

## Article

# Understanding Structural Changes in Recycled Aggregate Concrete under Thermal Stress

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**Abstract:** **Objective:** This study investigates the influence of high-temperature treatment on the deformation properties and structural deformation of recycled aggregate concrete (RAC) in response to potential fire hazards in the construction industry. **Methods:** Standard-cured 28-day RAC specimens were subjected to microwave heating at 300 °C and 600 °C, with subsequent uniaxial compression tests utilizing a WDW-2000 machine and a VIC 3D strain measurement system to analyze strain data through digital image correlation (DIC) technology. **Results:** After treatment at 300 °C, recycled aggregate concrete (RAC) demonstrated superior mechanical properties to fresh concrete aggregates. This enhancement may be attributed to the more robust siloxane bonds (Si-O-Si) in the recycled materials. Conversely, exposure to 600 °C intensified internal structural damage, notably lowering the material's elastic modulus and peak stress. DIC analysis highlighted the correlation among temperature, volumetric strain, and crack development patterns, with more extensive cracking at 600 °C. **Conclusions:** Moderate-temperature treatment enhances RAC's structure and deformation properties, while high-temperature treatment diminishes its performance. These findings provide valuable insights for assessing building safety post-fire and the application of RAC, emphasizing its suitability at moderate temperatures and risks at high temperatures.

**Keywords:** recycled aggregate concrete; high-temperature treatment; deformation properties; structural deformation; digital image correlation; fire resistance



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## 1. Introduction

In the construction industry, recycled aggregate concrete (RAC) has garnered significant attention as a sustainable material because of its utilization of construction waste as aggregate [1]. RAC not only effectively addresses the shortage of natural aggregates but also contributes to reducing RAC's environmental burden of construction waste [2–4]. Despite the differences in mechanical properties compared with conventional concrete, the environmental friendliness and cost-effectiveness of RAC have led to its widespread application in numerous construction projects [5–7]. However, the quality and performance of RAC are significantly influenced by the type of original waste and processing techniques, necessitating ongoing research and optimization efforts [8,9].

Fire is a significant risk factor in the construction industry, and high-temperature environments notably impact building materials, especially concrete. Numerous previous studies have established that concrete performance can improve up to 300 °C, primarily because of the loss of interlayered water, advanced curing, or the formation of stronger siloxane bonds (Si-O-Si) [10,11]. However, these studies have predominantly focused on conventional heating methods, leaving a gap in our understanding of the effects of microwave heating on RAC. Our study aims to fill this gap by exploring recycled aggregate concrete (RAC) behavior under high temperatures using microwave heating and digital image correlation (DIC) methods, which have been less explored in the existing literature.

Therefore, understanding the performance of different types of concrete, particularly RAC, in high-temperature environments is crucial for assessing their potential applications in extreme conditions.

As an efficient heating method, microwave heating technology finds broad applications in materials science, particularly demonstrating unique advantages in accelerating material heating processes and enhancing material properties [12]. Microwave heating can uniformly heat large volumes quickly by directly interacting with material molecules through electromagnetic waves. Compared with traditional conductive heating, this approach significantly reduces heat loss and energy consumption [13]. Furthermore, the rapid responsiveness of microwave heating enables more precise temperature control, thereby preventing overheating and potential material performance degradation [13]. In research on building materials, utilizing microwave technology for the high-temperature treatment of RAC not only simulates the environmental impacts after a fire but also explores new methods for material modification [14,15]. This involves optimizing the microstructure of the cement matrix in concrete by fine-tuning temperature and heating duration, thereby enhancing its mechanical strength and durability [14,16,17].

While existing research has focused on the performance of RAC at ambient temperature, studies regarding its performance changes at high temperatures, especially post-fire effects on structural safety, are relatively scarce. The existing literature predominantly examines the effects of high-temperature treatment on the mechanical properties of RAC using conventional heating methods, with little consideration for the potential effects and mechanisms of microwave heating. This oversight may lead to an incomplete understanding of the material's performance under extreme conditions, impacting the breadth of its applications and safety assessments [18,19]. Furthermore, the current research primarily emphasizes low- or ambient temperature treatments, leaving a gap in the investigation of performance at high temperatures, especially under extreme conditions, limiting the understanding and promotion of RAC in high-risk environments. It is, therefore, imperative to study the comprehensive behavior of RAC at high temperatures through more integrated experimental approaches, such as combining microwave heating with advanced imaging techniques, to ensure its structural integrity and functional reliability under extreme conditions.

The primary objective of this study is to investigate the effects of high-temperature treatment on the mechanical properties and structural deformations of RAC, particularly by simulating extreme high-temperature environments using microwave heating technology. Given the potential risk of fires in the construction industry, understanding the performance of RAC at high temperatures is crucial not only for evaluating its application potential under extreme conditions but also for its significant implications on the safety assessments of building structures post-fire. By integrating microwave heating technology with digital image correlation (DIC) techniques, this study accurately captures and analyzes the impact of high-temperature treatment on the mechanical properties of RAC. Through comparative analysis of untreated samples, samples heated to 300 °C, and samples heated to 600 °C, this research reveals the specific effects of microwave heating on RAC's structure and mechanical properties. These findings provide a scientific basis for construction engineers in material selection and fire protection design and offer experimental data and theoretical support for understanding and optimizing the application of RAC.

## 2. Materials and Methods

### 2.1. Experimental Materials

In this study, we prepared cubic specimens with dimensions of 100 mm × 100 mm × 100 mm. The detailed compositions of these specimens are listed in Table 1. We had a quantity of five specimens per group. The coarse aggregates used in the concrete mixture were sourced from concrete treated with microwave heating, as depicted in Figure 1. The mix design employed a water-to-cement ratio of 0.43, comprising 418 kg/m<sup>3</sup> of Portland cement, 586 kg/m<sup>3</sup> of standard sand, and 1194 kg/m<sup>3</sup> of RAC as aggregates. Additionally, 180 kg/m<sup>3</sup> of water was added to achieve the desired workability, supplemented by 2.10 kg/m<sup>3</sup> of

a superplasticizer for further enhancement. The selection of this particular mix design was aimed at investigating the performance of concrete incorporating microwave-heated recycled aggregates and assessing its suitability and behavior in structural applications.

**Table 1.** Mix proportions of recycled aggregate concrete.

| Mix Proportions/(kg/m <sup>3</sup> ) | W/C  | PC  | Sand | RCA  | W   | Water Reducer |
|--------------------------------------|------|-----|------|------|-----|---------------|
|                                      | 0.43 | 418 | 586  | 1194 | 180 | 2.10          |

Note: W/C: water-to-cement ratio, PC: Portland cement, RCA: recycled concrete aggregate, W: water, Water reducer: water-reducing agent.



**Figure 1.** Coarse aggregates recovered from concrete after microwave heating, showing the composition and size distribution.

The standard sand used in this study conforms to the ISO 679:2009 standard, primarily consisting of quartz sand with a purity of 99% and a particle size distribution ranging from 0.5 mm to 1.0 mm. This high-purity quartz sand exhibits excellent thermal stability in high-temperature applications, playing a crucial role in the consistency of the experimental results. The recycled aggregates were sourced from screened and processed construction waste, with a primary mineral composition of 70% calcite and 30% quartz, also controlled within a particle size range of 0.5 mm to 1.0 mm. Calcite may decompose under high temperatures, producing CaO and CO<sub>2</sub>, whereas quartz maintains its structural stability. The differing reaction characteristics of these minerals directly impact the concrete's thermal response and structural integrity.

## 2.2. Detection of Ca(OH)<sub>2</sub> in RAC Samples

In this study, we used X-ray diffraction (XRD) analysis to confirm the presence of Ca(OH)<sub>2</sub> in the RAC samples. The XRD patterns were obtained using a Rigaku D/Max-2200 diffractometer (Rigaku Corporation, Tokyo, Japan) with Cu K $\alpha$  radiation ( $\lambda = 1.5406 \text{ \AA}$ ) at a scanning rate of 2°/min in the 2 $\theta$  range of 5° to 70°. The diffraction peaks corresponding to Ca(OH)<sub>2</sub> were identified by comparing them with standard diffraction data (JCPDS card no. 44-1481). The presence of characteristic peaks at 18.1°, 28.7°, and 34.1° 2 $\theta$  confirmed the presence of Ca(OH)<sub>2</sub> in the samples (Figure S1).

## 2.3. Methods for Measuring Volume Strain, Ultimate Strain, Elastic Modulus, and Shear Modulus

The methods used to volume strain, ultimate strain, elastic modulus, and shear modulus were as follows: Volume strain was obtained by measuring the volume change in the specimen during uniaxial compression tests. During the compression process, high-precision displacement sensors were used to record the deformation of the specimen, from which the volume change was calculated. Volume strain ( $\varepsilon_v$ ) was calculated using the formula:

$$\varepsilon_v = \frac{\Delta V}{V_0} \quad (1)$$

where  $\Delta V$  is the volume change and  $V_0$  is the initial volume. Ultimate strain is the maximum strain the specimen can withstand before failure, recorded as the maximum strain value when the specimen fails during the uniaxial compression test, denoted as ( $\varepsilon_{ult}$ ). The elastic modulus was calculated from the initial linear portion of the stress–strain curve. During the test, the relationship between stress  $\sigma$  and strain  $\varepsilon$  was recorded, and the slope of the initial linear part of the curve was obtained through linear regression, which represented the elastic modulus ( $E$ ), calculated using the formula:

$$E = \Delta\sigma / \Delta\varepsilon \quad (2)$$

The shear modulus was calculated from the slope of the shear stress–strain curve. During the shear test, the relationship between shear stress  $\tau$  and shear strain  $\gamma$  was recorded, and the slope was the shear modulus  $G$ , calculated using the formula:

$$G = \frac{\Delta\tau}{\Delta\gamma} \quad (3)$$

These measurements were repeated for each group of six specimens, and the averages and standard deviations were calculated to ensure the statistical significance and scientific accuracy of the results.

#### 2.4. Experimental Investigation of the Thermal Effects of Microwave Heating on the Concrete Specimens

After completing the standard 28-day curing process, prefabricated cubic concrete specimens were removed from the curing environment for subsequent heat treatment experiments. The specimens were divided into three groups to assess the impact of different heating temperatures on concrete performance. The first group served as the control, remaining untreated to provide baseline data for comparison. The second group of specimens was heated in an industrial microwave heating device, AMPS0915-3615T (Hunan Changyi Microwave Technology Co., Xi'an, China), at 10 °C per minute up to 300 °C, simulating thermal stress in concrete structures under moderate fire conditions. The third group of specimens was heated to 600 °C at the same rate to simulate concrete's thermal response under extremely high-temperature fire scenarios. Once the target heating temperatures were reached, each group of specimens was held for 15 min to ensure uniform internal temperature distribution and consistent and reproducible heat treatment effects. Following the holding period, all specimens were allowed to cool to ambient temperature, mimicking the post-fire natural cooling environment. To ensure our study's innovativeness and scientific integrity, we thoroughly considered the advantages and limitations of using microwave heating and digital image correlation (DIC) technology for researching recycled aggregate concrete (RAC) under high temperatures. Microwave heating offers a faster and more uniform heat treatment than traditional methods, effectively reducing material damage caused by thermal gradients. Meanwhile, the non-contact, full-field strain measurement capabilities of DIC technology significantly enhance the accuracy and reliability of strain data. However, microwave heating may cause uneven heating when dealing with thick or composite materials, and DIC technology requires specialized equipment and software support under high-temperature conditions. This part of our study aims to showcase our methods' scientific innovation and application prospects by detailing the features of these advanced technologies compared to traditional techniques.

#### 2.5. Loading System and High-Precision Digital Image Acquisition Technology in Concrete Specimen Mechanical Testing

The experimental setup comprised loading and digital image acquisition systems, as shown in Figure 2. The loading system utilized the WDW-2000 testing machine operating in stress control mode with a loading rate set at 3 MPa/min to ensure the uniformity and controllability of the loading process. The digital image acquisition system consisted of the VIC-3D non-contact strain measurement system manufactured by CSI, employing two CCD

cameras with a resolution of  $2448 \times 2048$  pixels for image capture. These high-resolution cameras accurately recorded minute deformations during the testing process at a frame rate of one frame per second. Before the DIC analysis, specific surface treatments were applied to enhance the accuracy of image analysis. Matte white paint was applied to the bottom of the specimens during speckle creation, while random speckle patterns were painted with matte black paint on the surface. These speckles served as crucial visual markers for DIC analysis, aiding the software in accurately tracking material deformations during loading. Additionally, the DIC software (vic-3D 9.0) enabled high-precision deformation tracking, ensuring a resolution confidence level of 0.01 pixels for the image analysis. This high-resolution level guaranteed the precise capture of deformations at macroscopic and microscopic scales, providing detailed data for understanding the material behavior under loading conditions.

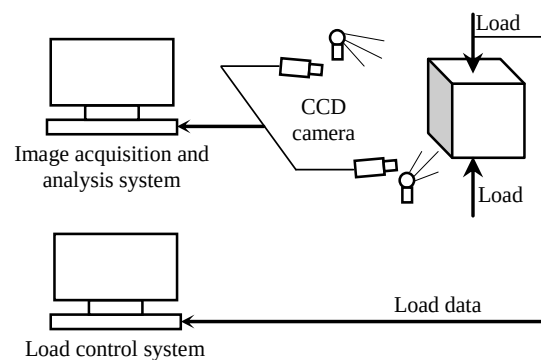


**Figure 2.** Schematic of the loading and data acquisition systems used for uniaxial compression testing, including the setup of the VIC-3D strain measurement system.

DIC is a non-contact, full-field optical measurement technique that simultaneously measures deformations and strains. DIC tracks the movement of multiple points during the deformation process, utilizing correlation functions to assess the similarity among regions of points. Two key correlation functions employed are the cross-correlation function and the normalized correlation function, represented by Equations (4) and (5), respectively.

$$C(u, v) = \sum_{x=-n}^n \sum_{y=-n}^n I_1(x, y) I_2(x + u, y + v) \quad (4)$$

$$C(u, v) = \frac{\sum_{x=-n}^n \sum_{y=-n}^n I_1(x, y) I_2(x + u, y + v)}{\sqrt{\sum_{x=-n}^n \sum_{y=-n}^n I_1^2(x, y)} \sqrt{\sum_{x=-n}^n \sum_{y=-n}^n I_2^2(x + u, y + v)}} \quad (5)$$

where  $I$  denotes image intensity and  $u$  and  $v$  denote positional changes in the  $x$  and  $y$  directions.

### 3. Results

#### 3.1. Analysis of Uniaxial Compression Strain in Concrete Based on DIC Technology

DIC is an advanced image processing technique to capture and analyze strain development in materials under loading conditions. In this study, we utilized DIC software to generate strain development images, enabling a detailed observation and analysis of concrete fracture behavior and its temporal evolution during uniaxial compression tests. This technology allows for full-field strain distribution, revealing stress distribution within the material and potential weak points. Specifically, this paper examined the lateral strain distributions of three groups of concrete specimens at different stress levels, including zero stress (0), 0.3 times the peak compressive stress (0.3  $f_c$ ), 0.5 times the peak compressive stress (0.5  $f_c$ ), 0.8 times the peak compressive stress (0.8  $f_c$ ), and peak compressive stress ( $f_c$ ). To facilitate a more intuitive analysis of these data, the lateral strain data were visualized in contour plots and summarized in Figure 3 to compare the strain response and behavior patterns of concrete at various stress stages. Through this approach, we gained detailed

insights into the strain behavior of concrete at different stress levels, providing a scientific basis for understanding its deformation properties and enhancing design improvements.

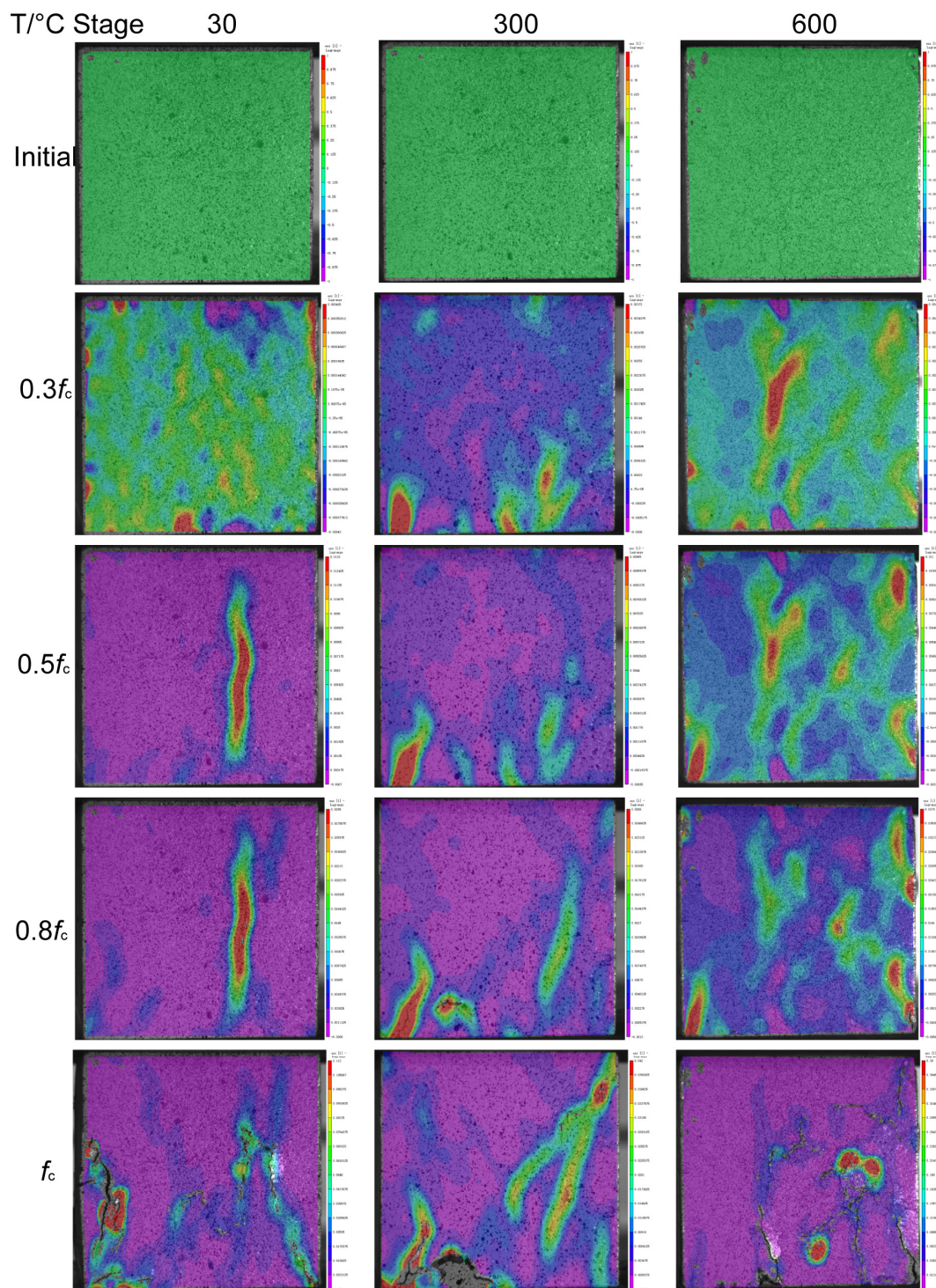


**Figure 3.** Strain distribution of concrete specimens under uniaxial compression testing at different temperatures. Note: Strain distribution of concrete specimens under uniaxial compression testing at the initial state and different stress levels (0.3  $f_c$ , 0.5  $f_c$ , 0.8  $f_c$ , and  $f_c$ ) at 30 °C, 300 °C, and 600 °C. The color maps in the figure show areas of strain concentration, with green indicating the minimum strain and red indicating the maximum strain. It can be observed that with the increase in temperature, areas of strain concentration and the development of cracks become more pronounced, especially at 600 °C.

Through uniaxial compression testing, strain contour analyses were performed on concrete specimens subjected to different temperature treatments. These contour plots revealed commonalities and variations in the strain behavior of the specimens under various temperature conditions. Regarding the formation and location of cracks, cracks on the specimen surface generally appeared at the intersections of lateral strain ( $\epsilon_x$ ) and longitudinal strain ( $\epsilon_y$ ) under all temperature conditions. As the stress on the specimen peaked, a significant increase in crack density was observed, with these cracks predominantly propagating from the surface towards the edges or corners. Regarding the influence of temperature on crack propagation, following treatments at room temperature and 300 °C, noticeable zones of concentrated lateral strain were observed on the surface of the concrete specimens. These zones typically expanded towards the center of the specimen, resulting in the formation of larger cracks. In contrast, specimens treated at 600 °C exhibited concentrated lateral strain zones on the surface but did not develop significant cracks in the central region. It indicates that high-temperature treatment severely compromised the particle connections within the material, leading to reduced overall integrity and a looser specimen. With the failure of the synergistic action in the internal material structure, effective load transfer was impeded, causing the specimen to fail globally before the concentrated lateral strain zones could extend toward the center.

These findings underscore the significant impact of temperature on concrete's structural integrity and crack formation and propagation mechanisms. By delving into these strain patterns, we can better understand concrete's structural behavior under varying temperature influences, thereby offering a scientific basis for the thermal treatment of building materials and post-disaster assessments.

### 3.2. Impact of Temperature on the Stress–Strain Behavior of RAC

Figure 4 presents the stress–strain curves of the RAC specimens subjected to temperature treatments at 30 °C, 300 °C, and 600 °C, where positive values on the x-axis represent lateral strain and negative values denote longitudinal strain. This research illustrates the significant influence of temperature treatments on the uniaxial compressive performance of RAC. Under the 300 °C treatment condition, the peak stress of the specimens was slightly higher than that of those treated at room temperature, as depicted in Figure 5. This phenomenon can be attributed to the further hydration of anhydrous cement particles within the specimens at elevated temperatures, thereby enhancing the structural strength of the concrete. Despite the partial moisture loss in the concrete due to high temperatures, the rapid temperature increase and short duration of high-temperature exposure resulted in the strengthening of cement hydration surpassing the strength reduction caused by dehydration.

However, following high-temperature treatment at 600 °C, a notable decrease in peak stress levels of the specimens compared to room temperature conditions was observed. This reduction can be attributed to a severe dehydration reaction of  $\text{Ca(OH)}_2$  in the concrete at high temperatures, resulting in decreased content. Additionally, rapid decomposition of the C-S-H gel occurred, significantly decreasing the concrete's overall strength. These findings emphasize the impact of temperature on the performance of RAC, especially concerning its mechanical behavior under extreme high-temperature conditions.

The stress–strain curves in Figure 5 demonstrate distinct mechanical responses of concrete after treatment at different temperatures. Volume strain, ultimate strain, elastic modulus, and shear modulus were determined using standardized methods. Volume strain was measured using the volumetric change in the specimens during the uniaxial compression tests. Ultimate strain was identified as the maximum strain the specimen could withstand before failure. The elastic modulus was calculated from the initial linear portion of the stress–strain curve, and the shear modulus was derived from the slope of the shear stress–strain curve. These measurements were repeated for each of the six specimens per group, and the resulting data were used to calculate averages and standard deviations. Under the high-temperature treatment of 300 °C, the concrete specimens exhibit

relatively minor changes in strength and reduced deformations compared to untreated samples. Specifically, the peak stress  $\sigma$  slightly increases by +4.44%, indicating that in this temperature range, the heat treatment may trigger subsequent hydration reactions of some unreacted cement particles within the concrete, thereby enhancing the material's structural integrity. However, after extreme high-temperature treatment at 600 °C, the deformation properties of the concrete are severely affected. The peak stress  $\sigma$  decreases by 30.77% compared with room temperature, with this significant reduction indicating degradation of the concrete's microstructure because of high temperatures, leading to a weakened overall load-bearing capacity. Additionally, the peak strain  $\epsilon$  increases by 19.58%, suggesting increased deformability of the concrete under extremely high temperatures, possibly because of moisture evaporation within the material and the decomposition of the C-S-H gel structure, further rendering the material brittle and prone to fragmentation. Overall, the performance of this material at high temperatures reveals potential performance degradation issues in practical applications, particularly in scenarios such as fires or similar high-temperature environments.

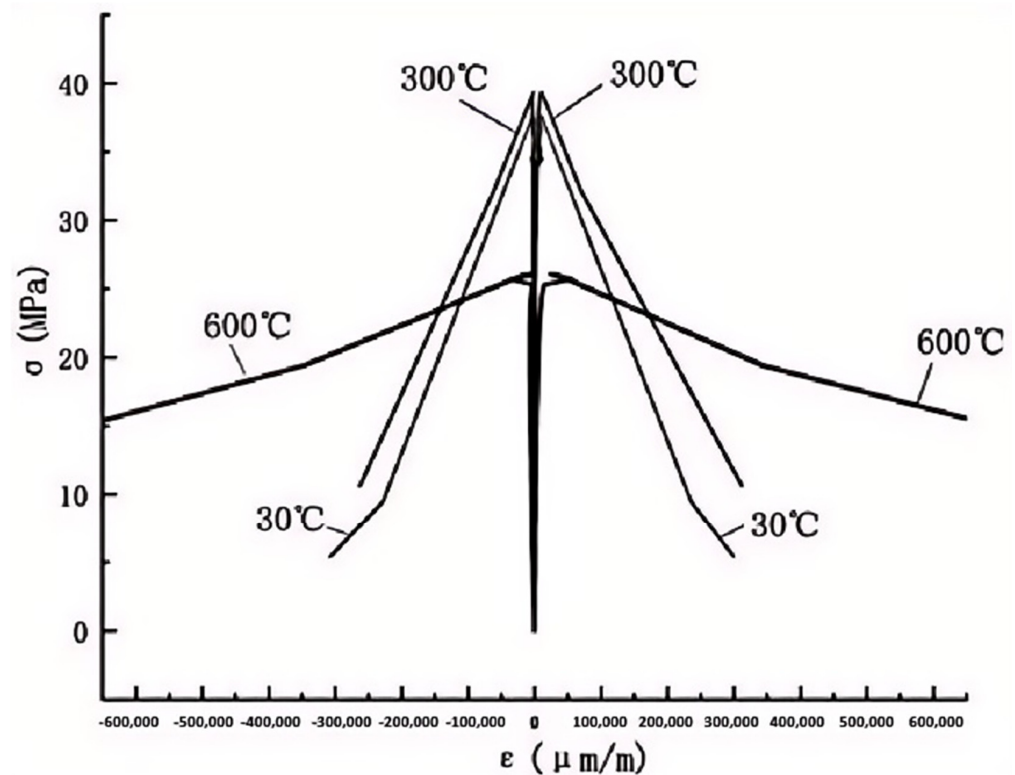


**Figure 4.** Uniaxial compressive stress–strain curves of the concrete specimens at various temperatures (30 °C, 300 °C, and 600 °C). Note: The stress–strain curves were created for the concrete specimens subjected to uniaxial compression tests at different temperatures (30 °C, 300 °C, and 600 °C). Symbol  $\sigma$  represents stress, measured in megapascals (MPa), and symbol  $\epsilon$  represents strain, measured in micrometers per meter ( $\mu\text{m/m}$ ).

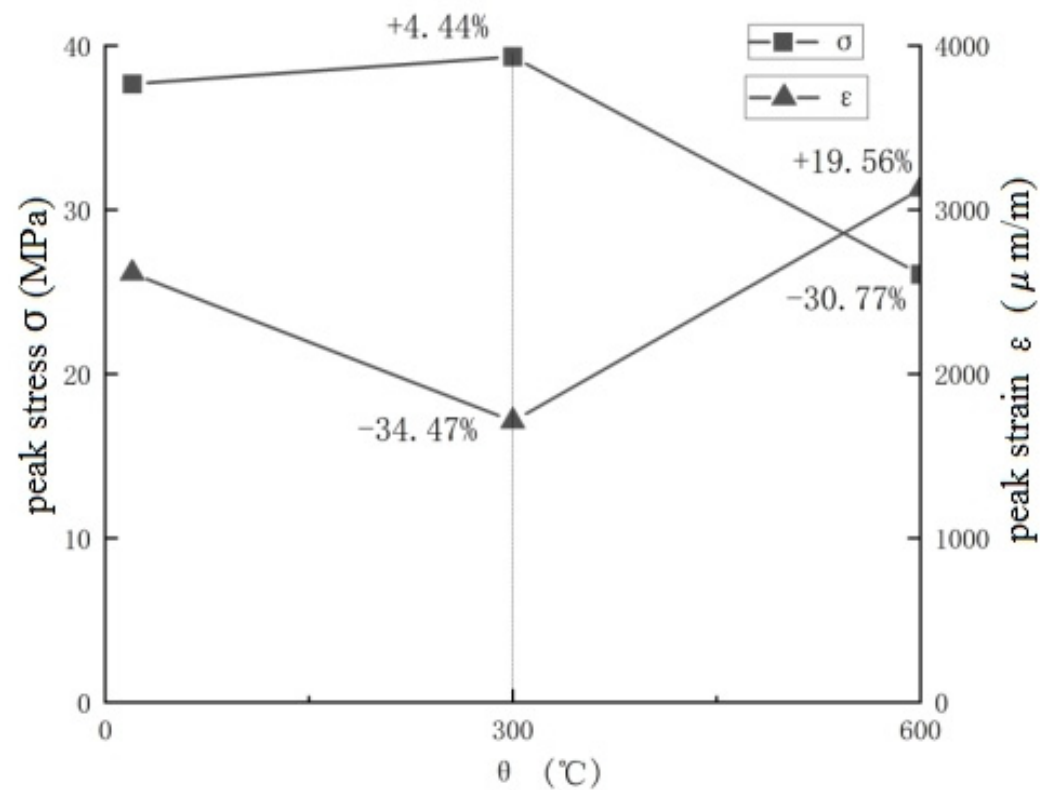


**Figure 5.** Variations in the peak stress and peak strain of concrete specimens subjected to different temperature treatments (30 °C, 300 °C, and 600 °C).

### 3.3. Quantitative Analysis of the Influence of High Temperatures on the Elastic and Shear Moduli of RAC

Figure 6 presents the values of  $E$  and  $G$  as they vary with temperature, revealing a significant decreasing trend. Concerning the elastic modulus  $E$ , concrete exhibits the highest elastic modulus at the initial state (approximately 20 °C). As the temperature rises to 100 °C and 200 °C, the value of  $E$  slightly decreases by around 5.68%. Upon further increase to 300 °C,  $E$  experiences a notable decline, reaching a reduction of approximately 73.15%. Under extreme high-temperature conditions of 600 °C, the  $E$  value drops even further to nearly a quarter of the initial value, marking a reduction of 94.41%. This significant decrease indicates that high temperatures severely affect the microstructure of concrete internally, leading to a sharp degradation in its overall deformation properties. Regarding the shear modulus  $G$ , at lower temperatures (100 °C and 200 °C),  $G$  experiences a minor decrease, reflecting the material's relatively well-preserved shear deformability at these temperatures. However, as the temperature rises to 300 °C,  $G$  undergoes a substantial decrease by 5.68%, further reducing by 73.33% at 600 °C. This suggests that the material's shear deformability is significantly impaired under high-temperature conditions.

From these analyses, it is evident that elevated temperature has a profound impact on the deformation properties of concrete, particularly on its elasticity and shear performance. High temperatures affect the load-bearing capacity of concrete and may alter its failure modes, which is important for the fire-resistant design and disaster assessment of concrete structures.

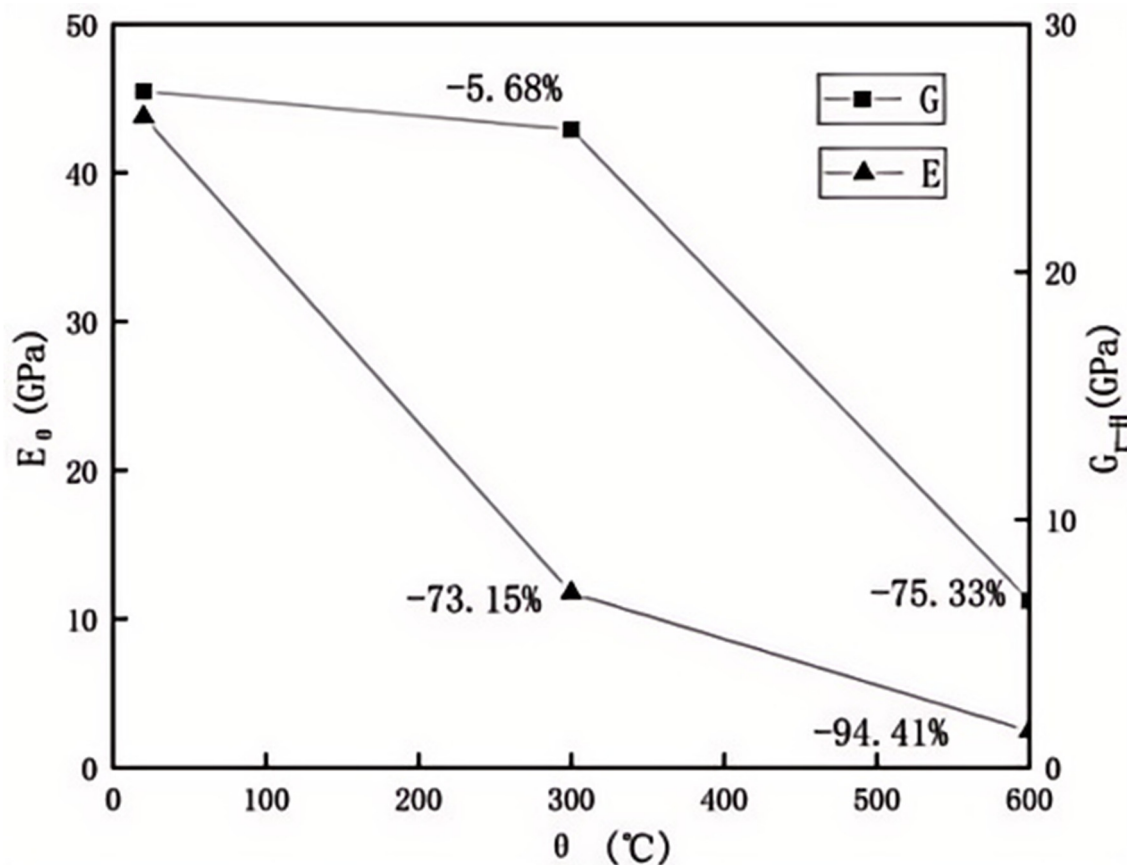


**Figure 6.** Relationship between the elastic modulus and temperature, illustrating the impact of thermal stress on concrete's mechanical properties. Note: The slope represents the rate of change in the elastic modulus with respect to temperature.

### 3.4. Quantitative Analysis of the Impact of Temperature on the Relationship between Concrete's Volume Strain and Stress

Figure 7 presents the relationship between the volumetric strain  $\Theta$  and the stress ratio of concrete after high-temperature treatment. The curve's changing trend indicates that the volumetric strain remains relatively stable before the stress ratio reaches 1.

During the phase when the stress ratio is less than 1, the volumetric strain  $\Theta$  remains stable with no significant changes. In this stage, the concrete specimens treated at 600 °C show similar volumetric strain changes as the specimens treated at other temperatures. As the stress ratio approaches 1, the volumetric strain rapidly increases. This result indicates that under extremely high temperatures, the compression process of concrete leads to significant internal microstructural changes, which may be related to the rapid evaporation of internal moisture and the formation of microcracks in the material. When the stress ratio is 1, the volumetric strain after 600 °C high-temperature treatment shows a significant decreasing trend. It suggests that the concrete specimens treated at high temperatures initially undergo substantial compression volumetric increase, but as the load continues to increase, the volume rapidly expands, indicating lower resistance to deformation and potentially significant structural damage and strength reduction. Under 600 °C conditions, irreversible changes in the concrete's chemical and physical structure occur at high temperatures, leading to significant differences in strain behavior compared with low-temperature conditions. The concrete specimens treated at 600 °C do not exhibit crack penetration zones in the strain contour map, possibly because of volumetric expansion and stress relaxation within the material at high temperatures. In contrast, the concrete specimens treated at 300 °C show no significant change in volumetric strain compared to the samples at room temperature, indicating minimal impact on the concrete's overall structure and performance at this

temperature. These observations provide crucial insights into the behavior of concrete materials under different temperature conditions for structural applications and are of significant importance for safety assessments of concrete structures in high-temperature environments such as fires.

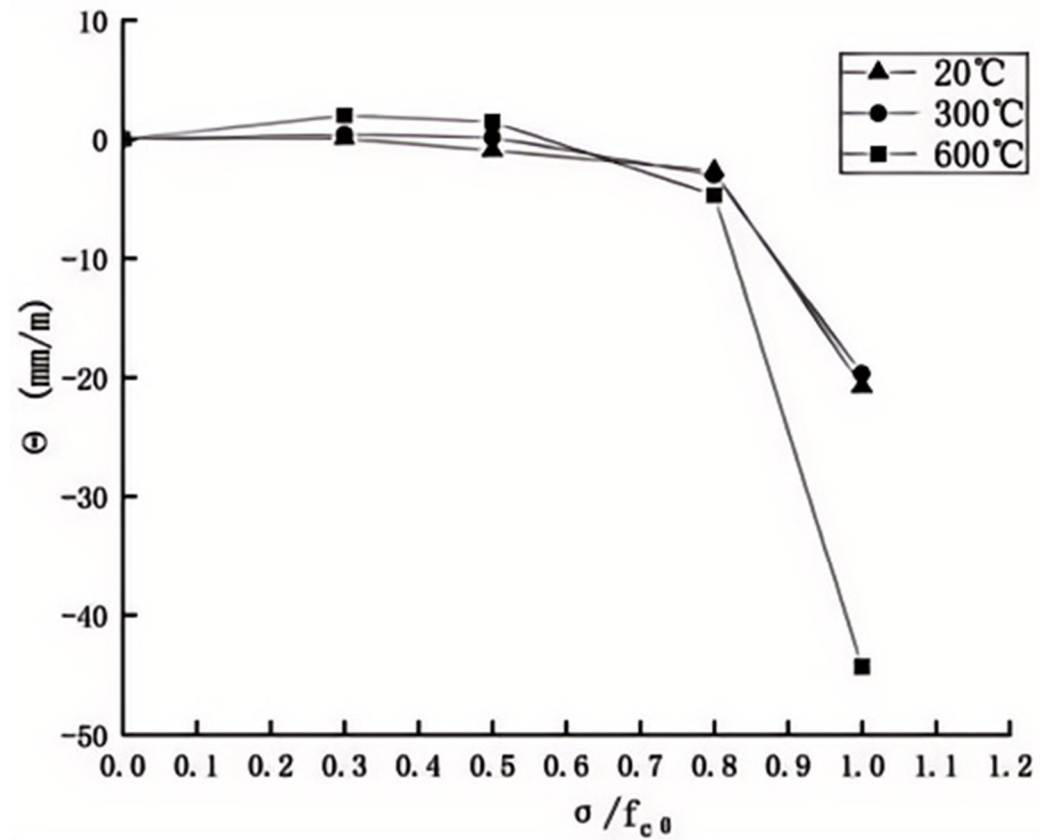


**Figure 7.** Relationship between volumetric strain and the stress ratio of concrete specimens after exposure to high temperatures, highlighting the changes in volumetric strain.

### 3.5. Analysis of the Characteristics of Ultimate Strain Variation in Concrete at Different Temperatures

The characteristic behavior of the ultimate strain of the concrete with temperature variation is revealed in Figure 8. Ultimate strain, representing the maximum strain a material can withstand before fracturing, is a key indicator of material toughness. The graph shows that as the temperature rises to 300 °C, the ultimate strain of the concrete decreases by 61.95% relative to room temperature conditions. This reduction suggests a constraint on the deformability of the material at moderate temperatures, possibly because of initial microstructural changes induced by temperature leading to the material losing toughness. Subsequently, as the temperature further increases to 600 °C, the ultimate strain of the concrete significantly increases to a level 151.18% higher than at room temperature. This significant increase indicates that under high-temperature conditions, more complex internal structural changes may occur in concrete, such as chemical bond breakage and internal moisture evaporation, leading to forming and propagating internal cracks, thereby enhancing the material's flexibility. It is important to note that the aggregates' mineral compositions significantly influence concrete behavior at high temperatures. The quartz in the standard sand maintains its structural stability, whereas the calcite in the recycled aggregates decomposes at high temperatures, producing CaO and CO<sub>2</sub>, which affects the overall mechanical properties of the concrete. The presence of Ca(OH)<sub>2</sub> and its behavior under high temperatures also play a crucial role in the observed performance changes.

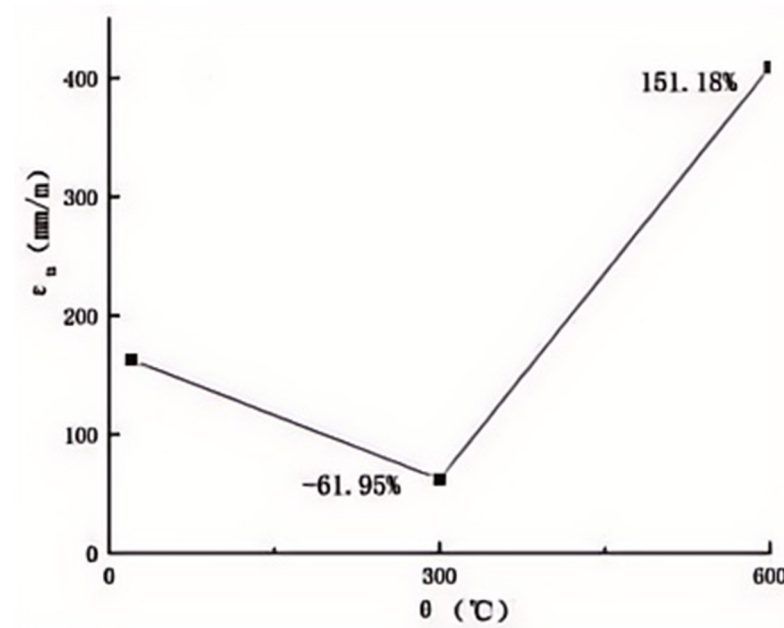


**Figure 8.** The relationship between ultimate strain and temperature, showing the maximum strain concrete can withstand before failure under different thermal conditions.

By analyzing the data presented in Figure 8, we can gain a deeper understanding of the influence of temperature on the mechanical behavior of concrete, particularly regarding ultimate strain. These observational findings offer insights into concrete behavior under high-temperature conditions and provide crucial information for considering ultimate strain in concrete structural design, especially in applications that may encounter elevated temperature environments.

### 3.6. The Impact of Different Temperature Treatments on the Shear Modulus and Its Influence on Brittle Behavior in Concrete

Figure 9 illustrates the relationship between the peak shear modulus  $G$  and temperature. It does not show the ultimate strain. The shear modulus measures a material's resistance to deformation; the lower the value, the higher the material's brittleness, and vice versa for its toughness. As depicted in the graph, the shear modulus  $G$  of the concrete is at its lowest point at room temperature. Upon increasing the temperature to 300 °C, the shear modulus  $G$  notably increased by 177.88%, indicating that moderate-temperature treatment significantly enhances the shear strength and deformability of the concrete, thereby reducing its brittleness. However, as the temperature further rises to 600 °C, the shear modulus  $G$  drastically decreases by 72.94%, signifying that the high-temperature treatment substantially diminishes the shear strength of the concrete, augmenting its brittleness and suggesting a loss in the toughness of the material under extremely high temperatures. This decline could be attributed to microstructural changes induced by high temperatures, such as the decomposition of hydration products in cementitious materials and microcracks' potential formation and propagation.

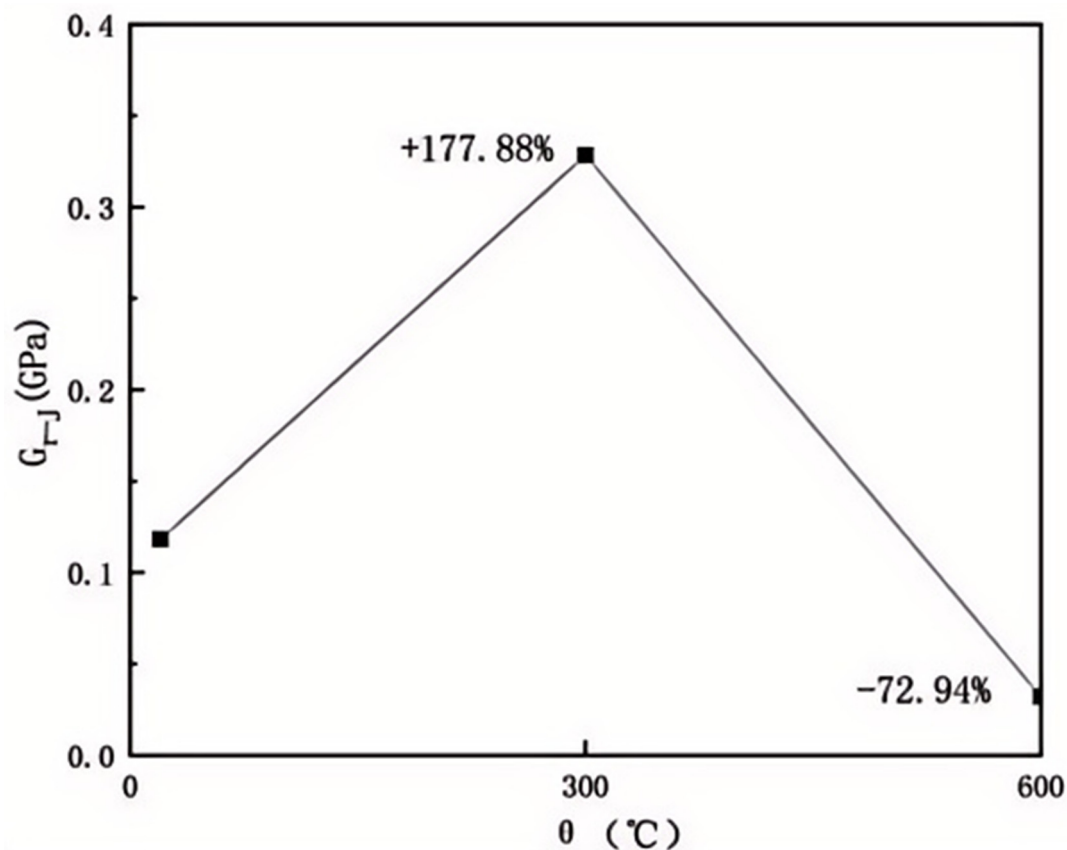


**Figure 9.** Variation in the shear modulus of the concrete specimens with temperature, indicating the material's resistance to deformation under different thermal conditions. Note: The slope indicates the rate of change in the shear modulus as the temperature varies.

Based on these observations, it can be concluded that there is a direct relationship between the brittleness of concrete and temperature treatments. Moderate temperatures (300 °C) can enhance the material's deformability and load-bearing capacity, thus improving its safety performance in structural applications, while extremely high temperatures (600 °C) may deteriorate the deformation properties of concrete, posing risks to structural integrity. These findings hold significant implications for understanding and designing fire-resistant concrete structures, especially in fire risk assessment and post-disaster reconstruction scenarios.

#### 4. Discussion

To investigate the behavior of RAC, particularly in high-temperature environments, this study conducted systematic high-temperature treatment experiments on RAC using microwave heating technology. The aim was to simulate the thermal impact under extreme conditions such as fire and assess its effects on the material's mechanical properties and structural deformation. Such research is crucial for the construction industry as it contributes to designing safer building structures, especially in regions prone to frequent high-temperature exposure [20,21]. Furthermore, as RAC utilizes reclaimed materials, it offers significant advantages regarding environmental sustainability and cost-effectiveness. However, it also poses challenges in ensuring the stability and safety of the materials under extreme conditions [22,23].

Previous research has predominantly focused on RAC's mechanical properties and durability at room temperature, with fewer studies addressing the effects of high-temperature treatment on its performance [24]. These studies typically employed conventional heating methods like electric furnace heating to treat RAC samples and assess changes in their

mechanical properties [25,26]. However, these methods often require prolonged heating times, potentially leading to uneven heating and affecting the accuracy and reproducibility of experimental results [27]. Moreover, advanced imaging techniques have rarely been integrated into traditional research to analyze the microstructural changes in materials thoroughly during the heating process [28].

In this study, microwave heating technology demonstrated unique advantages, particularly in providing rapid and uniform heating. This characteristic of microwave heating is highly suitable for material science experiments as it can mitigate the common temperature gradient issues seen in traditional heating methods, thereby reducing uneven damage within the materials due to thermal stress [29]. Compared with traditional heating techniques, microwave heating interacts directly with material molecules through electromagnetic waves, reducing the concentration of thermal stresses and gradients more effectively. This precise control of the heating process is crucial for preventing the formation of microcracks in materials, especially during high-temperature applications. Although microwave heating offers significant advantages in uniformity and efficiency, challenges in achieving even heating may still arise when processing large-sized or complex-shaped concrete structures, potentially affecting the consistency and repeatability of experiments.

Despite the relatively minor impact of moderate-temperature treatment at 300 °C on the concrete's volumetric strain in this study, high-temperature treatment at 600 °C notably increased the material's initial volume compression under compression. Furthermore, during the descending phase of the stress–strain curve, the high-temperature samples exhibited a faster volumetric expansion rate. This difference not only reveals the significant influence of high temperatures on the volumetric behavior of RAC but also validates the effectiveness and reliability of microwave heating technology in achieving precise control under experimental conditions. It indicates that microwave heating can serve as an optimized heating strategy to be widely adopted in future material testing and engineering applications.

DIC played a pivotal role in this study, significantly enhancing the precision of observing material strain and damage patterns. Unlike traditional strain measurement techniques, the non-contact and non-intrusive nature of DIC technology enables real-time capture of full-field strain images on a material's surface without disturbing the sample [30,31]. This technology enables researchers to observe material deformation, crack initiation, and propagation behaviors at a microscopic scale by dynamically recording subtle strain changes during loading. However, while DIC technology provides unprecedented detail and precision in strain measurement, its implementation requires complex data processing and high-quality image capture. Additionally, maintaining the stability and adaptability of the DIC system in high-temperature environments is crucial for the success of the experiments. Therefore, DIC technology enhances the quality of experimental data and provides valuable insights and tools for interpreting the underlying mechanisms of high-temperature effects on RAC performance.

This study reveals that RAC exhibits improved structural integrity and mechanical performance at a moderate temperature of 300 °C, possibly because of the healing of partial microcracks induced by temperature and the promotion of chemical reactions in the cementitious matrix. This finding indicates that RAC subjected to moderate temperature treatment can enhance its performance under certain conditions, rendering it more suitable for building structures, particularly under non-extreme conditions. However, a significant performance degradation at 600 °C poses a serious challenge to the utilization of RAC. The structural deterioration resulting from high temperatures implies potential safety concerns for building structures that may be exposed to such conditions as tunnels, bridges, and buildings in fire-prone areas. Therefore, engineers designing these structures must carefully consider the performance variations in RAC materials at high temperatures to ensure the long-term stability and safety of the structures. These insights contribute to optimizing RAC's engineering applications and provide a scientific basis for selecting appropriate building materials, further advancing sustainable construction practices.

While this study provides crucial insights into the impact of microwave heating on RAC performance, it also has some limitations that could affect the broad application and interpretation of the results. Firstly, the relatively limited sample size used in this study restricts the comprehensive verification of experimental results from a statistical perspective. Furthermore, there are significant differences between the high-temperature environment simulated in the laboratory and real fire scenarios, particularly in terms of temperature ramp-up rates and heat transfer mechanisms. In the laboratory setting, we controlled the temperature increase using microwave heating equipment, whereas, in actual fires, temperature changes occur at different rates and can be influenced by various factors such as airflow, types of burning materials, and the location of the fire source. These discrepancies may lead to variations in the high-temperature durability performance of RAC observed in laboratory testing and its actual behavior after exposure to real fire incidents.

Future research should address the limitations identified in this study by increasing the sample size to enhance result reliability and simulating more realistic fire environments, such as prolonged exposure to high temperatures and the effects of different types of fire sources. Furthermore, exploring the performance of recycled concrete from various aggregate sources under high temperatures and employing high-resolution thermal imaging techniques and advanced stress/strain monitoring devices to analyze material microstructural changes under extreme conditions in detail is essential. Research efforts should also delve into using novel modifiers like high-performance polymers and nanomaterials to optimize the formulation of RAC, enhancing its performance under extreme temperature conditions. These endeavors will further drive advancements in RAC technology, positioning it more prominently in the building materials market.

## 5. Conclusions

Concrete's performance undergoes significant changes in high-temperature environments, affecting its reliability in engineering applications. This study focused on the utilization of recycled aggregates, the performance of concrete at high temperatures, and the application of microwave heating and digital image correlation (DIC) techniques. We employed DIC technology to capture the accurate strain distribution of RAC under uniaxial compression and extensively analyzed its deformation characteristics at various temperatures.

The interaction of concentrated areas of strain in both transverse and longitudinal directions reveals a tendency for cracks to form and gradually propagate in these regions. At room temperature, these areas accurately reflect the stress state within RAC. However, with increasing temperatures, significant changes occur in these concentrated areas. Particularly at high temperatures of 600 °C, the crack formation and propagation rate accelerates notably, leading to overall material failure before significant cracks are evident and indicating a substantial worsening of internal damage by high temperatures. After the moderate temperature treatment at 300 °C, the ultimate strain of concrete decreases, suggesting a reduction in its deformability compared with room temperature, possibly because of the initial degradation of the cement matrix. Conversely, following the extremely high-temperature treatment at 600 °C, the ultimate strain of concrete increases significantly, indicating potential internal structural damage, rendering the material more brittle and fragile.

The significant decrease in the elastic modulus further confirms the extent of damage to the material at high temperatures. At 300 °C, the slight decrease in the elastic modulus may result from the further hydration of unreacted cement particles. However, at 600 °C, there is a sharp decline in the concrete's elastic modulus, reflecting the chemical and physical structural damage caused by high temperatures, particularly the dehydration of  $\text{Ca}(\text{OH})_2$  and decomposition of the C-S-H gel. Additionally, analysis of the stress–strain curve reveals that after treatment at 300 °C, the volumetric strain of concrete shows no significant change compared with room temperature, indicating the material's overall performance remains stable at moderate temperatures. Conversely, the extreme high-

temperature treatment at 600 °C leads to a drastic decrease in material performance, where the increase in volumetric strain and decrease in elastic modulus together signify the overall degradation of material properties. The observed results highlight the influence of moderate- and high-temperature treatments on the performance of RAC, revealing concrete's deformation and damage mechanisms under different temperature conditions (Figure 10). These findings provide valuable data for concrete structural design, particularly with significant practical applications in fire risk assessment and fire-resistant design.

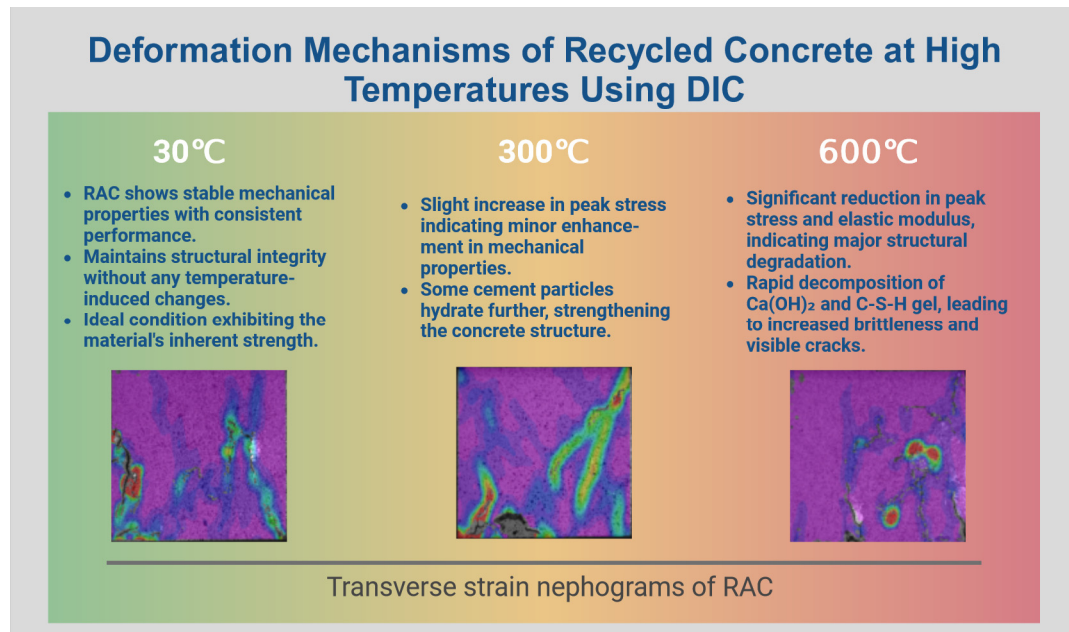


**Figure 10.** Deformation mechanisms of RAC at high temperatures as analyzed using DIC, demonstrating the development of strain and cracks.

Our research further demonstrates the importance of microwave heating and DIC technology in high-temperature treatment and strain measurement. Microwave heating provides a more uniform temperature distribution by reducing thermal gradients, while DIC technology offers high-precision full-field strain measurement, allowing us to assess the material's performance changes at high temperatures more accurately [32,33]. Additionally, through a detailed comparison of the performance differences between recycled aggregates and non-recycled aggregates at high temperatures, we found that the mechanical properties of the recycled aggregates significantly improved after treatment at 300 °C and 600 °C. This may be due to residual compounds in the recycled materials reacting at high temperatures, forming stronger chemical bonds [34]. Non-recycled aggregate concrete also showed some performance enhancement at high temperatures, but not as pronounced as with recycled aggregates [35]. In conclusion, these results clearly demonstrate the application value of recycled aggregates, the effectiveness of microwave heating, and the precision of DIC technology in studying the performance of recycled aggregate concrete at high temperatures.

**Supplementary Materials:** The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/buildings14092689/s1>, Figure S1: XRD Patterns of Recycled Aggregate Concrete (RAC) Samples Showing the Presence of  $\text{Ca(OH)}_2$ .

**Author Contributions:** S.C. and H.R. conceived the research idea and designed this study. S.C. conducted the experiments and collected the data. H.R. and X.C. performed the data analysis and interpretation. Both authors contributed to the writing and revision of this manuscript. S.C. and H.R. approved the final version to be published and agreed to be accountable for all aspects of the work. All authors have read and agreed to the published version of the manuscript.

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