters (Franssen and Gernay, 2017). The proposed model results are highly consistent with the experimental results, indicating the model's appropriate performance (Ali *et al.*, 2017).

Amonamarittakul found that the behavior of concrete members under the influence of high temperatures was studied by considering non-elastic deformation, and a mathematical model is proposed to determine the thermal conductivity and a transient strain model to determine the actual behavior of reinforced concrete structures at high temperatures. Accordingly, the ACI guide's estimate of high temperatures is lower than the laboratory results because the ACI guide ignores the thermal effects (Li *et al.*, 2021). The effects of fire, the ratio of reinforcement, and the presence of compressive load during a fire on the seismic behavior of reinforced concrete shear walls were investigated. For this purpose, five shear walls of reinforced concrete were tested under low cycle loads. Before the cyclic test, three samples were subjected to fire, and two samples were subjected to a constant axial load (Liu and Dai, 2018). It was found that one or more critical cracking can be observed for broken fire samples. In the samples exposed to the combination of axial load and fire, the inclined cracks' width is small during fracture, and the prominent diameter cracks are not known. This is due to (1) a decrease in the strength of concrete at high temperatures and a consequent increase in the ductility of concrete, and (2) an accidental micro-crack in the specimens and cracks visible on the non-flammable surface (dos Santos and Rodrigues, 2016).

A nonlinear concrete model is provided under cyclic loading and high temperatures. This model introduced the correct results for all loading modes of a new thermoplastic damage model for plate concrete exposed to the combination of thermal and cyclic loading using the concept of plastic-work-hardening and reducing stiffness in continuous mechanical damage mechanics. Two damage variables were used: mechanical effect and the other for thermal effect. Besides, thermomechanical induction strains were introduced to describe the effect of mechanical loading on the physical process of concrete thermal expansion (An *et al.*, 2017).

MATERIALS AND METHODS

Specifications of Consumables

The sand used in this design was a mixture of crushed limestone with a maximum aggregate size of 25 mm. The fine-grained sand was double-sanded, with a maximum aggregate size of 4.75 mm.

Table 1. The Specifications of Consumable Cement

Cement Components	Percentage (%)
Si02	26/20
Al2O3	28/5
Fe2O3	72/3
CaO	24/63
MgO	69/2
Na2O	258/0
K2O	533/0
Sio3	54/2
Other Components	49/1

Sand, gravel, and half of the cement were first mixed for one minute to mix the concrete components thoroughly, then half the water and the rest of the cement **(Table 1)** were added to the mixer. Finally, the remaining water was added to the mixture, and all the components of the concrete were mixed for another three minutes. After mixing, the slump test was performed on the samples, and the slump value was 7 cm. After pouring the homogeneous mixture obtained into the sample mold, they were compacted by a vibrating table and placed on flat surfaces 24 hours. After removing the mold samples, they were placed in water and lime tanks and processed for 28 days.

High Temperature and Heating Regime Considerations

Studying high temperatures on the mechanical properties of concrete samples is conducted differently. In some studies, the concrete sample experiences certain temperatures, and after cooling and reaching room temperature, resistance tests are performed on it. This type of test shows residual strength and is used to assess concrete member's post-fire behavior. Another method is to survey the strength characteristics of concrete when the sample is loaded simultaneously as it is exposed to a specific temperature. This method indicates the behavior of concrete members during a fire and provides useful data on reinforced concrete member's capacity when exposed to high temperatures. In this dissertation, experiments were performed in hot mode. The presence of a high percentage of free water in the concrete during the heating of the samples inside the furnace causes the spalling phenomenon's occurrence and the loss of laboratory data inside the furnace. Therefore, the samples were exposed to ambient temperature for 28 days after being removed from the water and lime tank and the heat. Testing operations were performed on 56-day samples in a hot state. This scenario for free water release in the concrete is performed in previous references (Ali *et al.*, 2017; Farzadnia *et al.*, 2013; Kim and Lee, 2015; Moghadam and Izadifard, 2019).

Another factor influencing the results of concrete strength tests and the effect of high temperatures on them is the increase in furnace temperature. High thermal rates are considered one of the factors for spalling concrete samples in the furnace; thus, the rate of increase in temperature of all studied samples was selected at about 3 °C per minute (dos Santos and Rodrigues, 2016; Mezzal *et al.*, 2021; Xie *et al.*, 2018) and required to provide temperature equilibrium conditions was about 3 hours. Further, the furnace's required temperature is supplied with a heat capacity of 1200 °C. After the was removed from the furnace, the completion time of the experiment was less than 5 minutes for the tested samples.

Vertical and Lateral Concrete-strain Compressive Strength Test

The compressive strength of concrete is regarded as one of the main features of concrete strength, which is considered a criterion for determining concrete quality. The compressive strength of concrete is based on legal considerations (ASTM, 2012) and is calculated by the equation $\sigma = \frac{F}{A}$.

The amount of concrete deformation in the direction of compressive loading to the initial length of the cylindrical sample is called the vertical strain. The relationship in determining the vertical strain is presented in the equation $\varepsilon_u = \frac{\Delta L}{L_0}$.

The amount of change in the cylindrical sample diameter due to compressive loading to the initial diameter of the cylindrical sample is called lateral strain. The relation of lateral strain determination is presented in equation$\varepsilon_l = \frac{\Delta D}{D_0}$.

Preparing the Sample Structures for Loading

A self-monitoring device is used to perform cycle load, which allows the computer to control the load during the test so that the data is recorded automatically during the test. This data is recorded at intervals by the settings on the device. This device is made of force and displacement. A central strain is obtained by dividing the stroke by the height of the sample (equivalent to 300 mm), through the stress-strain diagrams of the sample are extracted. Three samples were tested at each temperature, called Cyc1 (cyclic loading in the first place), Cyc2 (cyclic loading in the second row), and UCS (Uniaxial Compressive Stress). In other words, two samples were tested with cyclic loading and one sample with monotonic loading for each temperature. Each loop of initial diagrams contains 22 cycles, and the total number of cycles required for the failure of each sample is calculated from the product of the number of loops in the number of cycles. The experimental protocol was fixed displacement in which the range of displacement changes for each sample remained constant in each ring, and the amount of displacement increased in subsequent rings despite the constant displacement range.

RESULTS AND DISCUSSION

Investigating the Concrete Behavior under Monotonic Loading

The Effect of High Temperatures on Compressive Strength and Vertical Strain of Concrete

The standard cylindrical specimen's compressive strength at ambient temperature is 27.56 MPa. As the test temperatures increase up to 100 °C, the compressive strength of concrete decreases by 10.84% and reaches 25.99 MPa. The evaporation of water in the inner layers of concrete and the resulting internal pressure is considered to reduce the compressive strength in this temperature range. A further increase in test temperature to 300 °C further reduced concrete's compressive strength (Hao *et al.*, 2016). At this temperature, the compressive strength of concrete decreased by 15.92% compared to the ambient temperature (Tantawy, 2017). Placing concrete at a temperature of 400 °C has intensified the reduction in compressive strength of concrete so that it decreased by 34.25% to 20.32 MPa compared to the ambient temperature (Mobasher *et al.*, 2016; Rashad, 2015).

As the test temperature increases, the compressive stress is decreased, and the corresponding vertical strain is increased **(Figure 1)**. As the test temperature increased to 800°C, the compressive strength of concrete decreased by 84% compared to the ambient temperature, and the corresponding vertical strain increased by 75%.

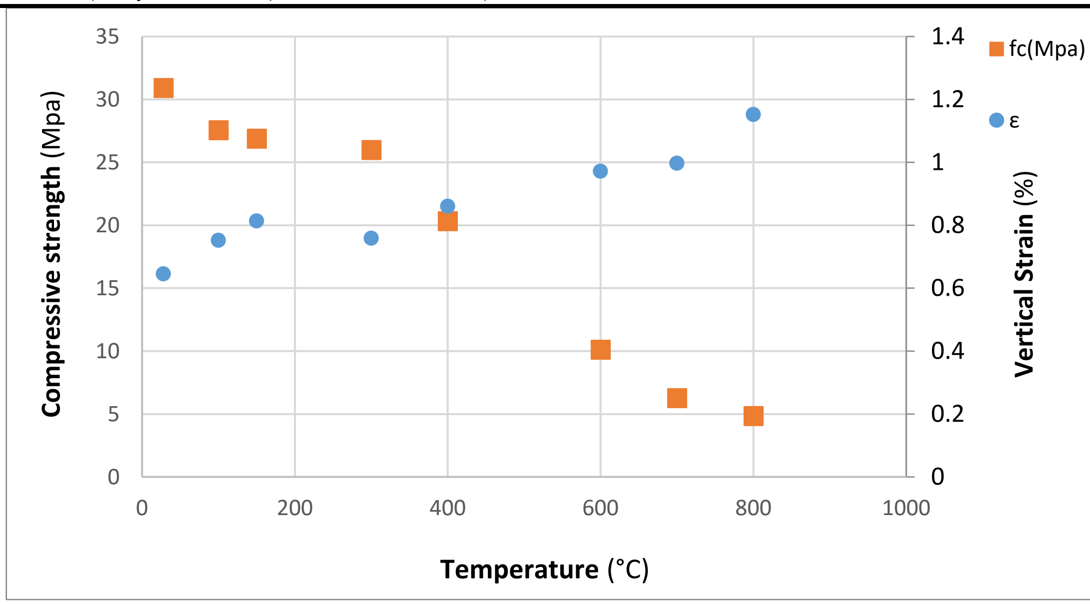


Figure 1. Compressive Stress and Vertical Strain Changes Corresponding to it at Different Temperatures

The Effect of High Temperatures on Compressive Strength and Transverse Strain of Concrete

Examining the compressive stress-strain diagram indicated that the concrete's behavior in the pre-peak stage is almost linear. The slope of this line, which represents the modulus of concrete elasticity, has been declining as the test temperature increases. Regarding the slope tangent to the descending branch, the amount of this slope at temperatures 100, 300, 400, 600, and 700 °C decreased by 23.49, 28.49, 50.69, 78.98, 86.889, and 92.23%, respectively, compared to ambient temperature (El-Gamal *et al.*, 2017; Maheswaran *et al.*, 2015). The sharp decrease in these concrete features at high temperatures is attributed to the damage caused to the components of concrete in these conditions. Surveying the descending branch of the diagram indicated that as the test temperature increases, the descending branch's slope approaches the parallel line of the horizontal axis of the chart (Lim, 2015). Besides, it is observed that as the test temperature increases, the vertical strain corresponding to the compressive stress increased maximally (Lim, 2015; Thomas and Gupta, 2015). A closer look at this chart indicated that as the compressive stress reaches its maximum, the graph's descending branch begins at the ambient temperature. However, the vertical strain increased slightly in the maximum force position, and then the compressive stress decreased (Karatas *et al.*, 2017).

As shown, as the test temperature increases, the compressive stress decreases, and the corresponding transverse strain increases **(Figure 2)**. As discussed in the vertical strain discussion, the compressive strength at ambient temperature decreases by 800 °C, and the corresponding transverse strain increased by 122%. Compared to vertical strain, the transverse strain has lower values than vertical strain, and the rate of transverse strain loss is higher than vertical strain, indicating more sensitivity to cross strain than the vertical strain (Wang *et al.*, 2021).

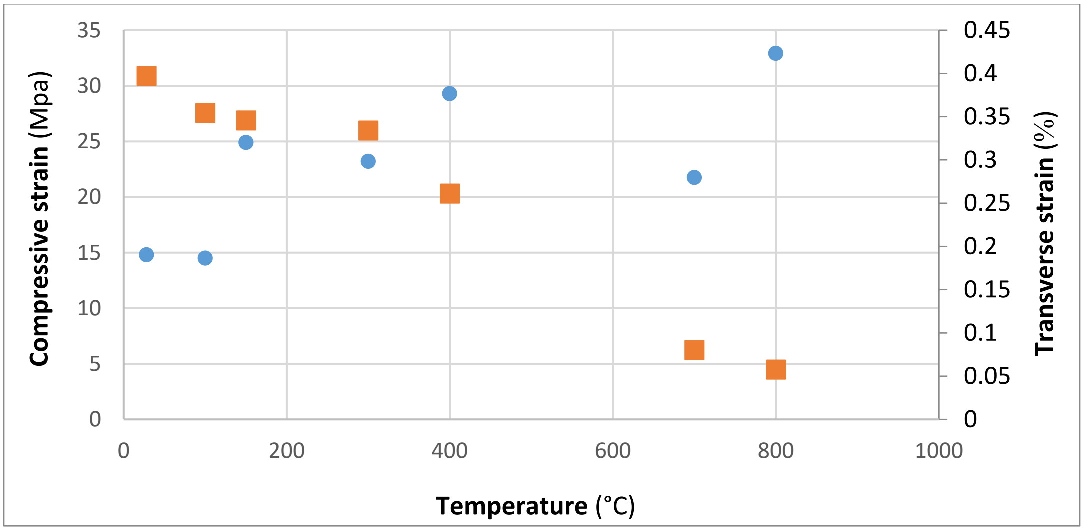


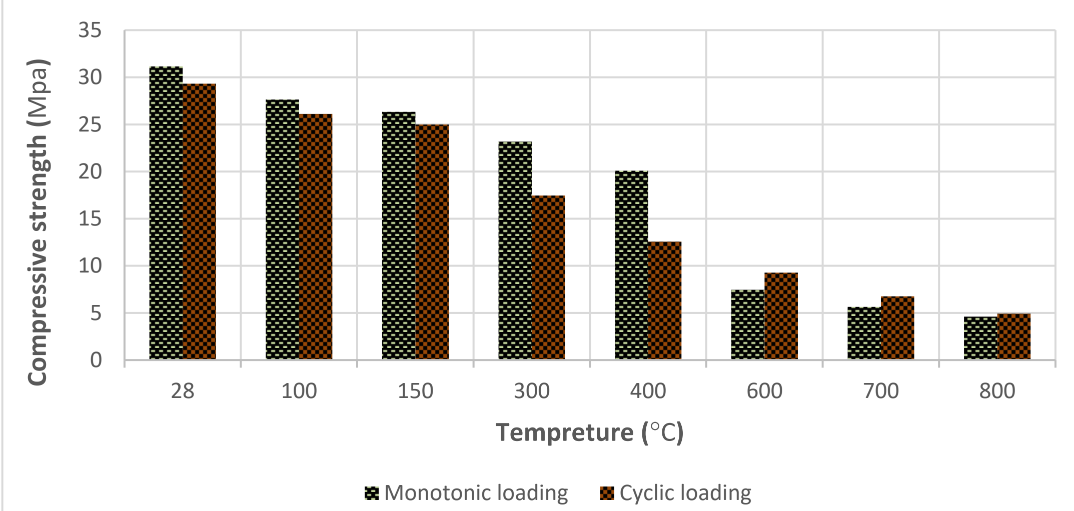
Figure 2. Compression Stresses and Corresponding Transverse Strains at Different Temperatures

Cyclic Loading

Compressive-vertical Stress Strength of Concrete

As the loading steps increase, the stress related to that step increases. After the sample's fracture, as the loading steps increases, the maximum stress in each step followed a downward trend. Surveying these values indicated that the compressive strength of concrete decreased 10.37, 15.64, 41.01, 56.55, 68.34, 79.18, and 84.19%, respectively, at temperatures of 100, 150, 300, 400, 600, 700, and 800 °C. Damaging the chemical composition of concrete is considered one of the essential factors in reducing concrete compressive strength due to high temperatures. As the test temperature rises to 200 °C, no significant chemical changes occur in the concrete's chemical composition. At this temperature, the decomposition of irrigating compounds is observed. Ettergat dehydration temperature is 80 to 150 °C, and its decomposition temperature is 150 to 170 °C. As further temperature increases, CaCO3 compounds decrease (Karatas *et al.*, 2017; Wang *et al.*, 2021).

As shown, the cyclic loading reduced concrete's compressive strength at all temperatures **(Figure 3)**. Besides, the compressive strength of concrete in the cyclic state decreased by 3.30, 6.71, 32.51, 36.43, 6.87, 1.16, and 2.99% at 100, 150, 300, 400, 600, 600, and 800 °C temperature, indicating the adverse effects of cyclic loading. No logical trend was observed related to the corresponding strain. In some temperatures, the strain corresponding to the maximum stress is more significant in the cycle load, and in others, the temperatures are lower. Besides, the stress-strain diagram had a linear behavior before initiating the cycle loading, and the slope of the cycle chart had a downward trend after initiating this loading as the loading steps increase.



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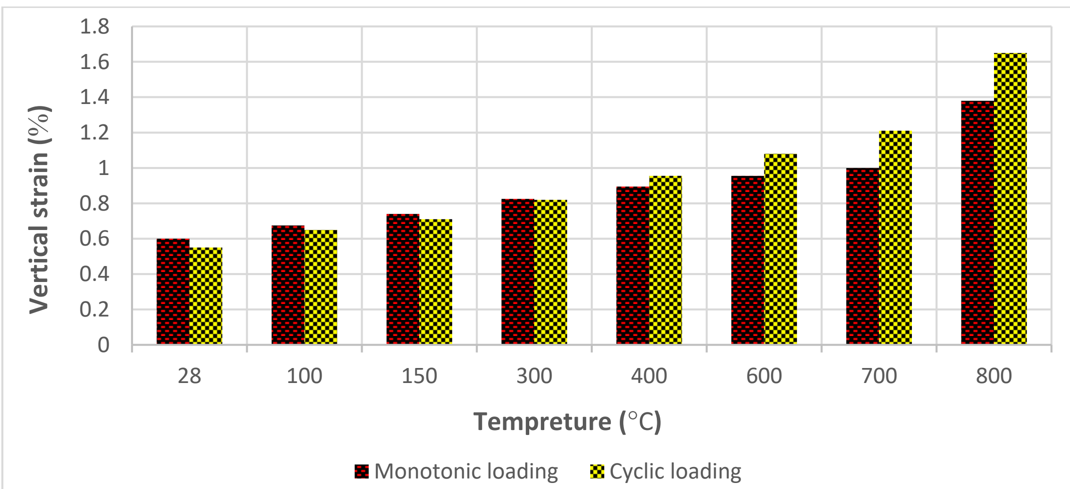

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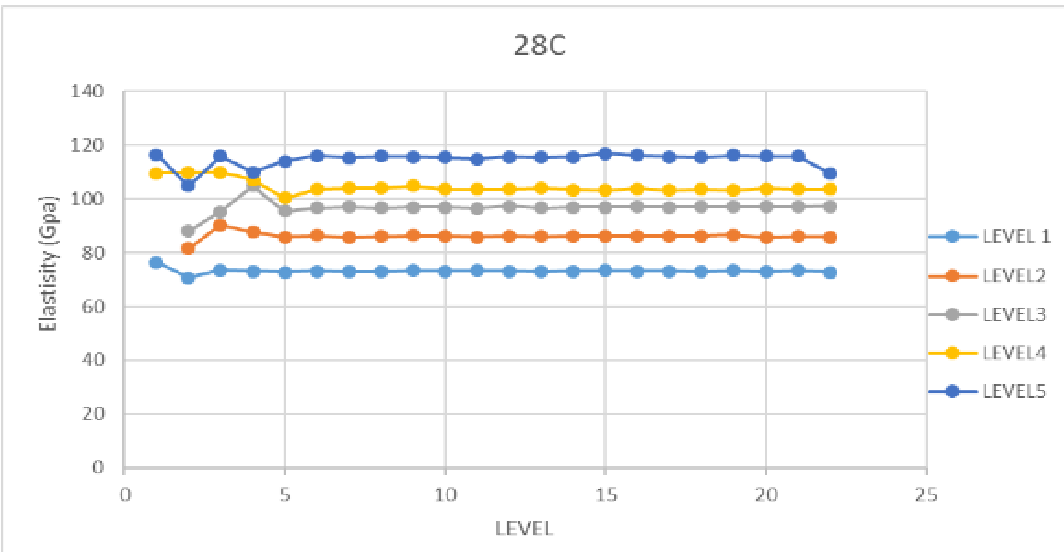
Figure 3. Comparing the Compressive Strength and Vertical Strain Corresponding to Monotonic and Cyclic Loading

The Compressive Strength-transverse Strain of Concrete

Examining the diagram of vertical stress-transverse strain changes indicated that in addition to reducing the compressive strength at temperatures that their reasons are mentioned, the transverse strain of concrete on monotonic loading increased. Besides, the transverse strain of concrete at 150, 300, 400, 700, and 800 °C increased by 68.22, 56.80, 97.90, 46.99, and 122.44%, respectively, compared to the ambient temperature. Comparing the transverse strain in monotonic and cyclic loading mode, it is observed that the value of this parameter in cyclic loading mode decreased significantly compared to the monotonic loading which the amount of transverse strain at temperatures of 100, 150, 300, 400, 700 and 800 °C has decreased by 75.21, 60.64, 60.65, 56.21, 71.94 and 63.25%, respectively, indicating the high impact of cyclic loading on the transverse strain of concrete.

The Effect of Cyclic Loading on the Concrete Elastic Modulus

Figure 4 shows the process of changes in the sequential modulus of the study samples' sequence is presented in different loading stages and for different loading cycles. According to these diagrams, it was observed that as the test temperature increases, the modulus of elasticity decreases in all loading steps, so that the concrete sequential elastic modulus in the first step at ambient temperature increased from 80 gigapascals to about 10 MPa at 800 °C. Also, examining this issue related to other loading steps has demonstrated this issue (Uygunoğlu and Topçu, 2012). This modulus of elasticity is 120 gigapascals at ambient temperature and has reached about 28 gigapascals at 800 °C (Gaifei *et al.*, 2015). Further examining these diagrams indicated that as the load cycles increase from 1 to 22, the modulus of elasticity is almost constant, and no significant changes are observed. Further, the sequential modulus of elasticity increased with increasing loading steps (Li *et al.*, 2021).



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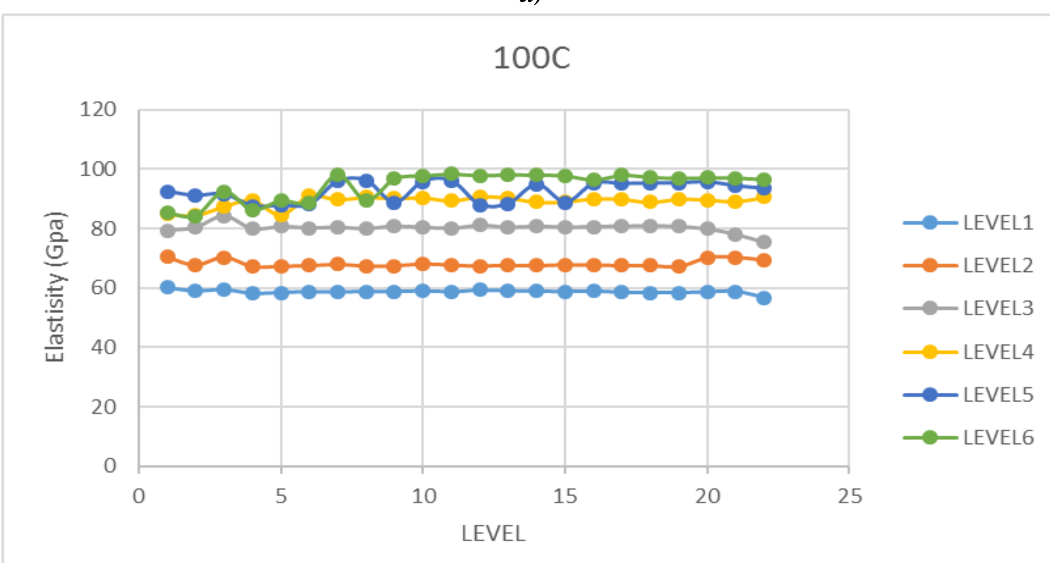

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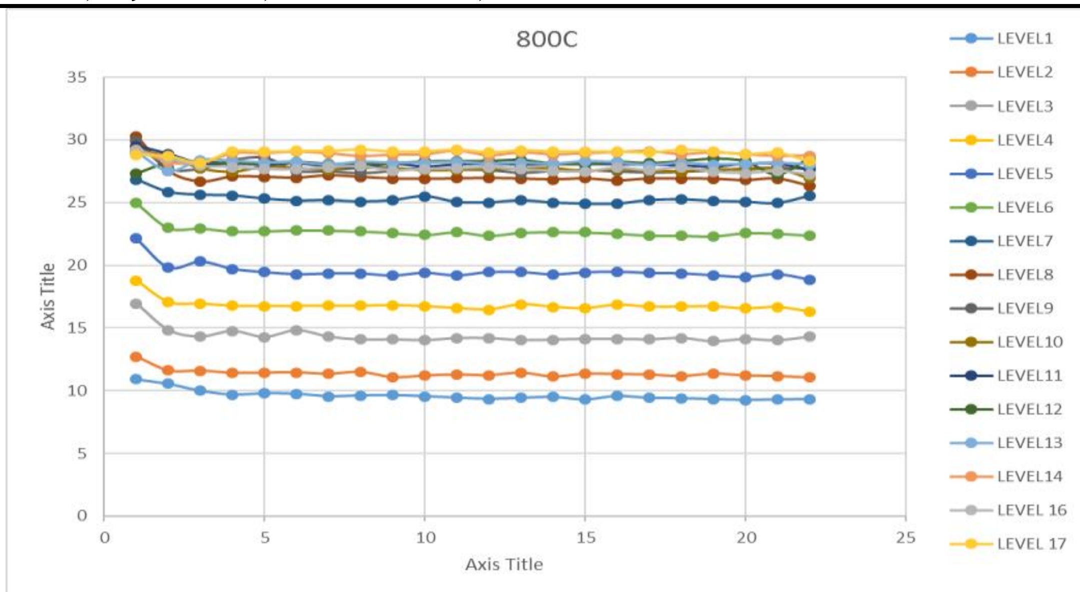

c)

Figure 4. Comparing the Sequential Elastic Modulus in Different Cycles

The Energy in Cyclic Loading

Figure 5 shows the amount of energy absorbed in the loading section in different loading steps for the study samples. As shown, in monotonic loading, the amount of absorbed energy decreased as the test temperature increased.

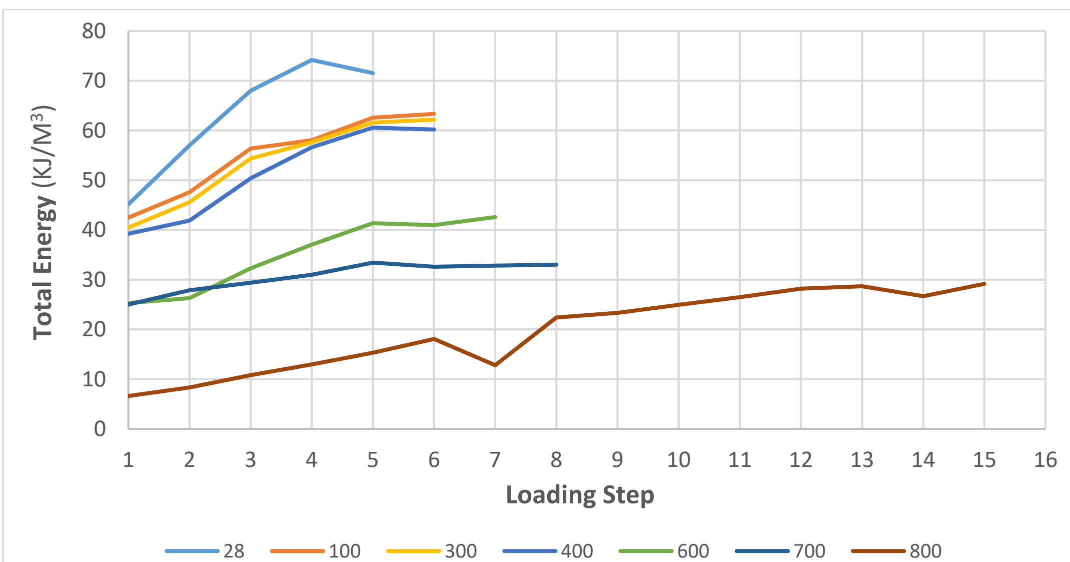

Figure 5. Loading Energy in Cyclic Loading at Each Step

The amount of energy dissipated in different loading steps is not significant. This parameter is also in the range of 0.2 to 0.5 kJ / m3, indicating that the cyclic loading rings are small. On

the other hand, as the loading steps increase, no logical trend is observed in dissipated energy changes.
Each temperature's total energy is equal to the sum of the energy at different steps. The total energy of loading and unloading is approximately equal up to 400 °C, which is about 300 kJ/m³.
However, the total amount of energy decreased at higher temperatures, so that it is reached approximately 250 kJ/m³ at temperatures of 600 and 700 °C. The temperature of 800 °C, where the energy reached about 300 kJ/m³, is related to increasing the loading and unloading steps mentioned in the load-time diagrams. Also, it is inferred that the unloading branch's total energy is less than that of the loading branch, indicating that the cycle loading rings are formed correctly.

Investigating the Effect of Heat on Damage to Concrete Specimens

The amount of damage based on the damage index in concrete samples are investigated. For concrete specimens subjected to cyclic loading, the amount of damage index is evaluated based on the amount of energy of the heterosis absorbed in the transfer cycles. Therefore, the following equation is used to investigate the amount of damage.

$$D = \sum_{i=1}^{N_i} |U_i^d| \Big/ \sum_{i=1}^{N} |U_i^d| \quad (1)$$

Where U_i^d is the amount of energy dissipated in the i^{th} cycle, and Ni is the number of cycles per stage of loading. Also, N is the number of total load cycles in a concrete sample.
Examining the damage index of concrete specimens at different temperatures indicated that the total damage inflicted on concrete specimens increases as the ambient temperature increases, but the amount of damage is reduced by loading in each cycle. It is important because increasing the ambient temperature and placing concrete in it cause the concrete sample to be less durable at each loading stage, which experienced less damage. However, more loading cycles are experienced because the concrete's final fracture will occur in specific damage.

Investigating the Effect of Heat on the Amount of Residual Strain in the Concrete Samples

Since the type of loading and unloading is partial loading and reloading, so there are strains less than the maximum strain of the previous loading at each stage of the cycles at each stage of partial loading after reloading (Piscesa *et al.*, 2019). Regarding partial loading after reloading to more than the maximum strain of the previous loading, the reloading path is defined by the phrase governing complete loading (Li and Wu, 2015; Moharrami and Koutromanos, 2016), given in the following equation.

$$\sigma_c = \sigma_{pr} + \left(\frac{1 - [(\varepsilon_c - \varepsilon_{un})/(\varepsilon_{pl} - \varepsilon_{un})]}{1 + 1 \cdot 2[(\varepsilon_c - \varepsilon_{un})/(\varepsilon_{pl} - \varepsilon_{un})]} \right)^{1 \cdot 2} \times (\sigma_{un} - \sigma_{pr}) \quad (2)$$

Since the amount of permanent strain is obtained in each stage of loading after deducting elastic strain, which is collected for the next stage of loading, thus the last amount of strain in the last step of the loading cycle after deducting the elastic strain of that cycle, which is eliminated in the partial loading stage, is considered as the permanent strain of the whole sample. It is essential in concrete specimens, as shown in **Figure 6**. Therefore, increasing the ambient temperature and placing the concrete in it increases the amount of permanent strain of concrete samples under cyclic loading and cycle as the amount of increase in permanent strain increased by 28, 616, n12, 37.16, 98.64, and 147%, respectively for the temperatures of 150, 300, 400, 600, 700, and 800 °C.

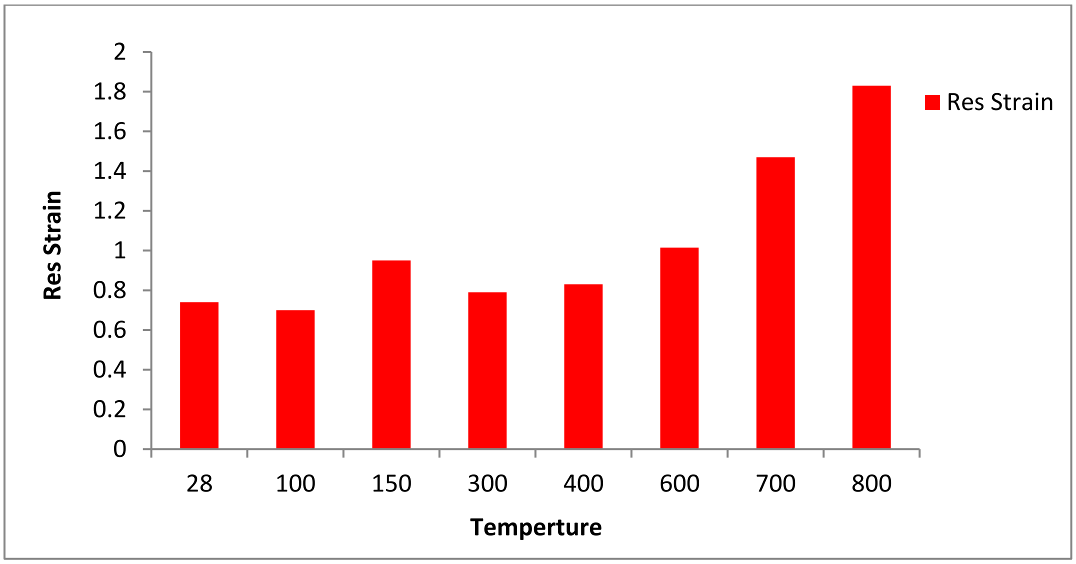

Figure 6. The Persistent Strain of Concrete Specimens

CONCLUSION

The findings in this article are as follows:

- The standard cylindrical sample's compressive strength at ambient temperature was 27.56 MPa. As the test temperature increases up to 100 °C, the compressive strength of concrete decreased by 10.84% to 25.99 MPa. A further increase in the test temperature to 300 °C further reduced concrete's compressive strength. At this temperature, the compressive strength of concrete decreased by 15.92% compared to the ambient temperature. Placing concrete at a temperature of 400 °C intensified the reduction in compressive strength of concrete so that it is reduced to 20.32 MPa 34.25% compared to the ambient temperature. Increasing the test temperature to 600, 700, and 800 °C reduced the compressive strength to 67.29, 79.74, and 86.13%. As mentioned in the mentioned temperatures, the compressive strength of concrete reached 10.11, 6.26, and 4.29 MPa.
- Examining the vertical pressure-strain stress diagram indicated that the pre-peak stage's concrete behavior is almost linear. As the test temperature increases, the slope of this chart decreases. The amount of this slope at temperatures 100, 300, 400, 600, and 700 °C decreased by 23.49, 28.49, 50.69, 78.98, 86.889, and 92.23%, respectively, compared to the ambient temperature.

- The process of changes in compressive strength and the corresponding transverse strain was investigated. It was found that as the test temperature increased, the compressive stress decreased, and the corresponding corticosteroid increased. The vertical strain found that the compressive strength at the ambient temperature of 800 °C decreased by 84%, and the corresponding transverse strain increased by 122%. Compared to the vertical strain results, it was found that transverse strain had lower values compared to vertical strain and the rate of transverse strain decreased compared to vertical strain, indicating more sensitivity of cross strain than the vertical strain.
- The cylindrical sample's compressive strength at ambient temperature under the monotonic loading was 30.91 MPa, which reached 29.73 MPa by decreasing 3.81% in the cyclic loading mode. This type of loading's fatigue effects yields the concrete sample at lower stresses than that of the monotonic state (Gaifei *et al.*, 2015). Concerning the strain corresponding to the maximum stress, it was found that this parameter increased by about 8% in the cycle loading mode.
- As the loading steps increase, the stress associated with that step increases. After the sample's fracture, as the loading steps increases, the maximum stress value in each step followed a downward trend. As shown, as the test temperature increases, the compressive stress had a maximum downward trend. Investigation of these values indicated that at temperatures of 100, 150, 300, 400, 600, 700 and, 800 °C, the compressive strength of concrete decreased 10.37, 15.64, 41.01, 56.55, 68.34, and 18%, respectively.
- Surveying the abrupt stress-transverse strain changes indicated that the transverse strain of concrete in cyclic loading increased. The transverse strain of concrete at 150, 300, 400, 700, and 800 °C increased by 68.22, 56.80, 97.90, 46.99, and 122.44% compared to ambient temperature, respectively. Comparing the transverse strain in the monotonic and cyclic loading model indicated that this parameter's value in cyclic loading mode decreased significantly compared to the monotonic loading. Also, the amount of transverse strain at 100, 150, 300, 400, 700, and 800 °C decreased by 75.21, 60.64, 60.65, 56.21, 71.94, and 63.25%, respectively, indicating the high impact of cyclic loading on the transverse strain of concrete.
- The process of changes in the samples' sequential elastic modulus was investigated in different loading steps and for different loading cycles. As the test temperature increases, the modulus of elasticity decreases at all loading steps, so that the concrete sequential elastic modulus in the first step at ambient temperature ranges from 80 gigapascals to about 10 megapascals at 800 °C. It was observed related to other loading steps. The modulus of elasticity was 120 gigapascals at ambient temperature and about 28 gigapascals at 800 °C. Further examination of these diagrams indicated that as the load cycles increase from 1 to 22, the modulus of elasticity is almost constant, and no significant changes are observed. Also, the sequential modulus of elasticity increased as the loading steps increased.
- The process of changes in the elastic modulus of concrete in monotonic loading was investigated. The modulus of concrete elasticity has been declining as the test temperature increased. It was found that it is reduced as 13.81, 29.99, 28.04, 47.65, 77.50, 85.19, and 87.38%, respectively, at 100, 150, 300, 400, 600, 700, and 800 °C. As shown, the significant damage to concrete is at temperatures above 500 °C.

- As the test temperature increases, the amount of energy required for sample fracture under monotonic loading decreases. The energy dissipated at ambient temperature is 147.56 KJ/m3 and at 600, 700, and 800 °C with 47, 60, and 72% decrease to 77.25, 58.87, and 40.91 KJ/m3. Also, the amount of energy absorbed decreases as the test temperature increases in cyclic loading. Further, as the loading step increases, the energy at all studied temperatures increases. Comparing the loading energy in the last step compared to the first step for ambient temperature samples, 100, 300, 400, 600, 700, and 800 °C increased by 58, 49, 53, 53, 68, 32, and 341%, respectively. In the loading mode, energy changes are similar to the load energy changes. As the test temperature and loading steps increase, the energy increases. The last step's loading energy increased by 100, 300, 300, 400, 600, 700, and 800 °C compared to the first step, for example, 59, 49, 54, 53, 71, 32, and 370%, respectively. Besides, it was found that the amount of unloading energy is less than that of the loading energy compared to loading and unloading energy, indicating the formation of cyclic loading rings.
- The results of damages to the samples indicate that exposing concrete samples to high temperatures leads to early separating the concrete specimens, and the amount of damage to concrete samples increased. However, it is worth noting that the amount of damage to concrete specimens exposed to high temperatures occurs at higher loading steps.
- The results of surveying the waste strain indicated that the amount of persistent strain in concrete specimens exposed to high temperatures is significantly higher than that of the specimens exposed to average temperature. It was significantly higher for 700 and 800 °C, indicating further deformations in these samples. As for 150, 300, 400, 600, 700, and 800 °C, the amount of increase in permanent strain increased by 28.6, 16/12, 37.16, 98.64, and 147%, respectively.

Suggestions

- Investigating other cyclic loading patterns on mechanical properties of concrete at high temperatures
- Surveying other scenarios of concrete heating samples on mechanical properties of concrete in cyclic loading mode
- Examining the mechanical properties of concrete in the cooled state and the effect of different cooling methods
- Exploring the effect of different types of fibers on the mechanical properties of concrete in cyclic loading mode
- Also, the effect of sub-zero temperatures on the mechanical and physical properties of concrete should be examined.

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ETHICS STATEMENT: None

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