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*Article*

# Mechanical Properties of Rubberized Concrete at Elevated Temperatures

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**Abstract:** The use of rubberized concrete has become increasingly popular as a means of disposing of waste materials, such as used and end-of-life tires, while also providing an effective solution for construction applications. The strength and durability of rubberized concrete can be negatively affected by temperature fluctuations, but little is known about the performance of this material. Hence, the work presented herein aims to evaluate the performance of rubberized concrete when it is exposed to different temperature levels. In this study, rubberized concrete specimens were prepared by replacing 5–20% of crumb rubber by volume of fine aggregate. The specimens underwent a curing process for 28 days, followed by exposure to temperatures of 200 °C, 400 °C, and 600 °C for a period of 2 h. The residual test and normal cooling method were adapted. Surface characteristics by visual inspection, the residual weight, compressive strength, splitting tensile strength, ultrasonic pulse velocity, and dynamic modulus of elasticity were assessed and compared to unheated specimens. The study's findings revealed that, when exposed to temperatures between 200 °C and 400 °C, rubberized concrete containing a 5% to 15% rubber content experienced less reduction in compressive strength than conventional concrete, which showed a reduction of 43% to 48.5%. Also, it was observed that the splitting tensile strength was more sensitive to elevated temperatures than the compressive strength.

**Keywords:** elevated temperatures; solid wastes; mechanical properties; rubberized concrete; normal cooling; residual test

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## 1. Introduction

Concrete is the most commonly used building material, requiring a considerable amount of natural resources. The continuous extraction and use of natural aggregates not only harms the environment but also depletes the remaining resources. Also, each year, the cement industry emits over 4 billion tons of carbon dioxide, contributing around 7% of global carbon dioxide emissions [1]. Therefore, it is crucial to develop environmentally friendly concrete that minimizes the use of natural resources [2–4].

The ability of a structure to withstand specific events or functional conditions relies heavily on the performance of its robust design when exposed to high temperatures. Although several research studies have explored the behavior of concrete structures under high-temperature conditions, the quality of these efforts has been insufficient to gain widespread acceptance in the design of concrete for elevated temperatures. Numerous studies have investigated the mechanical properties of concrete incorporating various waste materials. Generally, it was found that subjecting concrete to elevated temperatures can cause chemical and physical changes, resulting in significant damage and negatively impacting its mechanical properties and durability [5–7]. Three testing methods, namely transient, steady-state, and residual tests, are commonly used to assess the high-temperature properties of concrete. In the transient test, the specimen undergoes loading of up to 40% of its ultimate compressive strength and is subsequently heated until it fails. The steady-state method entails heating the concrete sample until it reaches a uniform temperature, followed by applying a load until failure occurs. On the other hand, the residual method involves initially heating the sample at a steady rate to the desired temperature level, without applying any load. Once the exposure time is reached, the sample is allowed to cool down to room temperature before being loaded to failure. This final method is particularly valuable in evaluating the properties of concrete following exposure to high temperatures and fire [8–11].

In recent years, there has been a growing interest in utilizing waste materials to replace conventional components in concrete. Numerous studies have been conducted to investigate the feasibility of using these waste materials, and several have shown promising results in enhancing the properties of concrete. One such material is fly ash, which can be used as an admixture, partially replacing cement, or as a substitute for a fine aggregate. Research has demonstrated that incorporating 20–40% of fly ash into cementitious composites improves their strength and durability [12,13]. In addition to fly ash, several other waste materials have also been explored as potential replacements for fine or coarse aggregates. These materials include rubber [14–17], marble dust [18–20], wood shavings [21], sawdust [22,23], waste glass [24,25], plastic [26], and construction and demolition waste [27]. The aim of using these waste materials is twofold: to recycle them and to reduce their impact on the environment.

The presence of discarded and used tires in landfills and open areas poses numerous risks to both humans and the environment. Tires are specifically designed to withstand the high temperatures generated by friction on the road. However, once a tire catches fire, it becomes extremely challenging to extinguish due to the tire's composition and the fact that 75% of its volume consists of air [15], providing abundant oxygen to fuel the fire. In certain instances, tire fires have persisted for varying durations, such as the Winchester, Virginia, fire in 1983, which burned for approximately 9 months; the Westley, California, fire in 1999, which lasted about a month; and the Sycamore, Ohio, fire in 1999, which consumed around 5 million tires [15]. Furthermore, the accumulation of scrap tires creates an optimal habitat and breeding ground for insects, rats, and snakes, posing significant health risks to nearby communities [15,17]. Extensive research has been conducted on utilizing crumb rubber derived from discarded tires as a partial substitute for fine and coarse aggregates. The investigations have unveiled distinct effects on the mechanical and non-mechanical characteristics of concrete depending on the size and quantity of the crumb rubber particles added. While the augmentation in both the size and quantity of crumb rubber particles adversely impacts the mechanical properties of concrete, this degradation can be mitigated by incorporating a limited amount of crumb rubber or subjecting these materials to pretreatment before blending them into concrete mixtures. Conversely, the incorporation of crumb rubber into concrete mixes has demonstrated improvements in non-mechanical properties, including density reduction, enhanced thermal and sound insulation, increased impact resistance, and improved ductility [13–27].

Due to the softer nature of rubber particles compared to mineral aggregates, the decrease in mechanical properties can be attributed to a reduced amount of load-bearing material in the mixture. Furthermore, the adhesion between the rubber particles and cement paste is compromised due to the characteristics of the rubber's surface [15,28–31]. Certain methods have been proposed to roughen the surface of rubber particles prior to their use, enhancing the bond between the rubber particles and cement paste. Certain pretreatment techniques have shown improvement in the compressive strength of rubberized composites [30], while others have mitigated the degradation in the mechanical properties of rubber-modified concrete [28,30,31]. The enhanced properties of rubberized concrete have prompted researchers to suggest various applications, including nonbearing walls, building facades, ground slabs, lightweight concrete blocks [32–34], pavements [35], bunkers, crash barriers around bridges, highway barriers [30,33], foundation pads for railway stations and machinery [33,36], earthquake shock-wave absorbers [33,36], sidewalks, driveways [37–39], thermal insulation material [15–17,34], sound barrier blocks [40], and architectural applications [28,29,36,37]. Understanding the behavior of concrete when exposed to high temperatures is crucial, especially in the case of concrete containing crumb rubber. Previous research conducted by Maciá et al. [5] examined the impact of high temperatures on concrete with varying amounts of construction and demolition waste. The findings revealed that as the temperature increased, the compressive strength of the concrete decreased, and the type of waste material used also influenced the degree of reduction. Specifically, concrete containing masonry waste experienced a greater reduction in compressive strength compared to concrete containing recycled concrete when subjected to the same temperature exposure. Another investigation focused on the substitution of a coarse aggregate (NA) with recycled aggregate concrete (RA) under elevated temperatures [41]. It was found that concrete containing up to 30% RA exhibited a 43% decrease in compressive strength at 450 °C compared to at ambient temperature, while concrete containing NA showed a 45% decrease under the same temperature conditions.

Furthermore, the effect of temperature exposure on concrete with different fiber contents was studied [42]. The results demonstrated that the inclusion of fibers had a positive impact on mitigating the reduction in basic mechanical properties such as the compressive strength and modulus of elasticity. Specifically, up to 450 °C, an increase in fiber content helped to mitigate the reduction in compressive strength. Another study [43] investigated the mechanical properties of concrete incorporating recycled concrete aggregate and a limited amount of crumb rubber (0.5–2%) when exposed to temperatures ranging from 20 °C to 450 °C. The research revealed that conventional concrete exhibited a higher unconfined compressive strength (UCS) than specimens containing crumb rubber at low temperatures. However, at higher temperatures (300 °C), the crumb rubber specimens demonstrated a higher UCS due to the melting of rubber at elevated temperatures.

Given the limitations of the aforementioned studies and the growing interest in using crumb rubber as a partial replacement for natural aggregates, there is a need to examine the behavior of rubberized concrete under different exposure conditions, such as fire exposure. Therefore, the objective of this study is to provide new data and improve our understanding of how these materials respond to varying levels of temperature exposure. This study aims to deepen our understanding and bridge research gaps pertaining to the behavior of rubberized concrete when subjected to high temperatures. The study builds upon a previous comprehensive investigation of the mechanical properties of rubberized concrete, which incorporated 5% to 20% rubber by volume of fine aggregate [28]. It is crucial to gain insight into the response of rubber concrete to elevated temperatures, particularly considering that the rubber in concrete has a lower ignition threshold than other components.

The present study examines the impact of high temperatures on various properties of rubberized concrete, including weight loss, compressive strength, tensile strength, ultrasonic pulse velocity, and the dynamic modulus of elasticity, in comparison to conventional concrete. The experimental approach involves the utilization of the residual method test and normal cooling techniques. After curing the concrete samples for 28 days, they were exposed to temperatures ranging from 200 °C to 600 °C. Subsequently, the results are compared with those obtained from unheated specimens tested at room temperature (21 ± 1 °C).

## 2. Materials and Methods

### *2.1. Materials*

The materials used in this research are Portland cement, coarse and fine aggregate, and crumb rubber. Portland cement type I (42.5 N), locally manufactured [44], was confirmed to fit the ASTM C150-12 standard. The chemical composition of cement is given in Table 1. The coarse aggregate was crushed limestone, and its gradation was confirmed to fit the ASTM C33 standard with a specific gravity and absorption of 2.59 and 1.8%, respectively. The bulk density, crushing, and impact values of the coarse aggregate were 1520 kg/m$^3$, 23%, and 18%, respectively. The fine aggregate was confirmed to fit the BS 812: Part 103: 1992 standard. The specific gravity, absorption, material finer than 75 microns, and bulk density of the fine aggregate were 2.7, 0.6%, 0.95, and 1714 kg/m$^3$, respectively. The crumb rubber (CR) used in this study, which was derived from scrap and end-life tires, was obtained from a local supplier. The size of crumb rubber particles ranged from 0.15 mm to 4.75 mm. The specific gravity, loose density, and fineness modulus of the crumb rubber were 1.08, 413 kg/m$^3$, and 2.95, respectively. The gradations for the fine aggregate, coarse aggregate, and crumb rubber are listed in Table 2. In addition, a superplasticizer (SP), a chloride-free liquid admixture of types A and F conforming to the standard ASTM C-494, was used with a dosage of 1% in cement.

**Table 1.** Chemical composition of Portland cement.

| | | | | | | |
|---|---|---|---|---|---|---|
| Oxide Composition | LO.I | CaO | $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | MgO |
| Weight (%) | 1.81 | 65.08 | 15.25 | 4.49 | 2.65 | 1.26 |
| Oxide Composition | $SO_3$ | $Na_2O$ | $K_2O$ | Cl | $TiO_2$ | MnO |
| Weight (%) | 2.29 | 0.25 | 0.7 | 0.007 | 0.3 | 0.033 |

**Table 2.** Grading limits for different aggregate materials.

| **Sieve Size (mm)** | **0.075** | **0.15** | **0.3** | **0.6** | **1.18** | **2.36** | **4.75** | **9.5** | **12.5** | **19** | **25** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Fine Agg. (%) | 0.34 | 10.56 | 45.05 | 80.70 | 99.04 | 99.76 | 100 | -- | -- | -- | -- |
| Crumb Rubber (%) | 0.1 | 4.52 | 14.58 | 32.29 | 64.81 | 89.17 | 99.91 | -- | -- | -- | -- |
| Coarse Agg. (%) | -- | -- | --- | --- | --- | --- | 6 | 47.95 | 62 | 94.45 | 100 |

*2.2. Samples Preparation and Designations*

Four different mixes were prepared with varying volumes of crumb rubber as a replacement for fine aggregate at 5%, 10%, 15%, and 20% to investigate the impact of elevated temperatures on rubberized concrete. The control concrete mix was designed according to the American Concrete Institute ACI-211. The remaining mixes were prepared by substituting 5–20% of the fine aggregate with crumb rubber by volume. The description and proportion of mixes are shown in Table 3.

**Table 3.** Mix designation and proportions per cubic meter.

| **Mix ID** | **CR%** | **Weight (kg/m$^3$)** | | | | | | **W/C Ratio** |
|---|---|---|---|---|---|---|---|---|
| | | **Cement** | **Water** | **Coarse Agg.** | **CR** | **Fine Agg.** | **SP** | |
| CM | 0 | 388 | 190 | 1003.2 | 0 | 767 | 3.88 | 0.49 |
| 5CR | 5 | | | | 15.34 | 728.65 | | |
| 10CR | 10 | | | | 30.68 | 690.30 | | |
| 15CR | 15 | | | | 46.02 | 651.95 | | |
| 20CR | 20 | | | | 61.36 | 613.60 | | |

As concluded by many studies [28–36], the lack of bonding between the crumb rubber and cement paste was recognized as a critical factor in the degradation of the mechanical properties of rubberized concrete. Hence, to improve the adhesion between CR particles and cement paste, a proposed treatment method by [14,28] based on a combination of chemical treatment and heat treatment was adapted herein. Using this method, CR particles were first immersed in a 2% concentrated sodium hydroxide solution (NaOH) for 72 h, then sieved on Sieve No. 200 and washed with clean water, and finally dried in the oven at

50–60 °C for 72 h [14,28]. A total of 60 (100 mm × 100 mm) cubic specimens and 60 (∅100 mm × 200 mm) cylindrical specimens (12 cubes and 12 cylinders for each replacement ratio) were prepared as specified in ASTM C192/C192M. After 28 days, the specimens were removed from the curing tank and allowed to dry at room temperature for two days.

### 2.3. Methodology

To examine the effect of heat exposure on normal and rubberized concrete, at the age of 28 days, samples were taken out of the curing tank and allowed to dry at ambient temperature. Firstly, the specimens were initially weighted using an electronic scale, and the ultrasound velocity was measured using the Ultra Pulse Velocity Test (UPV) as specified in ASTM C 597-16 prior to heat exposure. The UPV test results, along with the densities of the different mixes, were used to calculate the dynamic modulus of elasticity. The density of each specimen was calculated according to ASTM C 642-13. Secondly, to perform the heating procedure, an electronic furnace with a maximum temperature of 1600 °C (Carbolite Gero RHF model) was used. The specimens were first placed into the electric furnace, which had been previously adjusted to the desired temperature level. All specimens were exposed to elevated temperatures for a duration of 2 h (after the furnace reached the desired temperature). For each replacement ratio, three samples were heated to three selected levels of temperature, namely 200 °C, 400 °C, and 600 °C. After being exposed to heat, the samples were allowed to gradually cool down at room temperature for 48 h. The procedures followed in this study are illustrated in Figure 1.

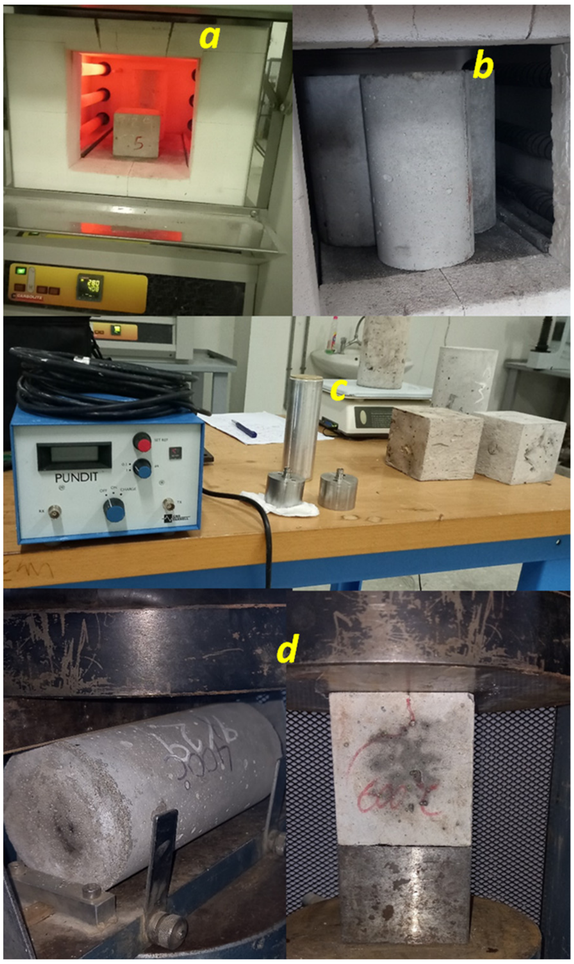


**Figure 1.** Experimental setup: (**a**) samples in the electric furnace; (**b**) samples allowed to cool for 48 h; (**c**) samples weighted and tested for the UPV test; and (**d**) compression and tensile tests.

Finally, after experiencing different exposure temperatures, the samples were weighed to calculate the loss of weight and loss of density, then tested for the UPV test, and the dynamic modulus of elasticity was calculated once more. Subsequently, samples were visually inspected to assess the surface changes and the damage to the specimens after heat exposure. Later, samples were tested for compressive and splitting tensile strengths. Similarly, unheated samples of each replacement ratio and the control mix were subjected to tests for compressive strength as per BS EN 12390-3:2009 [45], splitting tensile strength according to ASTM C496/C496M, and the UPV test. These tests were carried out to enable a comparison with the samples that were exposed to heat.

## 3. Results and Discussion

This section presents, discusses, and compares the effect of elevated temperature on various properties of rubberized concrete, including physical evaluation of the specimens by visual inspection, compressive strength, splitting tensile strength, weight loss, ultrasonic pulse velocity speed, dynamic modulus of elasticity by mean UPV test, and physical characteristics. Relevant results available in the literature are also considered and compared.

### *3.1. Temperature Effect on Physical and Chemical Features*

The effect of elevated temperature on rubberized concrete is illustrated in Figures 2 and 3. Figure 2 shows the change in color of the rubberized concrete, and Figure 3 depicts the cracks on the concrete's surface. The heat effect on rubberized concrete based on temperature-exposure level can be characterized into three scenarios as follows:

1. Up to 200 °C, the concrete's color becomes bright gray, and crumb rubber particles are not affected since the melting point of rubber materials is below 250 °C. A number of microcracks develop on the surface of the concrete. Considering the chemical composition of the concrete at this stage, the ettringites start to disintegrate and the evaporation of the interlayer and capillary water starts. Different studies report the same findings [46–52].
2. At 200 to 400 °C, the color of the concrete changes to a light brown 1–1.25 cm from the surface, and the core of the concrete turns a dark gray color. The rubber particles near the concrete's surface are partially burned, and far from the concrete's surface, the rubber is not affected by temperature exposure. At this stage, more cracks on the concrete surface have developed and become more visible. In view of the chemical composition, due to the temperature rise, the interlayer water has totally vanished, and a great portion of the capillary water has also vanished. Part of the CH transforms into water and lime, and the rest develops into more calcium silicate hydrates gel. Similar findings were reported by [46–52].
3. In the 400 to 600 °C range, the concrete becomes dark gray in color from the edges and turns into a darker gray, tending towards a blackish color. The change in color is due to the crumb rubber being totally burned and turning into ash. More cracks develop on the concrete's surface and become more pronounced. At this stage, crystal water starts to evaporate, which results in the disintegration of CH crystals and C-S-H gel. As reported by [46–52], a significant amount of CH and C-S-H decompose due to crystal water evaporation.

In regard to normal concrete, the effect of temperature exposure has similar effects in terms of surface damage and crack development; the only distinguished difference is the color of the tested specimens, which show a bright gray color after exposure to temperatures up to 400 °C, followed by a change into a darker gray upon heat exposures ranging from 400 °C to 600 °C. Finally, considering the geometry of the specimens, it is observed that all tested specimens have no visual change in geometry and no spalling of the concrete skin.

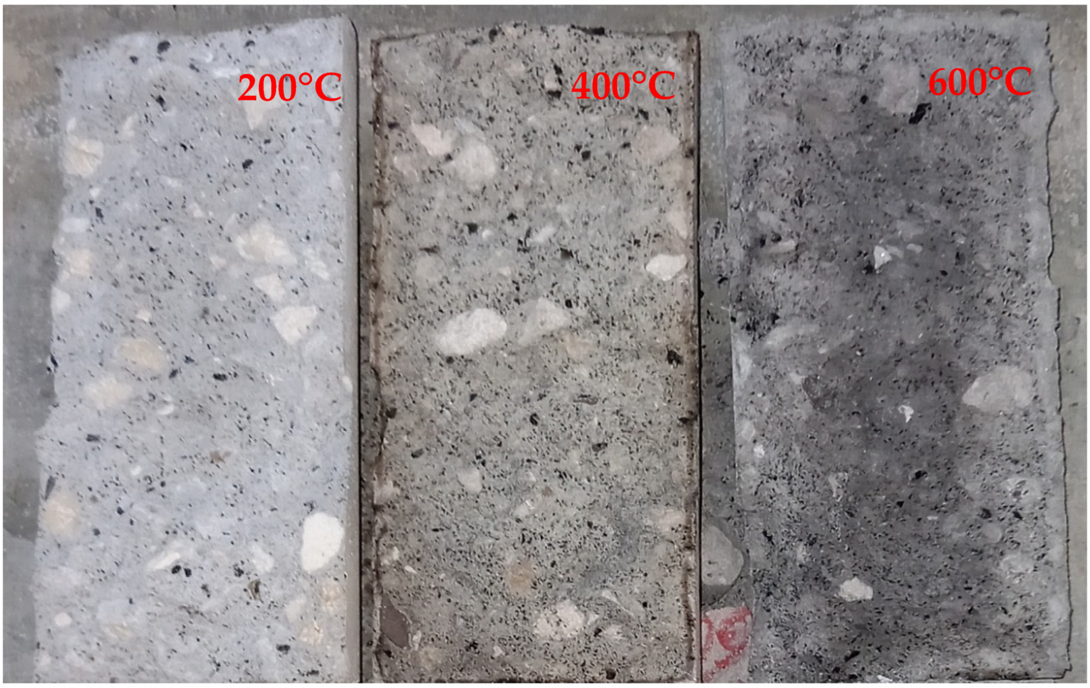


**Figure 2.** The effect of elevated temperatures on color change in rubberized concrete.

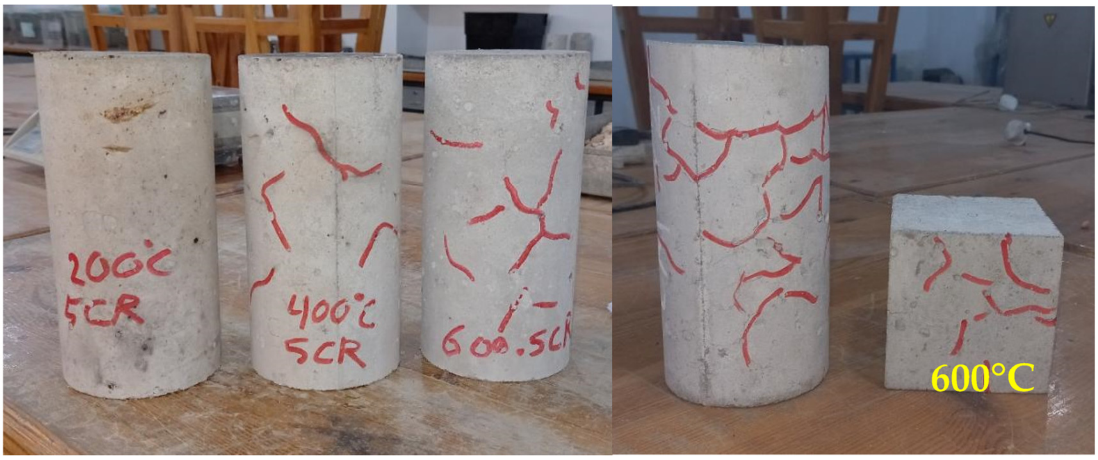


**Figure 3.** Cracks develop at the surface of rubberized concrete at different heat exposure levels.

## 3.2. Loss of Weight and Density

Weight loss is one way to measure the impact of heat exposure on concrete; the weight loss is the difference between the weight of the specimens before and after heat exposure. All concrete exposed to elevated temperatures experiences a loss of weight, and the weight loss increases as the temperature level increases. Figure 4 shows the weight loss for different mixes at different temperatures. At 200 °C, most rubberized concretes showed less weight loss compared to the control mix; the control mix recorded about a 7% decline in its weight, whereas the rubberized concrete's weight (10–20% of CR) reduction varied from 3.25% to 6.7%, and the 5CR mix weight loss was approximately equal to the CM. At 400 °C, all rubberized concretes experienced a weight loss higher than that of the control mix and higher than that of the 200 °C heat exposure. At 400 °C of heat exposure, weight loss of up to 9.1% was observed for rubberized concrete, while the control mix recorded 7.5%, which is a slight increase in weight loss compared to 200 °C. The post-exposure weight loss at 600 °C continued to increase and reached up to 9% for CM, followed by 9.2% for the 5CR mix, and varied from 9.95% to 10.5% for the rest of the rubberized concrete mixes.

The reduction in the weight of concrete samples might be due to the loss of moisture and capillary water, the chemical decomposition of CH crystals and C-S-H gel, and most importantly, the degradation and mass loss of rubber materials. The loss of weight was pronounced at high temperatures. A study conducted by [53] reported similar results, where the loss of weight in rubberized concrete ranged from 13% to 17% compared to 11% for conventional concrete at an 800 °C heating level.

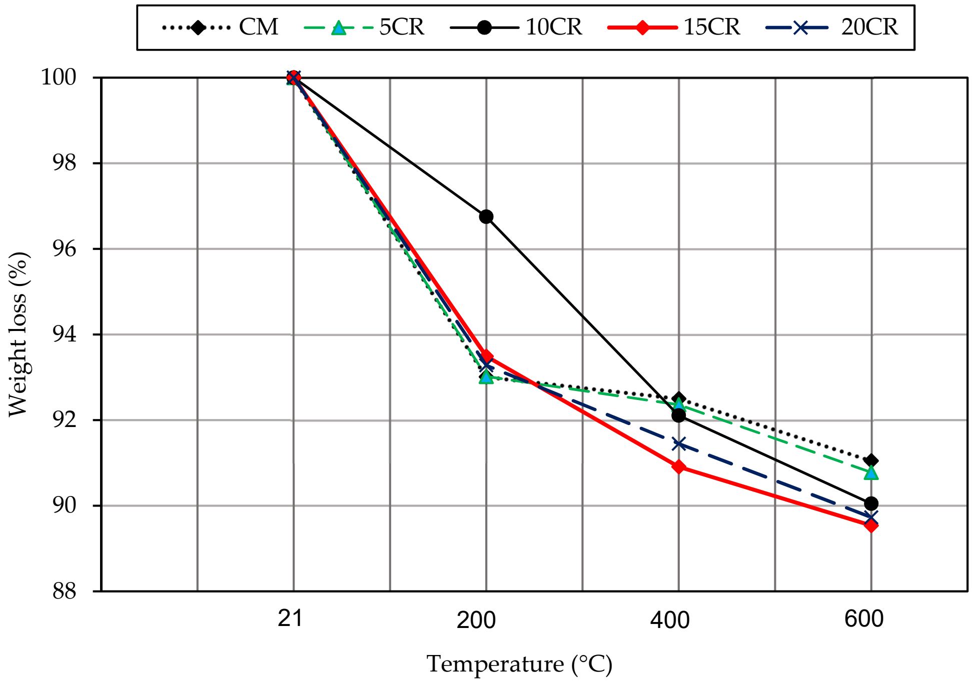


**Figure 4.** The effect of different temperatures on the weight of concrete.

Figure 5 shows the results of dry density at ambient temperature and at different levels of temperature exposure for different mixes. The results of the residual dry density of all mixes were measured based on ASTM C 642-13 before and after heating. The density was simply calculated by dividing the weight of the specimen by its volume. At an ambient temperature (21 °C), the density of rubberized concrete was found to decrease as the amount of crumb rubber increased. The decline in the dry density ranged from 3.25% to 6.7% compared to the control mix. The reduction in the dry density increased as the level of temperature exposure and crumb-rubber content increased. At 200 °C, the specimens experienced a density decline of 4.5% for the control mix, while for rubberized concrete, the reduction ranged from 5.7% to 7.3%. As the temperature increased, the reduction in density increased for CM. The reduction was in the range of 6–9% at temperatures ranging from 400 °C to 600 °C; at the same level of temperature exposure, rubberized concrete experienced density reductions ranging from 6.7% to 11.2%. The reduction in density was attributed to the loss of free water and bond water due to the dehydration process; similar findings were observed by [54].

### *3.3. Residual Compressive Strength*

The compressive strength test was conducted in accordance with the BS EN 12390-3:2009 specification. At room temperature (21 °C), the compressive strength of rubberized concrete declined as the amount of crumb rubber increased, as shown in Figure 6. The reduction was approximately 26% at a 20% CR amount. The effect of heating on concrete caused a loss of compressive strength, and the loss increased as the heating level increased. The reduction in compressive strength was evident at higher temperatures. At 200 °C, the rubberized concrete experienced a lower compressive strength decline than that of the control mix; the maximum reduction was about 48% at 20% CR. At 400 °C, the rubberized concrete exhibited a similar trend observed at the 200 °C temperature exposure; the reduction in compressive strength varied from 31% to 48% at a 5% to 20% replacement. At 600 °C, the control mix displayed a decline of 62.5%, while rubberized concrete at 5–10% showed a lower reduction compared to the control mix. At higher replacement levels (15% and 20%), the loss in compressive strength was higher than that recorded by the control mix. The reduction in compressive strength recorded by 10CR was the lowest for all mixes and all temperatures of exposure. Figure 7 illustrates the post-heat exposure compressive strength reduction in rubberized and normal concretes. The degradation in the compressive strength could be attributed to many reasons, mainly the alteration in the chemical composition of the cement paste and the inner pressure caused by the evaporation of free and capillary water, which led to the development of microcracks within the concrete matrix. Several studies have arrived at similar conclusions [45–51]. Moreover, at a lower rubber content ($\leq$10%) and heating up to 200 °C, the rubber melted and acted as an adhesive, which increased the bonds between aggregates and reduced the pores, thus reducing the compressive strength less than in other concretes; similar results were reported by [43].

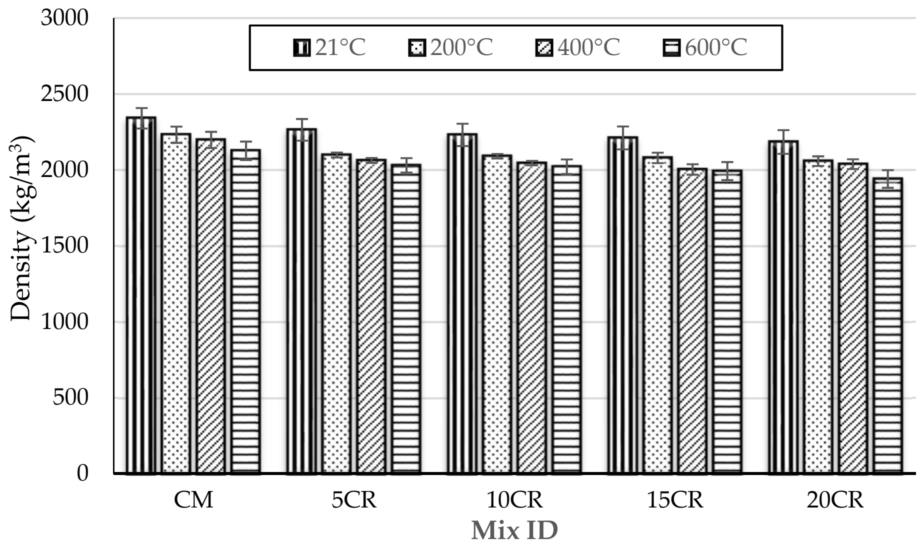


**Figure 5.** The effect of different heating levels on the density of concrete.

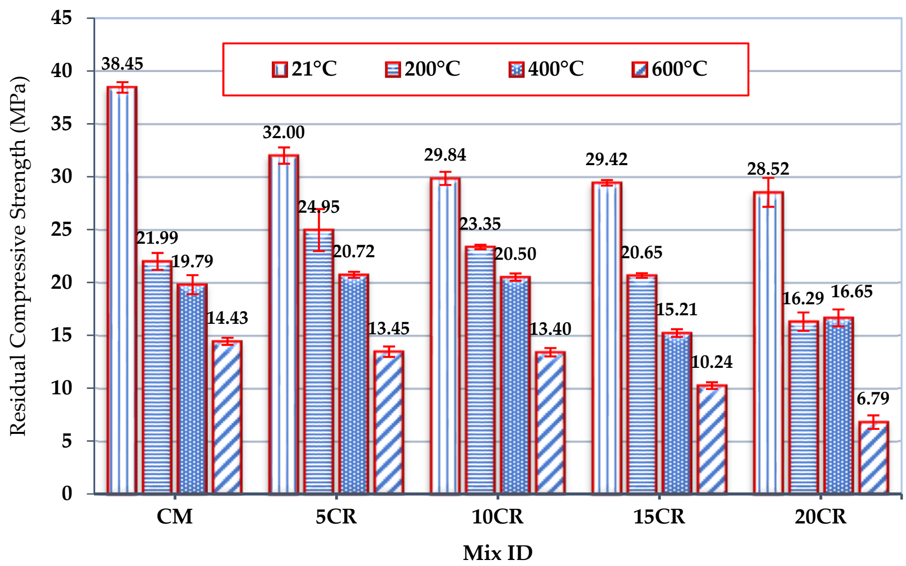


**Figure 6.** Residual compressive strength at elevated temperatures.

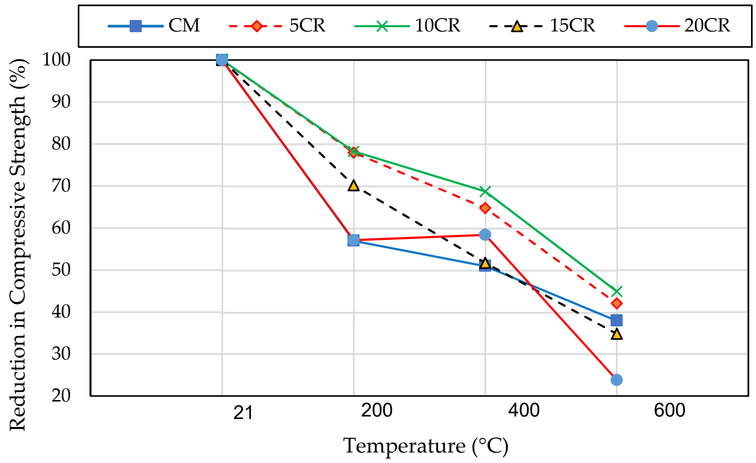


**Figure 7.** Loss of compressive strength vs. temperature exposure.

### 3.4. Residual Splitting Tensile Strength

The splitting tensile strength test was performed according to ASTM C496/C496M. The residual splitting tensile strength of the control mix and rubberized concrete after exposure to elevated temperatures is shown in Figure 8. The splitting tensile strength was severely affected by the temperature increase, and similar to the reduction of compressive strength, the reduction in tensile strength increased as the temperature increased. As the temperature increased, the conventional concrete experienced a reduction in splitting tensile strength of between 35% and 75%, where the splitting tensile strength dropped from 2.82 MPa to 0.7 MPa. In regard to rubberized concrete, the decrease in the splitting tensile strength increased with the increase in both the rubber content and the temperature level. The drop in the percentage of splitting tensile strength for rubberized strength was in the range of 36–49% at 200 °C, 60–81% at 400 °C, and 79–86% at 600 °C. The peak percentage decrease in the splitting tensile strength was 86% for 20% rubber at a 600 °C level of exposure. It was observed that the splitting tensile strength was more affected by the temperature elevation than the compressive strength. This could be due to the fact that the cracks generated inside the samples had a greater effect on the splitting tensile strength; furthermore, the decomposition of rubber particles and generation of more pores at high temperatures led to a higher percentage of degradation at higher temperatures. Similar conclusions were reported by [53,55].

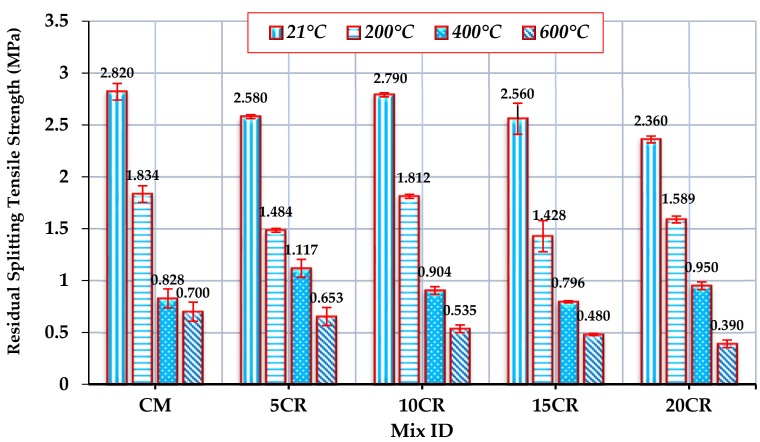


**Figure 8.** Residual splitting tensile strength at elevated temperatures.

### 3.5. The Effect of Elevated Temperature on Ultrasonic Pulse Velocity (UPV)

The test was conducted according to ASTM C 597–16. The test was conducted before and after heating exposure to assess the quality and uniformity of the concrete. The frequency of the transducer, ranging from 50 kHz to 60 kHz, was adopted as this range is valid for most common applications. Figure 9 illustrates the values of UPV before and after heat exposure. At room temperature, the UPV values decreased as the rubber content increased, reaching 12% at 20% rubber content. The UPV values of rubberized concrete were in the range of 4.24–4.55 km/s, whereas normal concrete's UPV value was 4.86 km/s. At 200 °C, the UPV values were found to decrease as the temperature increased. The decline in the UPV values ranged from 16.4% to 53.4%, and the 10CR mix was the least affected by temperature exposure. At 400 °C, the reduction in the UPV values continued and reached up to 69% for rubberized concrete and 50% for the control mix. At 600 °C, a similar trend was observed, and the reduction in the UPV values was 77.8%, 67.3%, 71.3%, 75.3%, and 78.1% for CM, 5CR, 10CR, 15CR, and 20CR, respectively. However, at this level of exposure, the 5CR and 10CR mixes had UPV values higher than the control mix. For unheated specimens, the decline in the UPV values was due to the increase in air voids and the reduction in the solid phase in rubberized concrete [3,14,28]. As for rubberized concrete at different temperatures, the decrease in the UPV values was mainly due to the increase in microcracks, the loss of free water, and the dehydration of cement paste, which increased as the heating level increased.

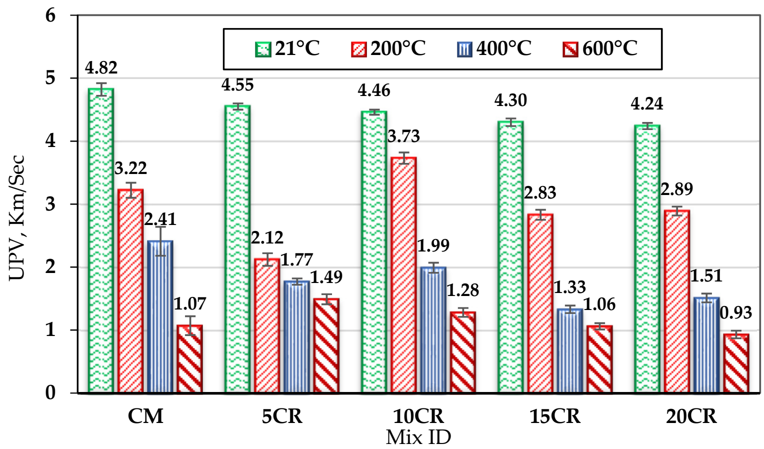


**Figure 9.** Results of the residual UPV test.

### 3.6. The Effect of Elevated Temperature on Dynamic Modulus of Elasticity

Figure 10 shows the effect of temperatures on the dynamic modulus of elasticity. The results of the UPV test were utilized to calculate the dynamic modulus of elasticity ($E_d$) of the different concrete specimens before and after temperature exposure using Equation (1). The equation included within the ASTM C 597-09 specification considers UPV, concrete density ($\rho$), and the passion ratio as the main factors affecting $E_d$ values. The dynamic passion ratio ($\mu$) is assumed to be equal to 0.28 for all target temperatures [3,28,56]. The static modulus of elasticity is an important parameter to assess the deformation of concrete members. The dynamic modulus of elasticity is usually 20–40% higher than the statics modulus of elasticity [57].

$$V = \sqrt{\frac{E_d(1-\mu)}{\rho(1+\mu)(1-2\mu)}} \tag{1}$$

where:

$V$: pulse velocity (m/s);
$\mu$: dynamic Poisson's ratio;
$E_d$: dynamic modulus of elasticity (MPa);
$\rho$: density (kg/m$^3$).

For unheated rubberized concrete, the $E_d$ values declined as the amount of CR content increased, and the values of $E_d$ were in the range of 30.7 to 36.7 GPa, whereas the normal concrete's average was 43.3 GPa. The increase in temperature was found to negatively impact the dynamic modulus of elasticity for both rubberized and normal concrete. The reduction in the dynamic modulus of elasticity was more evident than that of the compressive and tensile strengths. Normal concrete subjected to 200 °C experienced a reduction of 59.5%, while rubberized concrete showed a higher reduction, ranging between 61% and 80%. The only exception at this temperature level was the 10CR mix, which had the least effect in terms of dynamic modulus of elasticity (only a 31.1% reduction). At temperatures of up to 400 °C, all concrete containing rubber had a higher reduction in the dynamic modulus of elasticity values which ranged from 80% to 91% compared to the control concrete (77.3%). After exposure to 600 °C, the reduction in the dynamic modulus of elasticity was significantly affected regardless of the type of concrete and varied from 90.2% to 95.75%. The effect of different temperatures on the dynamic modulus of elasticity can be attributed to weight loss, deterioration of the cement paste matrix, the melting and decomposition of rubber, and excessive crack development; several studies have reported similar findings [41–43,53,54].

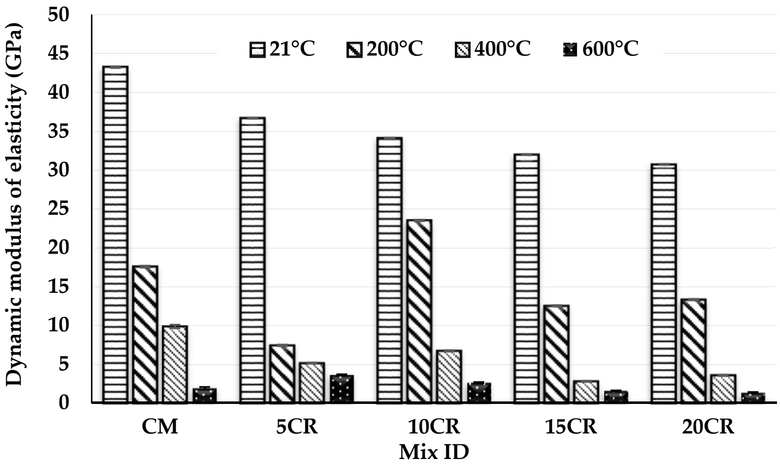


**Figure 10.** Dynamic modulus of elasticity at different temperatures.

### 3.7. Relation between Compressive Strength and UPV

The results of the UPV test and the compressive strength test were used to develop a relation between the two test results. A logarithmic formula based on regression analysis was derived utilizing the experimental results obtained from the residual compressive strength and residual UPV, Figure 11 illustrates the correlation between residual compressive strength and residual UPV. Equation (2) has a determination coefficient of 0.84. The derived equation is suitable for predicting the compressive strength of rubberized concrete exposed to a temperature range of 200 °C to 600 °C.

$$f_{cu} = 12.543\, ln(V) + 10.192\,,\ R^2 = 0.84 \tag{2}$$

where:

$f_{cu}$: residual compressive strength for cubic specimens (MPa);
$V$: residual velocity (km/s).

At an ambient temperature, the percentage difference between the compressive strength estimated by Equation (2) and the experimental results was 0.7–8.8%. In the 200 to 600 °C range, the amount of crumb rubber had a large effect on the predicted values of compressive strength, where the mixes containing 20% CR exhibited a percentage difference ranging from 36% to 44%. However, the derived equation is useful to estimate the compressive strength of rubberized concrete, which contains up to 15% CR for temperature exposure levels of up to 600 °C with up to 12% variation.

### 3.8. Correlation between Residual Compressive and Tensile Strengths

Figure 12 illustrates the correlation between the residual compressive and splitting tensile strengths for all heating levels. Based on the regression analysis results, the residual compressive and tensile strengths were found to be correlated in the logarithmic mode (Equation (3)) with a coefficient of determination of $R^2$ = 0.89. The average residual tensile to residual compressive strength varied depending on temperature exposure levels and the amount of rubber included in the mix.

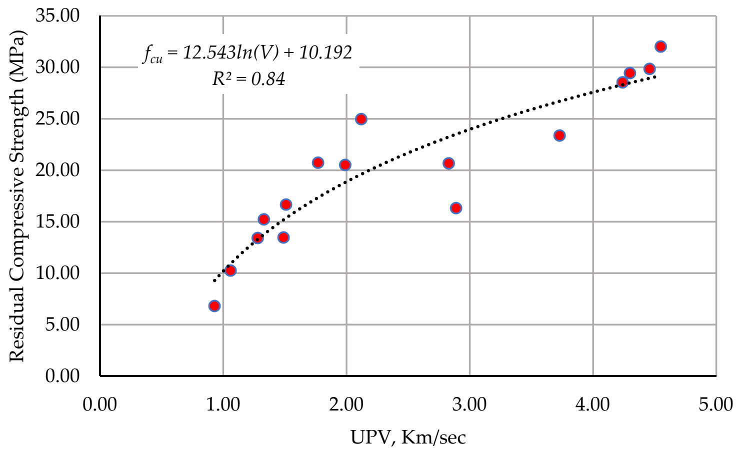


**Figure 11.** Correlation between residual compressive strength and residual UPV.

$$f_{cu} = 11.117\ ln(f_t) + 18.329,\ R^2 = 0.89 \quad (3)$$

where:

$f_{cu}$: residual compressive strength for cubic specimens (MPa);
$f_t$: residual splitting tensile strength (MPa).

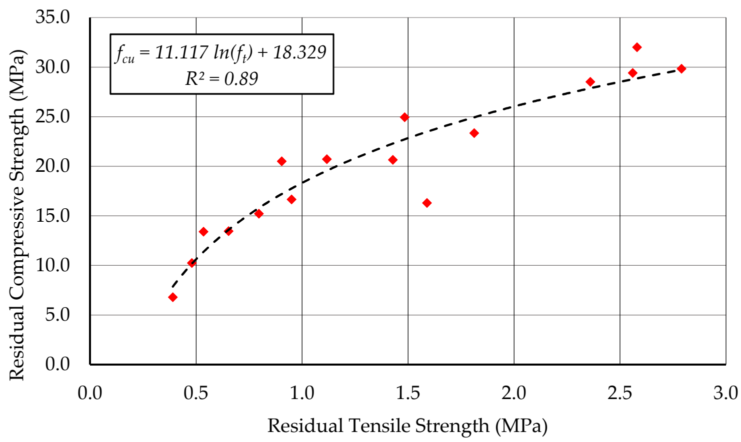


**Figure 12.** Correlation between residual compressive and tensile strengths at different heating levels.

In general, at temperatures up to 200 °C, the tensile strength was about 8% of the compressive strength; the average tensile strength was approximately 5% of the compressive strength for temperatures ranging from 400 °C to 600 °C, where the tensile strength to compressive strength ratio for unheated rubberized concrete was 9%. This supports the fact that the heating of rubberized concrete had a greater effect on its tensile strength than that its compressive strength.

## 4. Conclusions

The objective of this study was to assess the performance of rubberized concrete at high temperatures. To achieve this, various rubberized concrete mixes were subjected to temperatures ranging from 200 °C to 600 °C. Afterward, the specimens underwent assessments to determine their visual appearance, weight loss, compressive strength, tensile strength, UPV test score, and dynamic modulus of elasticity. The residual test and normal cooling (gradual cooling at ambient temperature) were followed. The findings of this research can be summarized as follows:

The specimens tested at different temperatures did not exhibit any visual physical damage such as spalling or crumbling; however, a number of microcracks on the concrete surface were observed at temperatures up to 200 °C. The development and propagation of cracks became more noticeable at higher temperatures (400 °C to 600 °C) (refer to Figure 2).

Rubberized concrete with a rubber content of up to 10% exhibited a lower weight loss than regular concrete at temperatures up to 200 °C. Even when exposed to temperatures as high as 600 °C, the maximum weight loss for such specimens did not exceed 10%. There was a slight increase in weight loss with increasing temperature, which can be attributed to the loss of free water within the samples.

The strength of rubberized concrete under compression decreased notably with higher temperature levels. Nevertheless, at a heating level of 200 °C, rubberized concrete containing a rubber content of up to 5% achieved a strength of approximately 25 MPa. The deterioration became more prominent within the temperature range of 400 °C to 600 °C.

The rubberized concrete lost an average of 35% of its initial splitting tensile strength at 200 °C. This trend held for 400 °C and 600 °C with increased losses of 60% and 70%, respectively, reaching up to an 86% reduction at 600 °C exposure for the 20CR mix. The tensile strength was more sensitive to heating than the compressive strength; this could be due to the microcracks developed within the core of the specimen and on its near surface.

As the temperature and the percentage of rubber increased, the UPV value of rubberized concrete decreased. Concrete with a 5% rubber content demonstrated a better performance and registered a higher UPV value at 600 °C, followed by concrete with a 10% rubber content. Among the rubberized concretes, the 10CR mix showed the highest UPV value at temperatures of up to 400 °C.

Regardless of the type of concrete, an increase in temperature had a severe impact on the dynamic modulus of elasticity, resulting in a reduction of 90–96% at 600 °C.

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