buildings

Review

Influence of Elevated Temperatures on the Mechanical Performance of Sustainable-Fiber-Reinforced Recycled Aggregate Concrete: A Review

Wisal Ahmed , **C. W. Lim *** and **Arslan Akbar**

Department of Architecture and Civil Engineering, City University of Hong Kong, Hong Kong SAR, China; wahmed7-c@my.cityu.edu.hk (W.A.); aakbar4-c@my.cityu.edu.hk (A.A.)
* Correspondence: bccwlim@cityu.edu.hk

Abstract: In recent times, the applications of fiber-reinforced recycled aggregate concrete (FRAC) in practical engineering have gained greater popularity due to its superior mechanical strength and fracture properties. To apply FRAC in buildings and other infrastructures, a thorough understanding of its residual mechanical properties and durability after exposure to fire is highly important. According to the established research, the properties and volume fractions of reinforcing fiber materials, replacement levels of recycled concrete aggregate (RCA), and heating condition would affect the thermal–mechanical properties of FRAC. This review paper aims to present a thorough and updated review of the mechanical performance at an elevated temperature and post-fire durability of FRAC reinforced with various types of fiber material, specifically steel fiber (SF), polypropylene (PP) fiber, and basalt fiber (BF). More explicitly, in this review article the residual mechanical properties of FRAC, such as compressive strength, splitting tensile capacity, modulus of elasticity, mass loss, spalling, and durability after exposure to elevated temperatures, are discussed. Furthermore, this study also encompasses the relationship among the dosages of fibers, replacement levels of recycled aggregate, and the relative residual mechanical properties of FRAC that would help in the optimum selection of the fiber content. Conclusively, this study elaborately reviews and summarizes the relevant and recent literature on recycled aggregate concrete containing SF, PP fiber, and BF. The study further provides a realistic comparison of these fibers in terms of the residual mechanical performance and durability of FRAC that would help in their future enhancements and applications in practical engineering.

Keywords: mechanical properties; durability; elevated temperature; fibers; sustainable concrete

Citation: Ahmed, W.; Lim, C.W.; Akbar, A. Influence of Elevated Temperatures on the Mechanical Performance of Sustainable-Fiber-Reinforced Recycled Aggregate Concrete: A Review. *Buildings* **2022**, *12*, 487. https://doi.org/10.3390/buildings12040487

Academic Editor: Lech Czarnecki

Received: 9 March 2022
Accepted: 13 April 2022
Published: 14 April 2022

1. Introduction

Recently, the employment of fiber-reinforced recycled aggregate concrete (FRAC) in practical engineering has obtained worldwide interest of researchers and industry due to its high mechanical strength and enhanced fracture properties [1–4]. FRAC is a highly sustainable construction material that helps in the effective utilization of construction and demolition (C&D) waste as recycled aggregate. Moreover, it valorizes recycled concrete aggregate and lowers the consumption of virgin aggregate which thereby helps in the circular economy [5–7]. The applications of fiber-reinforced concrete are now gradually shifting to large-scale concrete structures, such as columns and beams, bridge piers, precast concrete segments for tunneling, road pavements, and retrofitting of structural members [8–13]. Concrete structures during their service life might be subjected to fire incidents that could adversely affect their structural performance and safety, and may result in structural collapse in severe cases [14,15]. Thus, to use fiber-reinforced concrete in modern-day concrete structures, in-depth knowledge and understanding of its residual mechanical properties and post-fire durability is highly essential.

Fiber addition in concrete composites effectively bridges the microcracks, lowers the stress intensity at the tip of the crack, and controls the crack expansion [16,17]. Consequently, it results in superior mechanical properties of FRAC in terms of increased splitting tensile strength [18,19], high flexural strength [20,21], high shear strength [22,23], improved compressive strength [24,25], high torsional strength [26], high ductility [27], better crack resistance [28,29], and excellent fracture energy and fracture toughness [30]. The residual properties of FRAC after exposure to high temperature greatly depend on the selection of fiber material and its dosage [31–33]. In the past, various fibers, such as steel fiber (SF) [34,35] carbon fiber (CF) [36], basalt fiber (BF) [37], polypropylene fiber (PP) [38], and glass fiber (GF) [39], were incorporated to improve crack resistance and fracture parameters of recycled aggregate concrete (RAC) exposed to elevated temperatures. Generally, the addition of these reinforcing fibers significantly enhances the residual properties of concrete and its resistance against explosive spalling at high temperatures [17].

Based on the material properties, the reinforcing fibers are generally divided into high thermally stable fibers with high melting temperature and low thermally stable fibers having low melting temperature [40]. The reinforcing fibers such as CF, SF, and BF belong to high thermally stable fibers and their inclusion in concrete remarkably restrains the generation and propagation of microcracks via the fiber-bridging mechanism and prevents high strength loss in concrete during and after the fire. The PP fiber, polyvinyl alcohol fiber, and polyethylene fiber are called low thermally stable fibers which melt at elevated temperatures and thus provide pathways to the escape of water vapors. By virtue of the fiber melting mechanism, the vapor pressure reduces in the concrete matrix; thus, concrete resistance against spalling is improved. Furthermore, the type and content of recycled aggregate [41], the addition of admixtures and industrial wastes, such as rice husk ash [42], silica fume [43], ground granulated blast-furnace slag, and fly ash [44,45], unpredictably alter the physical properties, microstructure quality, and mechanical performance of FRAC. In addition, the heating and cooling method also affects the overall residual performance of concrete. For instance, the high-temperature, high heating rate, and holding time would result in lower residual mechanical properties and greater concrete spalling [46–48].

To apply FRAC in engineering structures, comprehensive knowledge regarding its mechanical performance and durability at high temperatures is indispensable. The available literature reveals that despite various research investigations made in the past, there are still some doubts with regard to the type and content of fiber and its influence on the temperature-dependent physio-chemical and mechanical properties of FRAC. Thus, it is important to elaborately review and critically discuss the relevant literature to realistically identify the prevailing attainments and highlight the potential research gaps in this field for further advancements. The current study presents information about the properties of reinforcing fibers such as SF, PP, and BF and comprehensive analysis and discussion of the residual mechanical properties, namely compressive strength, splitting tensile capacity, modulus of elasticity, concrete spalling, mass loss, and durability of FRAC. In addition, it provides the relationship between fiber content, RCA substitution level, and relative residual mechanical properties of FRAC that would help assess the effectiveness of these fibers at elevated temperatures. The flow chart shown in Figure 1 summarizes various key parameters of FRAC at elevated temperatures that are discussed in this comprehensive literature survey.

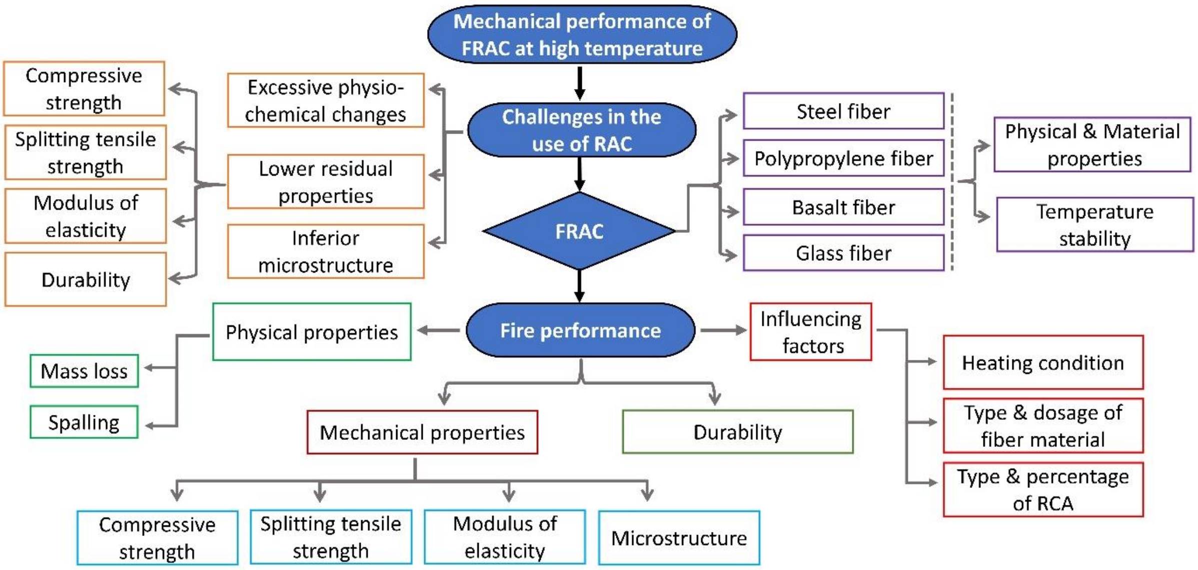

Figure 1. Systematic flowchart showing details of various key parameters of residual properties of FRAC that are covered in this review study [19,28,32,49–52].

2. Review Methodology

In this review article, the up-to-date and relevant literature on the influence of elevated temperature on mechanical performance of fiber-reinforced recycled concrete was gathered from reliable resources. The keyword search consisted of the search strings "recycled aggregate concrete" and "mechanical properties at elevated temperatures", "steel fiber reinforced concrete" and "mechanical properties at elevated temperatures", "polypropylene fiber reinforced concrete" and "mechanical properties at elevated temperatures", and "basalt fiber reinforced concrete" and "mechanical properties at elevated temperatures". Based on the keyword search, the established literature was collected and analyzed in detail. After the collection of necessary literature data, the keywords were searched in the main title and then in the abstract of each paper to confirm their relevance with the chosen topic. The relevant articles were then selected in this review article for further analysis and discussion.

3. Challenges in the Use of Conventional Recycled Aggregate Concrete

3.1. Excessive Physical and Chemical Changes

RAC is a multi-phase and multi-scale material, and its properties greatly depend on the quality and composition of its constituent materials. On exposure to fire, the disintegration of its materials occurs due to a phenomenon called thermal inconsistency of ingredients [53–55]. Furthermore, the exposure of RAC to elevated temperature results in several physical and chemical alterations, as shown in Table 1, which consequently result in major strength degradation. Unlike conventional normal aggregate concrete, the matrix structure of RAC is inferior and is generally associated with the old cement mortar attached to the surface of RCA. The weak quality of RCA is due to the presence of microcracks possibly during the recycling process, which results in weak and fragile ITZs [56–59].

Table 1. Physio-chemical changes in the microstructure of RAC with varying thermal exposure.

Refs.	Temperature Range (°C)	Physical and Microstructural Changes	Hydration Products	Water Evaporation
[37,60–62]	20–200	At ambient temperature, the surface color of RAC is light gray. The internal microstructure of RAC remains compact and little or no significant changes occur. Above 100 °C, some microcracks originate in the paste matrix while aggregate phase remains stable.	The chemical disintegration of ettringites starts. Aft and Afm phases dehydrates in the temperature range 110–150 °C.	During this temperature range, concrete loses all its free water and adsorbed water. Exclusion of non-evaporable water (interlayer water and capillary water) starts above 100 °C.
[42,62,63]	200–400	During this temperature range, surface color changes to yellowish, magnitude of cracking increases, relative concrete density decreases, and mass loss increases. Most of the aggregates still remain stable.	Most of the ettringite decomposes, while some of the CH either decomposes into lime and water or converts into additional CSH gel.	At about 300 °C, concrete loses interlayer water, while at 400 °C most of the capillary water is lost.
[37,60]	400–600	Above 400 °C, the surface color of RAC turns to gray-brown, microcracks grow further, and their intensity increases. At 570 °C, there occurs volumetric expansion of quartz (present in most of the aggregates).	Most of the CH crystals decompose due to evaporation of crystal water. Dehydration and decomposition of the CSH gel occurs.	Crystal water evaporates which results in decomposition of CH and CSH content.
[64–66]	600–800	The surface color of RAC becomes gray-white and its microstructure further deteriorates due to increase in porosity. Above 600 °C, decomposition of aggregate minerals occurs.	Most of the CSH gel decomposes and results in weaker microstructure. Decomposition of calcium carbonate occurs.	-
[62]	Above 800	Complete deterioration of microstructure and excessive concrete spalling occurs.	Concrete loses all its CSH gel content and results in poor mechanical properties.	-

3.2. Inferior Microstructure

The microstructure composition and quality of recycled concrete majorly affect its physical properties and mechanical performance at elevated temperatures. Generally, the microstructure of a recycled concrete matrix (Figure 2) after exposure to fire demonstrates severe degradation alongside several microcracks, especially at the junction of new mortar and RCA (ITZ) [59,67]. Furthermore, with higher replacement levels of recycled aggregates, the microstructure quality becomes worse and vulnerable to higher defects due to elevated temperature [68–71]. This consequently results in the lower physical and mechanical performance of recycled concrete such as high porosity, high water absorption, greater mass loss, higher strength degradation, and lower density [72–74].

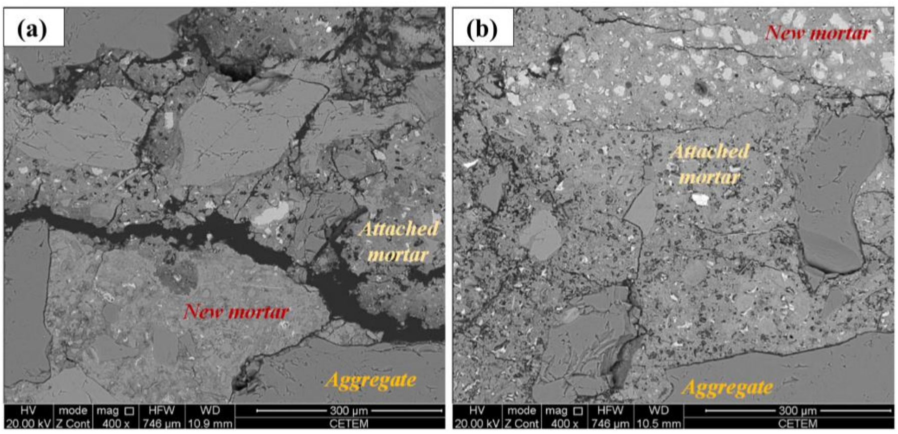

Figure 2. SEM micrographs of recycled concrete matrix (**a**) grade C25, and (**b**) grade C65, showing several microcracks after heating at 650 °C. Copyright permission is taken from [74].

3.3. Residual Mechanical Performance

In terms of residual mechanical properties, several research studies found that the use of recycled aggregate in concrete as a substitute for NCA both in partial and complete replacement mode showed strength degradation with the rise in temperature [66,75]. The findings of Vieira et al. [66] revealed a maximum decrease of 12.2%, 36.1%, and 35.1% in the residual compressive loading strength, residual splitting tensile strength, and elastic modulus of recycled concrete exposed to 800 °C, respectively. Furthermore, the mechanical property degradation of RAC turns out to be more severe with the use of combined recycled fine and coarse gravels. For instance, Zhao et al. [60] reported a loss of about 9–87% and 5–96% in the residual compressive strength and modulus of elasticity of recycled concrete fabricated with recycled coarse and fine aggregate with a temperature increase from 200 °C to 800 °C. Furthermore, the origin and composition of RCA also affect the mechanical performance of RAC. For instance, the use of recycled quartzitic aggregate, recycled granitic crushed stone aggregate, and recycled siliceous aggregate will alter the mechanical performance of recycled concrete. The experimental results of [76] revealed that upon exposure to 500 °C, a reduction of about 21%, 27%, and 35% was observed in the values of ultrasonic pulse velocity (UPV) of RAC containing recycled quartzitic aggregate, recycled granitic crushed stone aggregate, and recycled siliceous aggregate, respectively. Similarly, in the case of dynamic elastic modulus and compressive strength, these recycled concretes showed 48%, 56%, and 73% and 5%, 10%, and 20% reduction. Other research studies [77,78] also indicate high compressive strength loss and excessive concrete spalling in recycled concrete after exposure to elevated temperatures, especially beyond 450 °C. In Figure 3, the post-fire condition of a typical RAC matrix is demonstrated which reveals degraded cement mortar having several microcracks and pores.

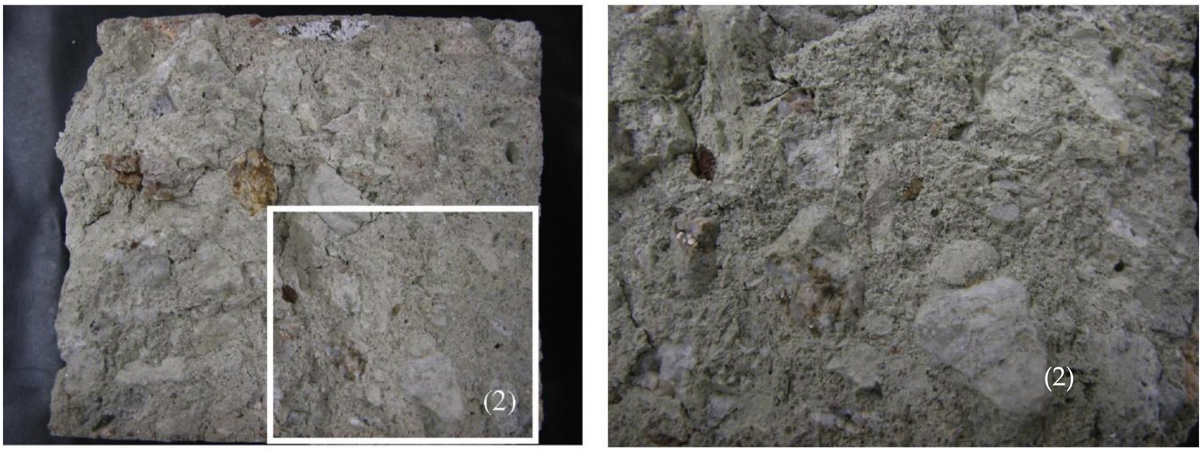

Figure 3. Interior surface of typical recycled concrete exposed to elevated temperature at 800 °C for 4 h. Copyright permission is taken from [79].

Moreover, the post-fire durability of RAC is adversely affected by elevated temperatures [62,66]. Available literature indicates that RAC containing 100% recycled aggregate results in greater water absorption, lower carbonation resistance, and increased volumetric shrinkage in comparison to NAC [80,81]. Similarly, the experimental findings of [79] indicated inferior microstructure of RAC comprised of partial (50%) and complete (100%) replacement of RCA. Their test results, as shown in Figure 4, depict a rise in the moisture absorption of RAC. This rise in the moisture absorption of RAC is generally ascribed to the lower concrete matrix quality (Figures 2 and 3) which is mainly due to fragile cement–aggregate interphases, and porous mortar to the surface of RCA [71,82].

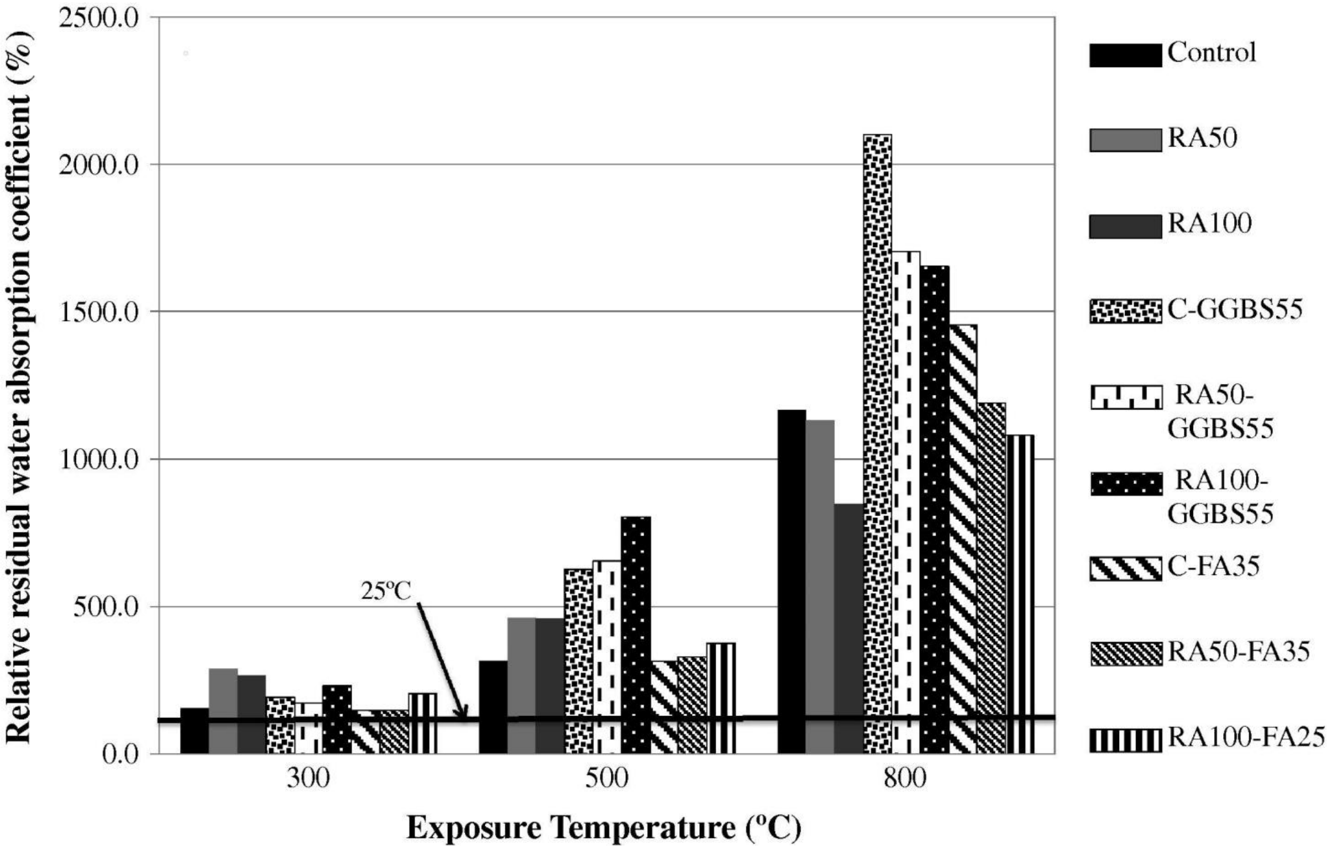

Figure 4. The capillary water absorption coefficient of RAC. Copyright permission is obtained from [79].

It is well established that the residual performance of RAC is critically affected due to exposure to high temperatures. To understand these further, we present a graphical relationship among the relative residual compressive strength, relative residual tensile strength, and relative residual modulus of elasticity of RAC with varying temperature and percentages of RCA in Figures 5–7, respectively. Generally, the residual properties of RAC are undesirably affected at elevated temperatures. For instance, by increasing temperature from 25 to 800 °C, the relative residual compressive and splitting tensile strength of RAC reduced from 1.0 to 0.14 and from 1.0 to 0.24, respectively. This drop in the relative residual compressive strength and relative residual splitting tensile strength values is mainly owing to the weak and porous microstructure of RCA, which results in the inferior mechanical performance of concrete on exposure to high temperatures. Moreover, the outcomes of previous studies suggested that with a high heating rate and peak temperature, the degradation of microstructure and mechanical properties is more severe [60,75]. Furthermore, in the case of residual modulus of elasticity, a decrease from 1.0 to 0.05 occurs when temperature is increased from 25 to 800 °C. Furthermore, the available literature suggests that with both partial and complete replacement of NCA by RCA, there is a similar decreasing trend in the relative residual strength of RAC with rising temperature. A detailed summary of the available literature with regards to the residual properties of RAC after exposure to high temperatures is presented in Table 2.

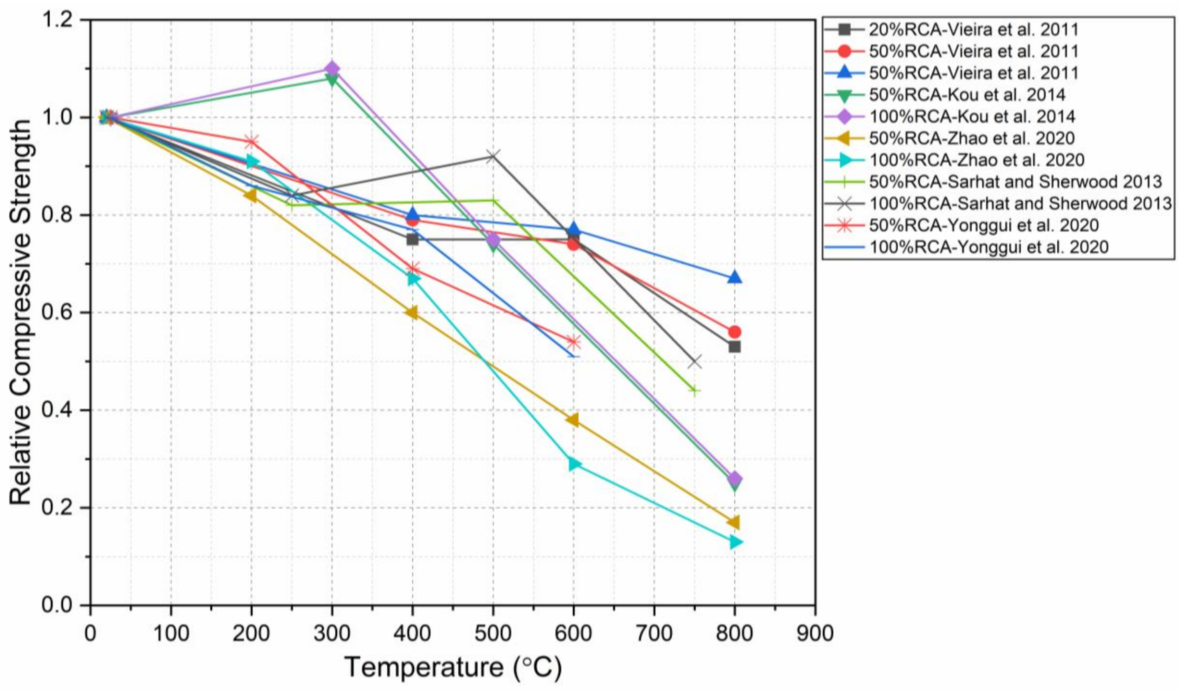

Figure 5. Relative compressive strength of RAC with varying elevated temperature and proportions of RCA [37,60,66,75,79].

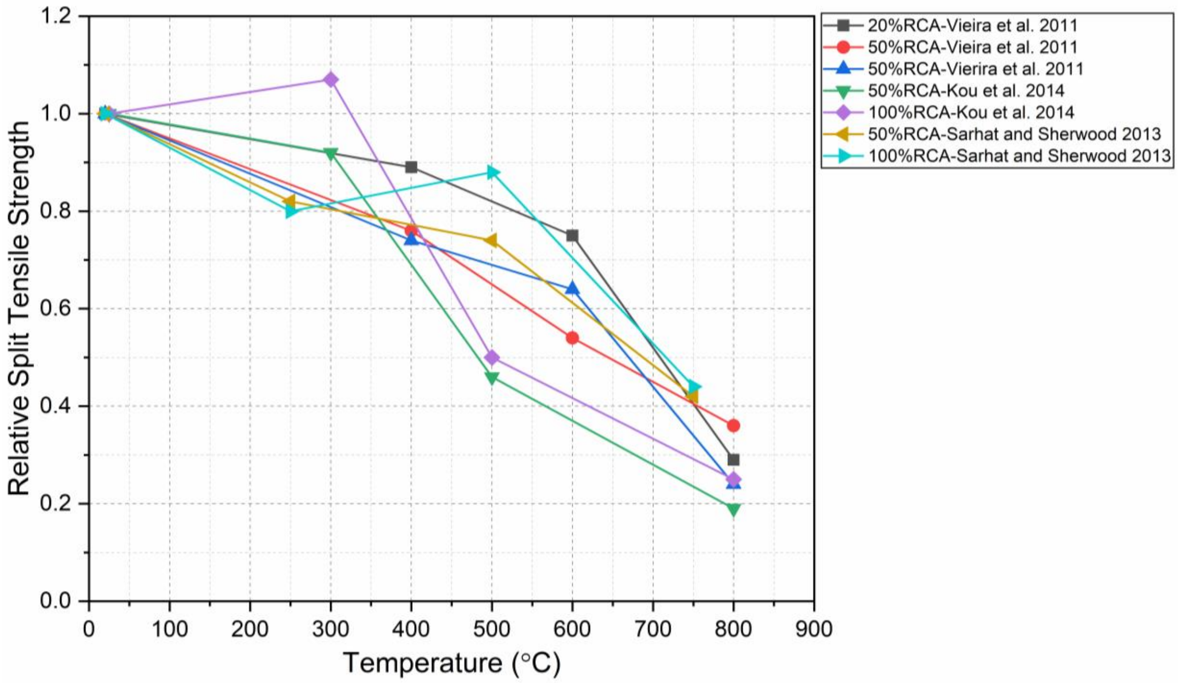

Figure 6. Relative splitting tensile strength of RAC with varying elevated temperature and proportions of RCA [66,75,79].

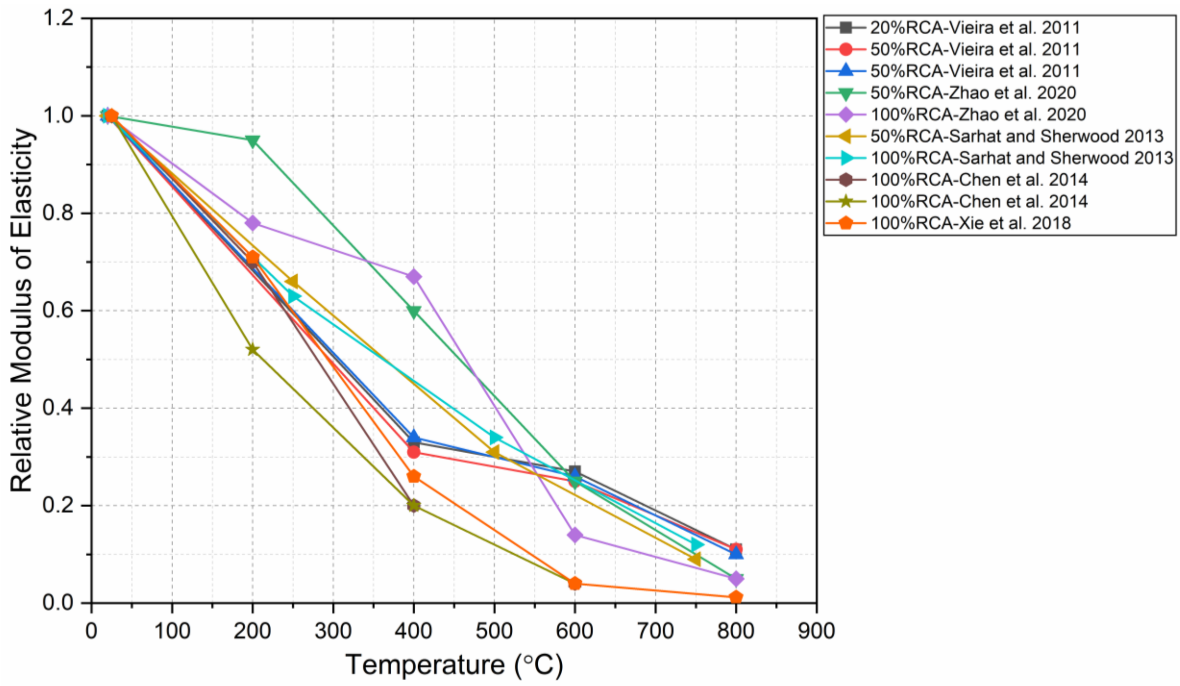

Figure 7. Relative modulus of elasticity of RAC with varying elevated temperature and proportions of RCA [50,60,66,75].

Table 2. Residual properties of RAC at various temperature conditions and replacement percentages of recycled aggregate.

Refs.	RCA	Heating Temperature	Heating Rate	Mechanical Properties	Remarks
[79]	50 and 100%	300, 500, and 800 °C	5 °C/min	RAC with maximum replacement of recycled concrete showed 26.6% and 24.8% improvement in the residual compressive and splitting tensile strength after exposure to 800 °C.	The porous ITZ in RAC prevents the pore vapor pressure and thus results in smaller inner cracking.
[66]	20, 50, and 100%	400, 600, and 800 °C	Standard fire	RAC showed residual compressive strength of 78%, 75%, and 60%, residual splitting tensile strength equal to 82%, 65%, and 32%, and modulus of elasticity equal to 32%, 26%, and 11% at 400, 600, and 800 °C elevated temperatures, respectively.	The mechanical performance of RAC at elevated temperatures significantly degrades with rise in RCA content.
[60]	50 and 100%	200, 400, 600, and 800 °C	12 °C/min	Compressive strength of RAC decreased in the range 9–20%, 33–40%, 62–71%, and 83–87% after exposure to 200, 400, 600, and 800 °C, respectively.	No concrete spalling was observed in RAC on exposure to elevated temperatures.
[76]	75%	500 °C	-	Ultrasonic pulse velocity decreased by 45%, dynamic modulus of elasticity reduced by 77%, static modulus decreased by 49%, and compressive strength reduced by 21%.	RAC fabricated with lower water to cement ratio was better in terms of elevated thermal–mechanical performance.
[78]	100%	150, 300, 450, and 600 °C	Standard fire	RCA combined with 2% crumb rubber depicted 8.74% improvement in the residual unconfined compression strength at exposure temperature of 450 °C.	Excessive concrete spalling was observed when temperature value was greater than 450 °C.
[83]	30, 50, 70, and 100%	300, 400, and 500 °C	-	Relative residual compressive strength and residual peak strains showed maximum values of 0.99, 0.98, and 1.22, and 1.09, 1.21, and 1.05 for temperature exposures of 300, 400, and 500 °C, respectively.	Higher content of RCA results in higher compressive strains and greater damage in concrete on exposure to high temperatures.

Table 2. *Cont.*

Refs.	RCA	Heating Temperature	Heating Rate	Mechanical Properties	Remarks
[84]	50 and 100%	600 and 800 °C	8 °C/min	Maximum reduction of 70 and 85% was found in the compressive strength of RAC on exposure to 600 and 800 °C, respectively.	During high temperatures, the mechanical properties of RAC highly degrades due to the weak ITZ and porous microstructure of recycled aggregate.
[59]	30 and 100%	500 °C	2 °C/min	All samples fabricated with RCA showed strength degradation (less than 40%) when exposed to 500 °C.	The weak mechanical performance of RAC is largely due to the inferior quality of recycled aggregates.
[75]	50 and 100%	250, 500, and 750 °C	10 °C/min	RAC showed about 11%, 8%, and 50% loss in residual compressive strength and 20%, 12%, and 54% loss in residual splitting tensile strength after exposure to 250, 500, and 750 °C respectively.	RAC with 50% RCA presented better residual mechanical properties than conventional concrete.
[77]	30, 50, 70, and 100%	200, 300, 400, 500, 600, 700, and 800 °C	Standard fire	Residual compressive strength of RAC decreased by more than 75% when temperature was increased to 800 °C.	Despite low strength, RAC showed better spalling resistance at high temperatures.

4. Elevated Temperature Properties of FRAC

Fiber reinforcing is one of the effective and persuasive techniques that strengthen the microstructure of RAC and enhance its mechanical properties. Incorporation of a suitable type and dosage of fiber material helps RAC in improving the deficient interfacial transition zones (ITZs) and retarding the development and growth of microcracks, thereby resulting in better fracture properties, enhanced ductility, and excellent post-cracking behavior of recycled concrete. Among commercially available fibers, the SF [29,85–88], PP [84,89,90], BF [91–94], and GF [95,96] are commonly utilized in fiber-reinforced concrete. Figure 8 shows the percentage distribution of literature data reported in the period 2004–2021 on the topic of recycled aggregate concrete strengthened with fiber materials that depict the growing popularity of reinforcing fibers such as SF, PP, BF, and GF. The mechanical properties of FRAC at elevated temperatures may vary with changing mix composition, type and dosage of fiber, and percentage replacement of RCA, and mineral admixtures, i.e., silica fume, ground granulated blast-furnace slag, fly ash, etc. Among these factors, the content and type of fiber, and replacement percentage of RCA significantly influence the residual properties of FRAC; hence, they are the main focus of this study.

4.1. Fiber Material

In the past, various reinforcing materials, such as steel fiber [97,98], carbon fiber [99,100], glass fiber [101,102], basalt fiber [103,104], polyvinyl alcohol fiber [105,106], polypropylene fiber [107,108], cellulose fiber [109], nylon fiber [110,111], jute fiber [112], and other natural fibers [113–116] were utilized for the enhancement of mechanical and fracture properties of concrete. In the case of recycled aggregate concrete, few fiber materials (namely SF, PP, BF, and GF) have been widely used, owing to their incredible crack bridging and strength-enhancing abilities [117–120]. Among these, SF is the most persuasive reinforcing fiber that has a high tensile strength and melting temperature and it remarkably enhances the fracture mechanics in RAC [121]. PP belongs to the family of polymer fibers that possess a lightweight structure and imparts excellent toughness and shrinkage resistance to concrete [122–124]. BF is the new prominent synthetic fiber, widely recognized as a non-polluting green fiber, and it offers excellent tensile strength and thermo-chemical stability [125–127]. GF is the extremely fine fiber of glass that has a non-crystalline structure and possesses high tensile strength like SF. The sample of commonly used SF, PP, BF, and GF is displayed in Figure 9, while their material properties are presented in Table 3. To understand the post-fire mechanical properties and durability of FRAC, knowledge of the type and dosage of fiber is essential. Fiber material differs with regards to its physical, mechanical, and thermal properties, thus, it shows different functions when used in concrete. For instance, reinforcing fibers such as SF, BF, and GF possess high tensile strength and melting point that result in significant development in the residual properties of concrete, while the use of PP fiber can reduce pore vapor pressure and improve concrete resistance against spalling due to its lower melting temperature. Furthermore, the smaller dosages of fiber may be ineffective in terms of strength enhancement, while the higher dosages of fiber could lead to workability issues, difficulty in compaction, and strength reduction. Thus, it is also important to identify the optimum dosage of fiber material for its effective performance in the FRAC.

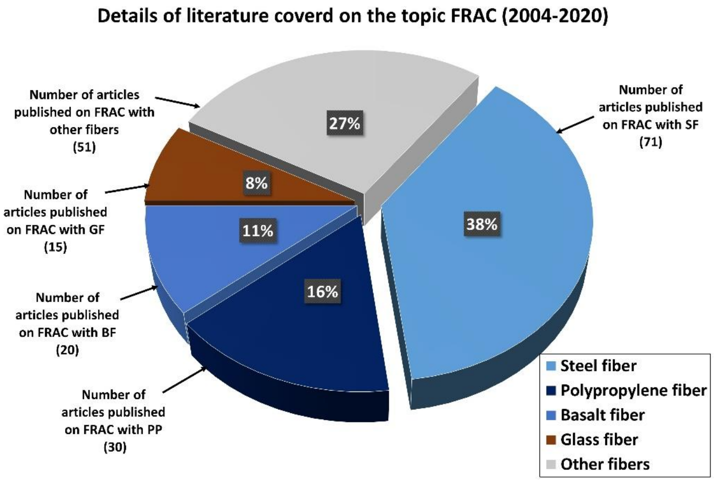

Figure 8. Details of literature data (2004–2021) on recycled aggregate concrete produced with frequently used fibers such as SF, PP, BF, and GF and all other synthetic and natural fibers.

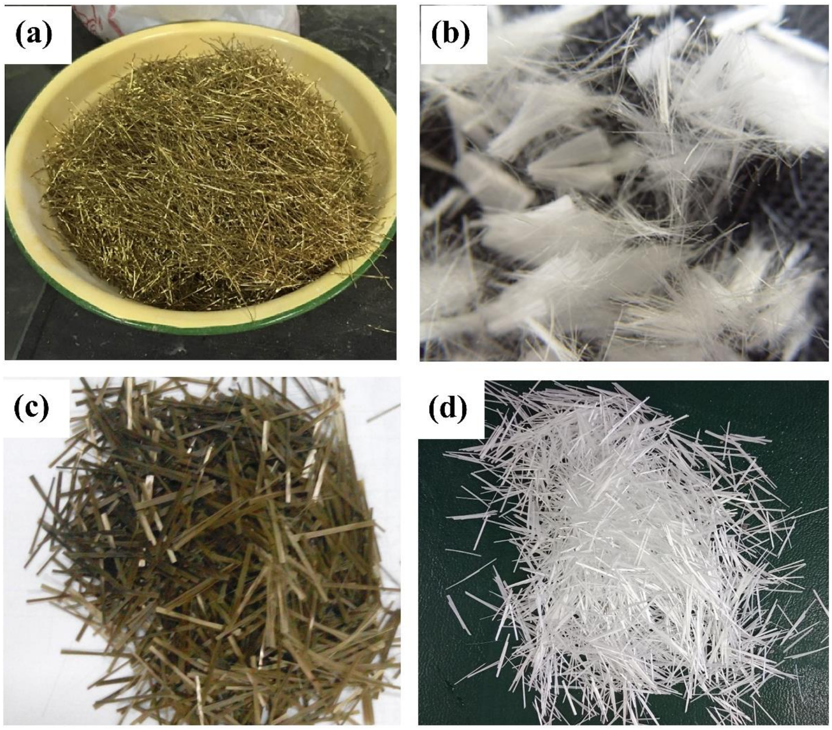

Figure 9. Commonly used reinforcing fibers in recycled aggregate concrete. (**a**) SF, (**b**) PP, (**c**) BF, and (**d**) GF. Copyright permission is obtained from (**a**) [128], (**b**) [129], (**c**) [130], (**d**) [96].

Table 3. Physical properties of SF, GF, BF, and PP [40].

Type of Fiber	Tensile Strength (MPa)	Young's Modulus (GPa)	Specific Gravity	Melting Point (°C)
Steel fiber	2760	200	7.8	1370
Glass fiber	1034–3792	72	2.5–2.7	860
Basalt fiber	872–2800	89	2.8	1700
Polypropylene fiber	552–690	3.45	0.9	170

4.2. Mechanical Properties

The thermal endurance of fiber-reinforced recycled concrete during fire is vital for its application in modern-day buildings and other infrastructures. It has been widely reported that the mechanical properties of conventional recycled aggregate concrete highly degrade at elevated temperatures [54,131]. To overcome this issue, the technique of fiber reinforcing in recycled aggregate concrete is used, which at present is one of the most promising and persuasive strengthening techniques that results in better thermal endurance of FRAC. However, the choice of a suitable type and of volume fractions of reinforcing fiber along with percentage replacement of RCA is important for the desired performance of FRAC. To understand these factors, a detailed discussion regarding the residual mechanical properties and durability of FRAC is presented in the following sections.

4.2.1. Compressive Strength

Several laboratory investigations were performed in the past to assess the compressive strength of FRAC fabricated with various types and dosages of reinforcing fiber [19,28,49,132]. Generally, with increasing fiber content, the compressive strength of FRAC improves; however, beyond a certain limit it either results in an insignificant rise or causes strength degradation. For instance, the experimental results of [19] indicated that by adding 0–0.7% dosage of SF, the compressive loading capacity of FRAC improved by 0–24.7%, while test results of other researchers [133,134] suggested an insignificant rise in the values of compressive strength of FRAC with the further addition of SF. Similarly, in the case of PP fiber research studies, [49,135] concluded strength improvement of up to 25% with 1% volume fractions; however, with further addition (1.5%) of PP fiber, test results indicated a slight improvement of 7.73% in the values of compressive strength of FRAC [136]. Furthermore, BF and GF do not make an appreciable change in the compressive strength of FRAC. Alnahhal and Aljidda [137] in their study concluded about a 10.2% improvement in compressive strength with 1.5% volume fractions of BF while the experimental findings of Ali and Qureshi [132] revealed about a 6% increase in compressive strength of FRAC with 0.5% volume fractions of GF. A detailed discussion about the influence of these fibers on the compressive strength of FRAC reinforced with SF, PP, BF, and GF can be found in the recently published review article by Ahmed and Lim [138].

With regards to elevated temperature conditions, several attempts were made to counteract the adverse effects of fire on the mechanical performance of FRAC composites and to prevent the undesired structural failure of buildings and other infrastructures during a fire that may result from the loss of concrete strength. The incorporations of fiber materials such as SF, PP, BF, and GF were found to be highly influential in retaining most of the residual compressive strength of FRAC [32,37,50,51]. Owing to the remarkable reinforcing ability, these fibers help prevent excessive strength loss in FRAC even after exposure to elevated temperatures. Chen et al. [50] in their study added 0, 0.5, 1, and 1.5% volume fractions of SF in RAC and studied its compressive strength at elevated temperatures, i.e., 200, 400, and 600 °C. Their test results, as displayed in Figure 10, indicate significant improvement in the compressive strength of FRAC of about 12–29% at a temperature of 400 °C and 15–92% at a temperature of 600 °C with increasing SF dosage from 0.5–1.5%. Similarly, Guo et al. [32] evaluated the residual properties of recycled concrete reinforced with 1% of SF and found that RAC reinforced with SF retained about 84.3, 49.7, and 24.8% of its compressive strength at elevated temperatures of 200, 400, and 600 °C, respectively.

Furthermore, a recent study [52] evaluated the mechanical behavior of RAC fabricated with 0.25, 0.5, and 1% of SF by concrete volume and exposed to elevated temperatures at 150, 300, 450, and 600 °C. Their findings showed a remarkable increase in the residual compressive strength at all temperatures due to the reinforcing ability of SF that resulted in uniform distribution of microcracks and prevention of strength loss. Maximum increases of about 26.3, 37.6, 29.4, and 40% were obtained with 1% dosage of SF exposed to 150, 300, 450, and 600 °C elevated temperatures, respectively. The use of SF was also found to be advantageous in enhancing the residual compressive strength of self-compacting lightweight recycled concrete exposed to 100, 300, 600, and 900 °C [51]. Furthermore, Xie et al. [139] explored the combined influence of silica fume and SF on the residual compressive stress–strain relationship of RAC and found that the SF was greatly influential in improving the stiffness and peak stress of recycled concrete. The authors attributed this to the better microstructure of RAC, owing to the addition of silica fume and SF that resulted in uniform distribution of internal stresses and improved crack resistance.

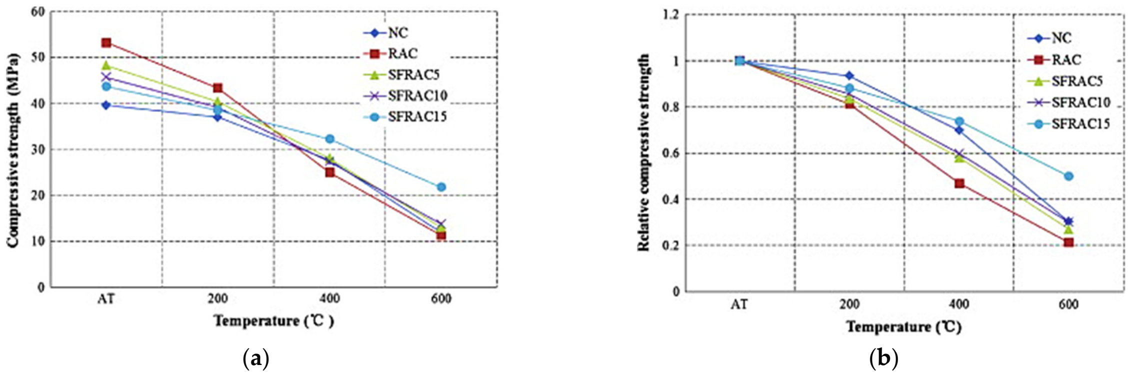

Figure 10. Effect of elevated temperatures on (**a**) compressive strength and (**b**) relative compressive strength of recycled concrete reinforced with SF. Copyright permission is obtained from [50].

The incorporation of PP fiber in FRAC for the enhancement of mechanical properties has also been the topic of significant research [21,129,140–142]. At room temperature, the FRAC reinforced with 1% and 2% volume fractions of PP fiber was found to produce about 15.6% and 35.7% greater compressive strength than that of the control specimen [23]. Similarly, other researchers [38,51] also found a major improvement in the compressive strength of FRAC. In the case of elevated temperatures, unlike SF, the profitable effect of PP fiber in preventing strength loss of FRAC diminishes at high temperatures, specifically after 300 °C [51]. This is primarily due to the low thermal stability of PP fiber [40]. This impact of PP fiber on the residual strength of FRAC was also confirmed in [84], where a higher strength loss in recycled concrete reinforced with PP fiber after exposure to high temperature (600 °C) was reported. Furthermore, established results [38] indicated about a 74% decrease in compressive strength of FRAC reinforced with 3.3 kg/m^3 and exposed to 1000 °C. However, other research studies [40,140] found better spalling resistance of FRAC reinforced with PP. In another study, Aslani and Kelin [51] investigated the residual properties of FRAC strengthened with 0.05, 0.1, 0.15, and 0.2% volume fractions of PP fiber and exposed to high temperatures of 100, 300, 600, and 900 °C. The authors observed a significant improvement of about 41% in the residual compressive strength with the addition of 0.1% dosage of PP fiber. The PP fiber can counteract the excessive physicochemical degradation inside the concrete matrix that may prevent the greater strength loss in the FRAC composites. For instance, the experiment findings of a recent study [140] as shown in Figure 11, revealed that the residual compressive strength of PP-fiber-based concrete was well improved in comparison to the reference concrete. In addition, this could also be associated with the lessening of vapor pressure in the FRAC matrix (Figure 12) due to the presence of voids and pressure-induced tangential spaces that result from the melting of PP fiber [108,143].

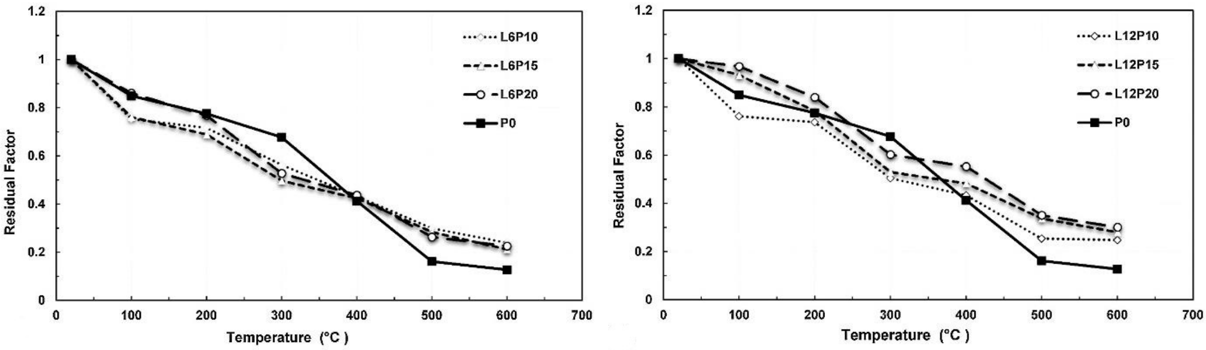

Figure 11. Variations in residual compressive strength of conventional and polypropylene-reinforced concrete with rising temperature, where L denotes the length of polypropylene fiber, i.e., 6 and 12 mm, while P denotes the volume fractions of polypropylene fiber, i.e., 1, 1.5, and 2 kg/m^3. Copyright permission is obtained from [140].

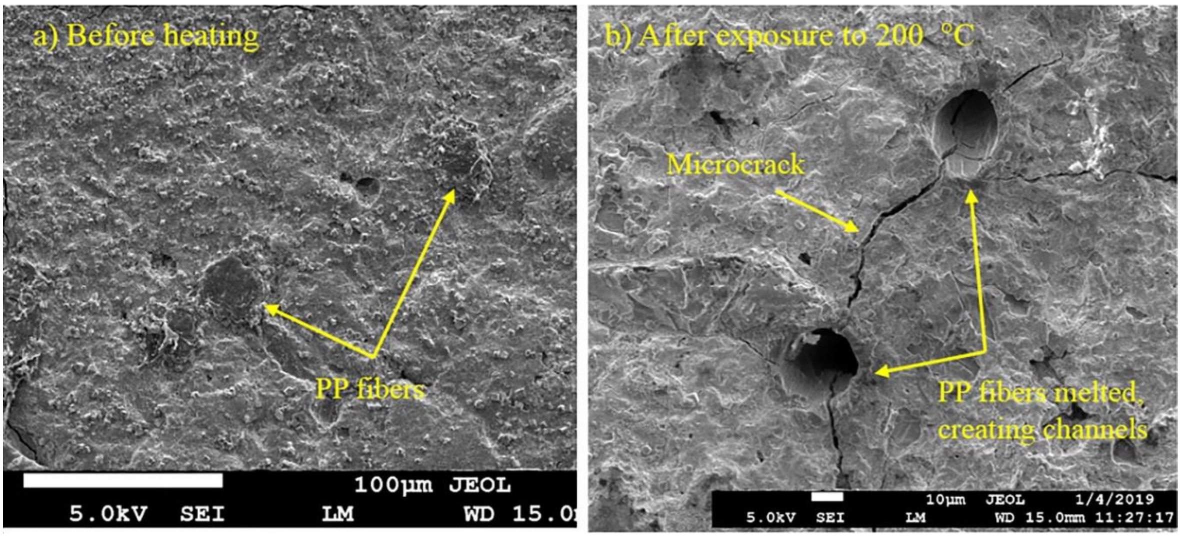

Figure 12. Comparison of preheating and post-heating exposure of FRAC microstructure reinforced with PP fiber. (**a**) The micrograph shows that before heating the PP fibers are embedded in cement mortar and no sign of cracks. (**b**) The micrograph shows few microcracks and channels in concrete matrix due to the melting of PP fiber after heating to 200 °C. Copyright permission is obtained from [143].

BF is a highly thermochemically stable and environmentally friendly fiber that improves the mechanical and fracture properties of concrete by virtue of its excellent crack resistance ability. Due to the small diameter, BF is greatly effective in bridging the microcracks in concrete and consequently results in enhanced fracture mechanics and ductility, and results in better post-cracking response [144–146]. At ambient temperature, the incorporation of BF in concrete was found to enhance the flexural strength capacity and fracture energy by 9–13% and 126–140%, respectively, and lower the abrasion wear by 2–18% [147]. In the case of elevated temperatures, only a few experimental investigations were reported that confirmed the usefulness of BF as a reinforcing material for the improvement in residual strength of FRAC. A recent study [37] assessed the mechanical properties of FRAC reinforced with 1, 2, and 3 kg/m^3 dosages of BF and exposed to 200, 400, and 600 °C. The results as shown in Figure 13 indicate that at high temperatures (up to 400 °C), the residual compressive strength of FRAC reinforced with BF was better than that of the control specimen. Furthermore, a maximum increase of about 27.42% and 28.23% in the residual compressive strength of FRAC containing 2 and 3 kg/m^3 of BF, respectively, were reported. Other studies [103,148] also discovered the better performance of BF in terms of enhancing the residual strength and thermal stability of recycled concrete at elevated temperatures. A detailed summary of the past studies regarding the effects of elevated temperature on mechanical properties of FRAC reinforced with SF, PP, and BF is shown in Table 4.

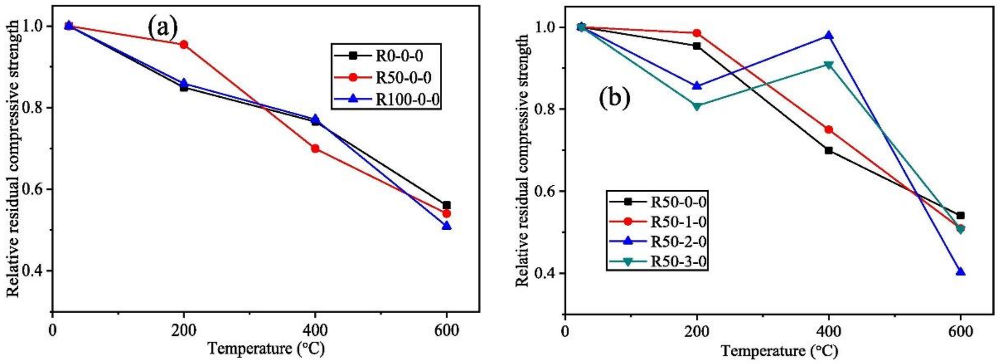

Figure 13. Influence of elevated temperatures on the relative residual compressive strength of (**a**) conventional recycled concrete, and (**b**) recycled concrete containing basalt fiber. Copyright permission is taken from [37].

Table 4. Effects of type and dosages of fiber on the elevated thermal–mechanical properties of FRAC.

Refs.	Fiber Type and Dosage	RCA	Heating Temperature	Heating Rate	Mechanical Properties	Remarks
[50]	SF (0, 0.5, 1, and 1.5%) by volume	100%	200, 400, and 600 °C	2.5 °C/min	RAC reinforced with maximum SF dosage showed 69.56% and 77.94% reduction in maximum crack width and improvement of 266.67% and 131.82% in the toughness values at exposure to temperatures 400 and 600 °C, respectively.	With addition of 1.5% SF dosage, higher residual compressive strength can be obtained. The low heating rate prevents excessive concrete spalling.
[32]	SF (1%) by volume	100%	200, 400, and 600 °C	8 °C/min	RAC containing 1% SF and 4% crumb rubber showed 16.48% and 25.24% increase in the residual compressive strength and Young's modulus, respectively, at 600 °C.	Utilization of 1% SF in conjunction with 4% crumb rubber exhibited improved thermal endurance in RAC.
[52]	SF (0, 0.25, 0.5, and 1%) by volume	25%	150, 300, 450, and 600 °C	Standard fire	Addition of 1% SF and 20% metakaolin in RAC presented 12.33% reduction in mass loss, 61.6% improvement in the residual compressive strength, and 2.2 times greater residual splitting tensile strength after exposure of 600 °C.	The synergic effect of SF and metakaolin exhibited enhanced thermal endurance of recycled concrete.
[51]	SF (0, 0.25, 0.5, 0.75, and 1%) and PP (0, 0.05, 0.1, 0.15, and 0.2%) by volume	20%	100, 300, 600, and 900 °C	Standard fire	Overall, addition of SF and PP improved the residual properties of recycled concrete. SF-reinforced concrete showed 22.1% greater residual splitting tensile strength in comparison to PP-reinforced concrete after exposure to 900 °C elevated temperature.	Addition of SF and PP up to dosages of 1% and 0.15%, respectively, enhanced the residual mechanical properties of concrete.
[139]	SF (1%) by volume	100%	200, 400, 600, and 800 °C	2.5 °C/min	Incorporation of 1% SF resulted in 15.28% increase in peak strain, 123.19% enhancement in residual compressive strength, and 89.66% improvement in elastic modulus of recycled concrete after exposure to 800 °C.	SF, owing to the crack bridging action, presented better mechanical properties of RAC at elevated temperatures.

Table 4. *Cont.*

Refs.	Fiber Type and Dosage	RCA	Heating Temperature	Heating Rate	Mechanical Properties	Remarks
[35]	SF (0, 0.25, 0.5, and 1%) by volume	100%	200, 400, and 600 °C	2.5 °C/min	RAC with 1% SF dosage displayed 42.42% reduction in maximum crack width, 5.53% decrease in mass loss, 170.19% increase in peak load value, and 344.44% improvement in CMOD, at elevated temperature of 600 °C.	At elevated temperatures, SF remarkably improves the fracture energy and toughness of RAC by delaying and preventing crack initiation and propagation, respectively.
[38]	PP (3.3 kg/m^3)	100%	1000 °C	10.88 °C/min	At ambient temperature, recycled concrete showed 2% increase in compressive strength, while at elevated temperature it retained only 26% of its initial compressive strength.	The use of PP in RAC is beneficial in terms of spalling resistance at high temperatures.
[108]	PP (0.3 and 0.5%) and Jute fiber (0.3 and 0.5%) by volume	100%	>600 °C	Standard fire	Recycled concrete reinforced with 0.5% dosages of PP and jute fiber displayed lower vapor pressure, improved spalling resistance, and comparatively lower damage after exposure to elevated temperature.	PP and Jute fiber effectively prevent the heat-induced spalling in recycled concrete via creating voids and pressure-induced tangential spaces.
[84]	PP (0.1%) by weight	50 and 100%	600 and 800 °C	8 °C/min	PP-reinforced concrete showed significant compressive strength reduction of about 40% on exposure to 800 °C.	The melting of PP at higher temperatures results in voids and causes strength degradation.
[37]	BF (0, 1, 2, and 3 kg·m^{-3})	50 and 100%	200, 400, and 600 °C	5 °C/min	In the case of 50% RCA, the residual splitting tensile and compressive strength increased by 10.58% and 28.23%, respectively, with maximum BF dosage, while in the case of 100% RCA these strengths showed improvement of 60.93% and 4.47% with 2 and 3 kg·m^{-3} BF dosage, respectively.	BF, owing to its remarkable, crack arrestability, improve the residual mechanical properties of RAC.

From the above detailed discussion, it is evident that among the commercially available fibers, SF is one of the most effective reinforcing fibers that, due to the crack bridging and reinforcing abilities, strengthens the microstructure of recycled concrete composites and counteracts the adverse effects of high temperatures on its compressive strength. It has been found that the dosage of SF greatly affects the residual compressive strength of FRAC. Based on the previous experimental findings shown in Table 4, it can be concluded that the volume fractions of SF up to 1.5% can be successfully utilized for the desired compressive strength of FRAC at elevated temperatures. However, some researchers argued that the thermal compatibility of SF and the concrete matrix is low which leads to ineffective bonding of SF with the adjacent concrete matrix as shown in Figure 14 [143]. The PP fiber, unlike SF, possesses a low melting point and tensile strength and thus has an insignificant contribution in preventing high strength loss of FRAC at high temperatures. However, from the literature [40,108,140], it was found that the incorporation of PP fiber (up to 0.5% volume fractions) could result in lower vapor pressure and better concrete spalling resistance at high temperatures. In the case of BF, the small diameter of fibers results in better crack resistance and improves the compressive strength of FRAC at high temperatures [37]. However, it has been also reported that the higher dosage of BF produces fragile ITZs due to the lower content of CSH near BF (Figure 15), which is undesirable [148]. To further understand the effect of varying content of BF on the compressive strength of FRAC at elevated temperatures, further research is required.

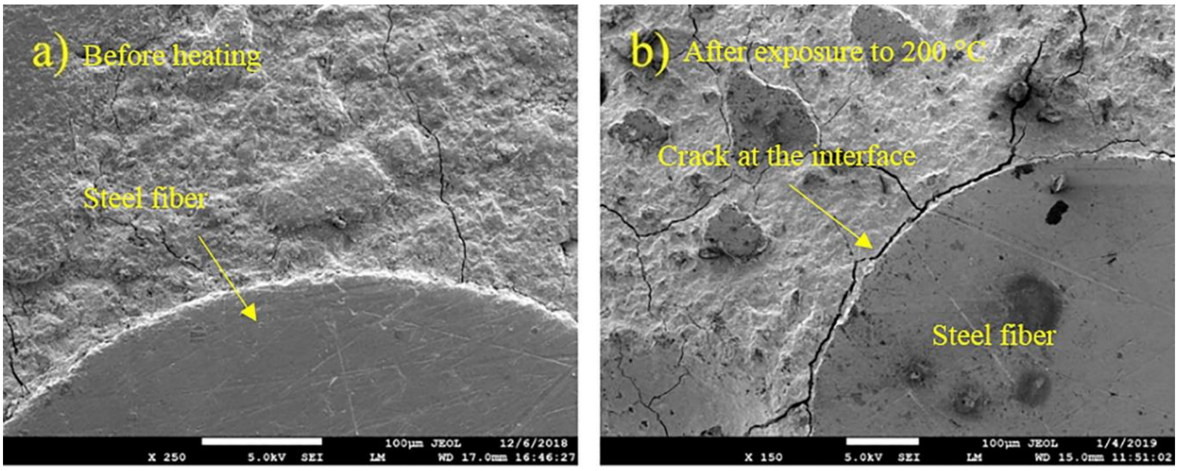

Figure 14. SEM micrographs of SF-based FRAC demonstrating SF and concrete matrix interaction (**a**) before heating and (**b**) after heating at 200 °C. Copyright permission is obtained from [143].

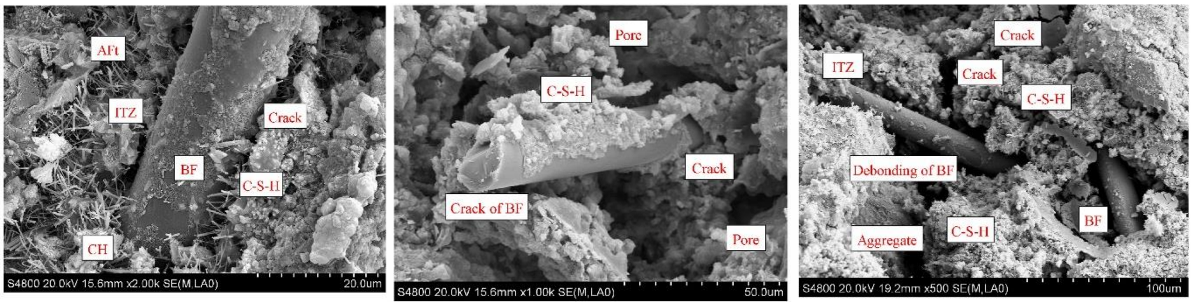

Figure 15. SEM micrographs of BF-based FRAC demonstrate the effect of higher BF dosage and concrete matrix interaction at elevated temperature. Copyright permission is obtained from [148].

4.2.2. Splitting Tensile Strength

The splitting tensile strength of FRAC majorly depends on the initiation and propagation of microcracks inside the matrix. The addition of fiber in recycled aggregate concrete effectively controls the microcracks via crack reinforcing and crack bridging abilities and thereby results in improved splitting tensile strength capacity [149–152]. Various laboratory investigations confirmed the usefulness of reinforcing fibers such as SF, PP, and BF in the development of the splitting tensile capacity of RAC at ambient temperature [28,153,154]. Similarly, the crack prevention and retardation abilities of SF enable FRAC to retain splitting tensile strength at elevated temperatures. Established results [51] indicate improved residual splitting tensile loading capacity of FRAC reinforced with SF and exposed to elevated temperatures, i.e., 100, 300, 600, and 900 °C. An increase of about 47% in the residual tensile strength of FRAC with 0.25% dosage of SF was reported. In addition, the recycled concrete fabricated with SF depicted about 22.1% greater strength than that of PP-reinforced recycled concrete, exposed to 900 °C. The fiber-bridging ability of SF, as shown in Figure 16, greatly helps the weak matrix of the recycled concrete composite to withstand the greater splitting tensile load.

Figure 16. Fiber reinforcing effect in recycled concrete tested for residual splitting capacity. Copyright permission is taken from [51].

Similarly, other researchers [35,155] also discovered improvements in the splitting tensile strength of SF reinforced FRAC. Furthermore, SF results in better fiber–matrix interlocking which enables effective stress transferring from the surrounding concrete matrix to the fiber. This effect was also reported in a recent study [52] that assessed the influence of various quantities of SF on the residual splitting tensile capacity of FRAC exposed to elevated temperatures, i.e., 150, 300, 450, and 600 °C. The authors reported improvements of about 22.1, 31.9, and 59.9% at ambient temperature with the incorporation of 0.25, 0.5, and 1% volume fractions of SF, respectively. While considering the elevated temperature (600 °C), the tensile strength of SF-reinforced concrete was 2.2 times greater than that of the control specimen. Similarly, Gao et al. [155] performed an experimental investigation in order to gauge the usefulness of SF in the enhancement of ground granulated blast-furnace slag concrete. The content of SF equal to 0.5, 1, 1.5, and 2% was incorporated in concrete and subjected to elevated temperatures of 200, 400, 600, and 800 °C. The concrete specimen reinforced with SF performed better in terms of residual strength than that of concrete without SF. The authors found an increase of about 36.1% in the splitting tensile strength of concrete with an addition of 2% of SF. Furthermore, SF was also found effective in conjunction with PP that resulted in about 40% greater residual splitting capacity of high-strength concrete (HSC) in comparison to the control specimen [99].

The PP fiber has been widely known to improve the splitting tensile capacity of FRAC at room temperature due to its excellent crack arrestability [49,136,142]. The findings of previous studies suggested that the dosage of PP fiber up to 1.25% results in a major improvement in the splitting tensile strength of FRAC [135,138]. In the case of elevated temperatures, the usefulness of PP fiber is limited, owing to its low melting point, usually reported as 170 °C [40]. However, the findings of other studies [156,157] showed better thermal endurance of PP-fiber-reinforced concrete. Likewise, the experimental results of [33] concluded an improvement of about 7.7% and 15.4% in the residual tensile loading capacity of fiber-reinforced concrete (exposed to 400 °C) with the addition of 0.5% and 1% of waste PP fiber, respectively. Furthermore, Aslani and Kelin [51] investigated the influence of 0.05, 0.1, 0.15, and 0.2% volume fractions of PP fiber on the residual properties of recycled concrete and found that the tensile strength of PP-fiber-reinforced recycled concrete was better than that of the control specimen. Their key findings, as displayed in Figure 17, shows a maximum increase of about 22% in the residual splitting tensile loading strength with an addition of 0.1% of PP fiber. Moreover, the literature study [155] also revealed better tensile strength of ground-granulated-blast-furnace-slag-based concrete with the addition of PP fiber. The authors concluded strength improvements of about 9.5, 14.5, and 6.7% for the dosages 0.6, 0.9, and 1.2 kg/m^3 of PP fiber, respectively, at an elevated temperature of 400 °C.

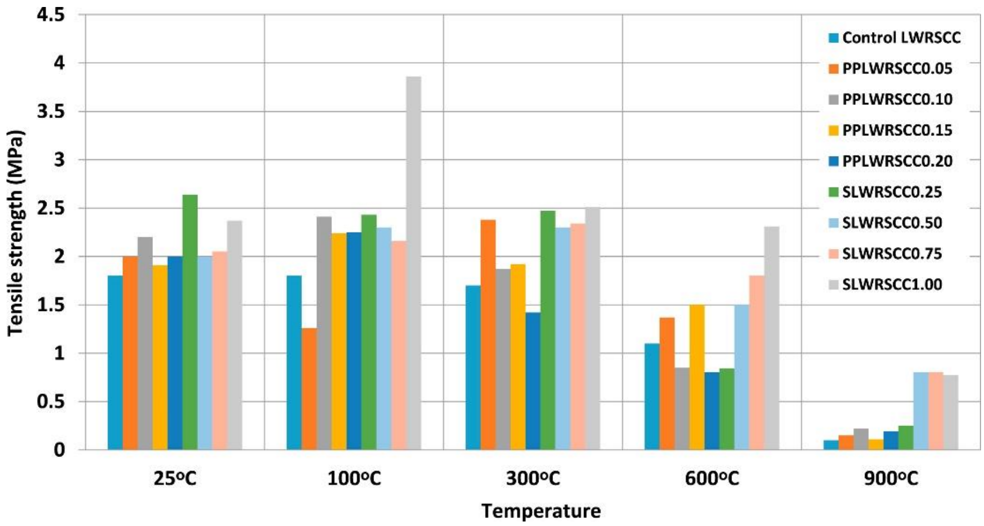

Figure 17. Impact of changing volume fractions of PP fiber and SF on the tensile loading capacity of FRAC. Copyright permission is obtained from [51].

Similar to SF and PP fiber, the utilization of BF in FRAC was also found to be beneficial in improving the splitting tensile strength by several researchers [28,152]. BF, owing to its small diameter, helps the weak matrix of RAC to arrest the microcracks and improve its mechanical properties. However, considering the thermal–mechanical properties of BF-reinforced FRAC at high temperatures, limited work has been carried out in the past. A recent research study [37] explored the influence of 1, 2, and 3 kg/m^3 dosages of BF on the residual properties of FRAC exposed to temperatures of 25, 200, 400, and 600 °C, and found better strength results for the BF-reinforced FRAC. Their test results depicted a maximum increase of about 60.9% (at 400 °C) in the tensile strength of FRAC with the addition of 2 kg/m^3 of BF. Furthermore, the findings of [103] also suggested that an addition of 2% (by weight) dosage of BF in polymer concrete (at 250 °C) retained more than 80% of the splitting tensile strength, almost double that of the control specimen. The available literature suggests that the fiber-reinforcing technique is highly effective in preventing splitting tensile strength loss in FRAC at elevated temperatures. The residual splitting tensile strength of FRAC greatly depends on the type and quantity of the reinforcing fiber. Among the reinforcing fibers, the use of SF and BF in FRAC could better alleviate the adverse effects of elevated temperatures on the tensile strength owing to their excellent crack bridging and reinforcing capabilities. Unlike SF and BF, the PP fiber, owing to its low melting point and tensile strength, possesses an insignificant effect in the improvement in post-fire splitting tensile strength of FRAC. The summary of the previous experimental findings is presented in Table 4.

4.2.3. Modulus of Elasticity

The modulus of elasticity is one of the important indicators for assessing the thermal endurance of concrete at elevated temperatures. In general, the modulus of elasticity of FRAC depends on the constituent materials' composition, properties of ITZ, and type and volume fractions of fiber. The literature has shown that among the residual mechanical properties of FRAC, the modulus of elasticity is most adversely affected at elevated temperatures [32,158]. The incorporation of a suitable type and dosage of the reinforcing fiber could prevent a greater loss of residual modulus of elasticity of FRAC at elevated temperatures. It has been found that at ambient temperature, the incorporation of fiber possesses little effect on the modulus of elasticity of FRAC; however, during high temperatures, the modulus of elasticity of FRAC was slightly better than that of conventional RAC [40]. These impacts of SF on the modulus of elasticity of FRAC were also reported by [50]. Their experimental findings, as shown in Figure 18, suggest lower elastic modulus of FRAC at room temperature. However, after exposure to high temperatures (400 °C and 600 °C), the FRAC reinforced with SF depicted slightly greater values of modulus of elasticity than those of conventional RAC. The findings of other studies [32,139] also depicted similar trends in the modulus of elasticity of FRAC reinforced with SF.

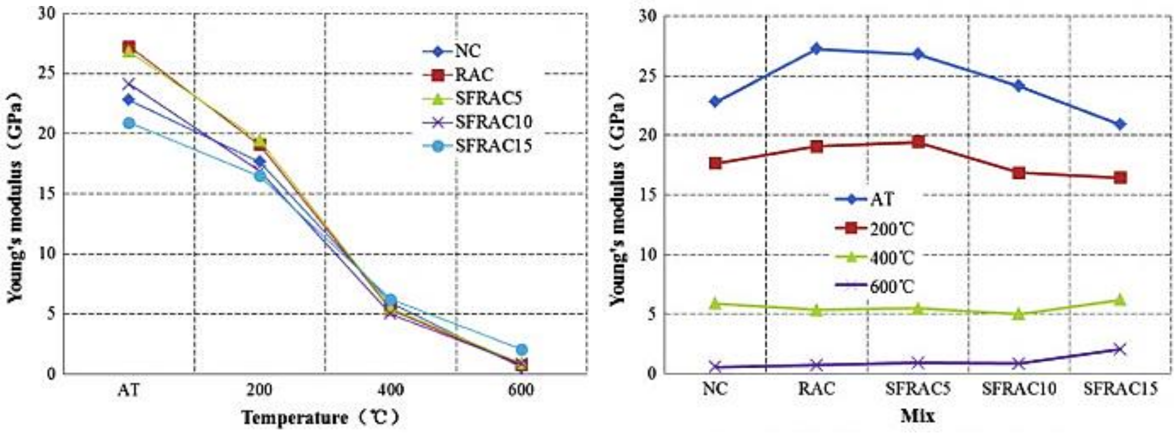

Figure 18. Young's modulus of SF-reinforced recycled concrete at ambient and high temperatures. Copyright permission is obtained from [50].

Similarly, the addition of PP fiber was also found useful in improving the residual elastic modulus of FRAC subjected to elevated temperatures. Furthermore, the findings of a recent study [51] indicated a better modulus of elasticity of PP-fiber-reinforced FRAC, up to a temperature of 300 °C. However, according to some other studies [140,159], the influence of PP fiber in the improvement in modulus of elasticity reduced with an increase in temperature, especially above 600 °C. BF is also discovered to be greatly effective in enhancing the residual modulus of elasticity of FRAC. For instance, a recent study [148] investigating the residual performance of FRAC with BF revealed that the dosage of BF, i.e., 2 kg/m^3 and 6 kg/m^3, helps the concrete matrix to retain about 87% of its modulus of elasticity of concrete after exposure to high temperature, i.e., 500 °C. This improved response of FRAC is attributed to the remarkable crack-arresting ability and thermally durable property of BFs in host concrete matrices as shown in Figure 19.

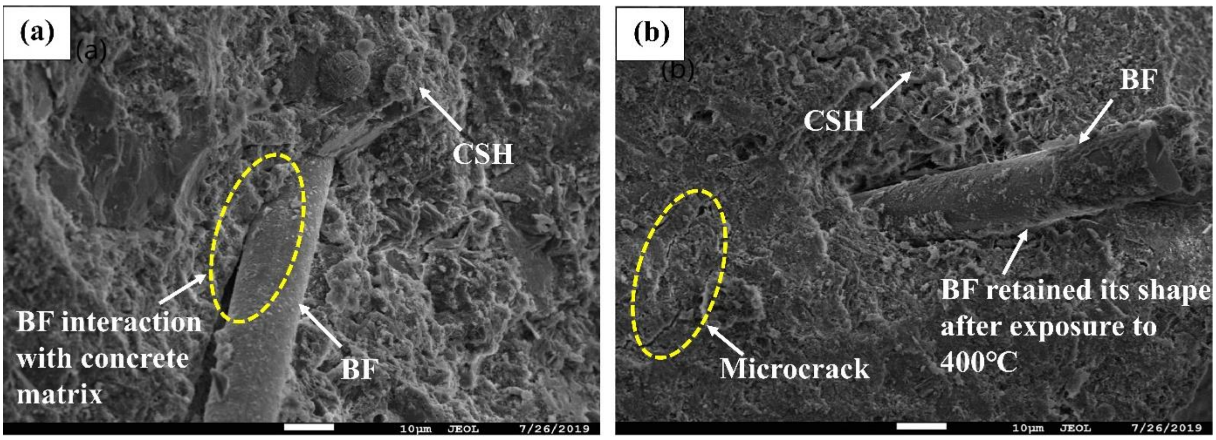

Figure 19. Microstructure of FRAC demonstrating the BF interaction with the host FRAC matrix at temperature exposure of (**a**) 200 °C and (**b**) 400 °C. Copyright permission is obtained from [37].

4.2.4. Concrete Spalling

Among the elevated temperature properties of concrete, spalling is an essential indicator that depicts the thermal endurance of concrete. This spalling phenomenon adversely affects concrete integrity and deteriorates its properties by exposing the inner part of concrete to the elevated temperature [160,161]. Generally, it has been observed that in a dense concrete microstructure and lower porosity, the chances of spalling are high as it causes hindrance for the escape of water vapor during high temperatures and thus favors concrete spalling [62,162]. In addition, the heating rate and temperature gradient between inner and outer concrete surfaces are also influential in concrete spalling [163]. The addition of a suitable type and dosage of SF can prevent spalling in FRAC at high temperatures. It is primarily ascribed to the better fiber matrix interaction in SF-reinforced concrete that counteracts the internal pore pressure and thermal stresses caused in the microstructure of FRAC due to high temperatures. For instance, the findings of [32] indicated improved concrete performance with the addition of SF in terms of concrete spalling resistance at higher temperatures. Similarly, the outcomes of [50] suggested no explosive concrete spalling in FRAC reinforced with SF at a low-temperature rate of 2.5 °C/min. On the contrary, some researchers [164,165] argued that the crack retardation and prevention abilities of SF could enhance the spalling chances in FRAC during high temperatures. In the case of PP fiber, the available literature [166–168] showed an increase in the spalling resistance of FRAC exposed to elevated temperatures. The melting of PP fiber makes microcavities inside the concrete matrix which helps in the lessening of pore vapor pressure and thereby prevents the spalling phenomenon [169]. This effect of PP fiber was also endorsed by other researchers [38,170]. Their findings revealed that despite low compressive strength at high temperature (1000 °C) the PP fiber-reinforced concrete showed excellent resistance against spalling. Furthermore, the addition of 0.22% and 0.44% volume fractions of PP fiber was found to be beneficial in preventing spalling in high-strength concrete and ultra-high-strength concrete, respectively, subjected to high temperatures above 600 °C [171,172]. Similarly, in the case of BF, significant improvements have been reported by researchers in the overall concrete cracking behavior (Figure 20) and spalling resistance of FRAC after exposure to high temperatures [173]. The small diameter of BF helps in the crack-bridging action which thereby upgrades the FRAC resistance against explosive concrete spalling due to increasing vapor at high temperatures [170].

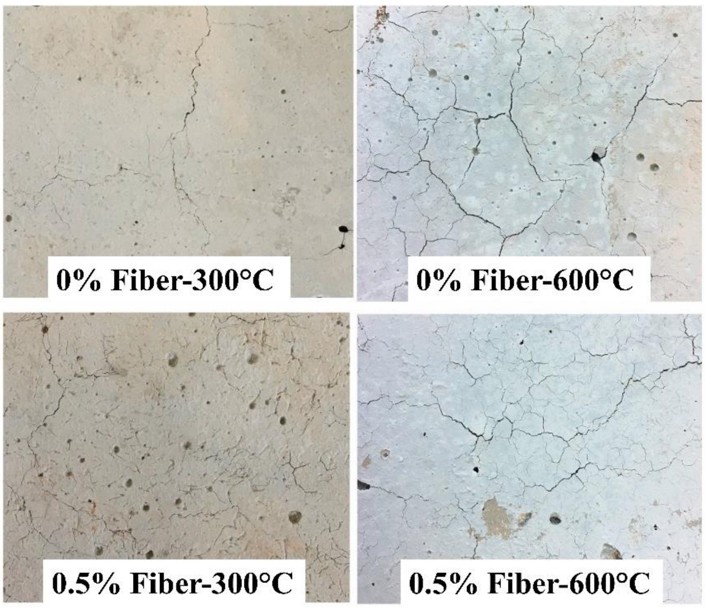

Figure 20. The surface condition of BF based FRAC demonstrates physical appearance and crack development at 300 °C and 600 °C. Copyright permission is obtained from [170].

4.2.5. Mass Loss

Mass loss is another key indicator for assessing the thermal endurance of FRAC exposed to high temperatures and it is expressed as the ratio of mass of concrete after the exposure to an elevated temperature to the mass of concrete at ambient temperature. The mass loss in FRAC majorly depends on the physicochemical changes that occur inside the matrix as a result of high temperature. In addition, aggregate properties also affect the mass loss of concrete. In Figure 21, the mass loss in FRAC with respect to elevated temperatures as reported in the literature [32,51,52,164] is presented. It has been found that both in the case of SF and PP-fiber-reinforced FRAC, the mass loss increases with rise in the temperature. It is mainly due to the loss of internal moisture and breakdown of calcium silicate hydrate (CSH). In addition, some researchers argued [40,174] that the use of low thermally stable fiber such as PP fiber could result in greater mass loss due to the melting of fiber. The findings of Aslani and Kelin [51] indicated mass loss of about 10% and 8% for FRAC containing 1% SF and 0.2% PP fiber, respectively, after exposure to 600 °C. When the temperature was further increased to 900 °C the same specimen demonstrated an approximate mass loss of 14% and 11%. Similarly, the outcomes of [32] revealed about 10.6% mass loss in FRAC reinforced with 1% SF after exposure to 900 °C. Other studies [52,164] also found similar trends in the mass loss of FRAC when exposed to elevated temperatures. In the case of BF, literature lacks sufficient information about the effect of elevated temperatures on the mass loss of FRAC and hence further research investigation is needed.

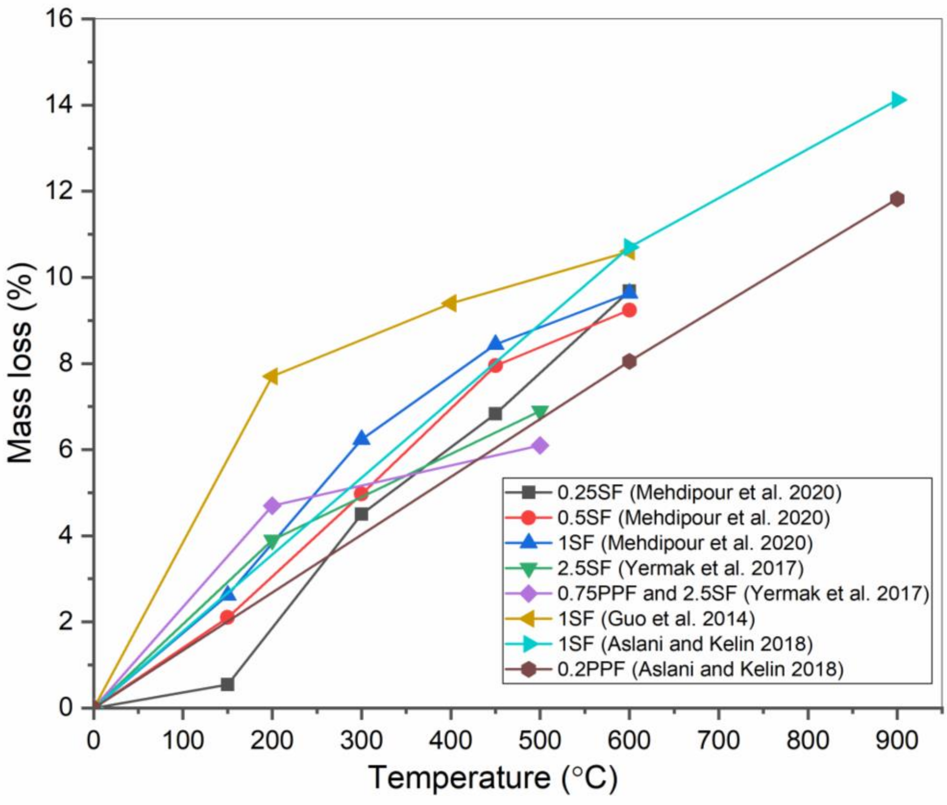

Figure 21. Variations in the mass loss of fiber-reinforced concrete with the increase in temperature [32,51,52,164].

4.2.6. Durability

Durability is an important characteristic of concrete that indicates the quality of microstructure as well as the mechanical properties of concrete at elevated temperatures. Generally, the durability of concrete is measured through laboratory tests namely sorptivity, electrical resistance, water penetration depth, and weight loss [62,175,176]. It has been widely known that the microstructure of RAC is usually comprised of several micro and macro pores that not only result in inferior mechanical performance but also make concrete more vulnerable to chloride ion attacks. In addition, the exposure to high temperatures creates additional pores inside the concrete matrix that consequently result in high permeability and lower durability of concrete. The addition of fiber material in the FRAC has revealed improved durability performance in comparison to conventional RAC [45,177]. The findings of a recent experimental investigation [52] revealed that the inclusion of SF (up to 1% dosage, by volume) and 20% metakaolin in RAC retained most of its strength and showed high durability (lower mass loss rate). Similarly, the experiment findings of [176] also confirmed the usefulness of SF in terms of reducing sorptivity coefficient and decreasing water penetration depth of fiber-reinforced concrete at a temperature of 650 °C. The authors reported a significant reduction of about 55.46% and 42.09% in the sorptivity coefficient and water penetration depth. Unlike SF, the incorporation of PP fiber in FRAC could result in greater permeability at elevated temperatures. As explained earlier, the PP fiber belongs to the low-thermal-stability fibers, and upon exposure to elevated temperature it melts and thereby creates additional pores in the FRAC. Several researchers [172,178,179] reported that the permeability of FRAC reinforced with PP fiber and exposed to a temperature of 200 °C was significantly higher (about 85 to 100 times) than that of the control specimen. In the case of BF, the available literature lacks information about the post-fire durability of FRAC. To explore this aspect of BF-reinforced FRAC, further research is required.

5. Discussion

Fiber-reinforced recycled concrete produced with suitable reinforcing materials such as SF, PP, and BF offer greater benefits than conventional normal aggregate concrete. The incorporation of a suitable dosage of these fibers prevents the formation and propagation of microstructural cracks via their crack bridging and reinforcing abilities and thereby results in higher tensile strength capacity and fracture properties of FRAC. Furthermore, the fiber-reinforcing technique remarkably restrains the growth of shrinkage and thermal cracks and thus produces a durable FRAC. Based on the previous experimental findings, a detailed discussion about the dosage of fiber, replacement levels of recycled aggregate, and their influence on the mechanical properties of FRAC at elevated temperatures is presented in the following sections. It would help in establishing a thorough understanding about the content of SF, PP fiber, and BF for the desired mechanical properties of FRAC.

5.1. Compressive Strength

The impact of varying dosages of fiber and various replacement levels of RCA on the relative residual compressive strength of FRAC at various elevated temperatures is demonstrated in Figure 22. In the current study, the relative residual compressive strength of FRAC was determined by taking the ratio of compressive strength of FRAC at high temperatures to the compressive strength of FRAC at room temperature. The incorporation of SF and PP fiber helps recycled concrete in retaining its compressive strength at high temperatures. The findings of previous studies reveal that for the same elevated temperature condition, the residual compressive strength of FRAC enhances with an increase in the dosage of fiber [50,51]. For instance, at an elevated temperature of 200 °C, the utilization of 0.5, 1, and 1.5% volume fractions of SF showed an average residual compressive strength of 0.83, 0.87, and 0.88, respectively. Similarly, at 400 °C the average relative residual compressive strength was about 0.58, 0.59, and 0.73, while at 600 °C these values were recorded as 0.27, 0.3, and 0.49 for the respective SF dosages of 0.5, 1, and 1.5% [50].

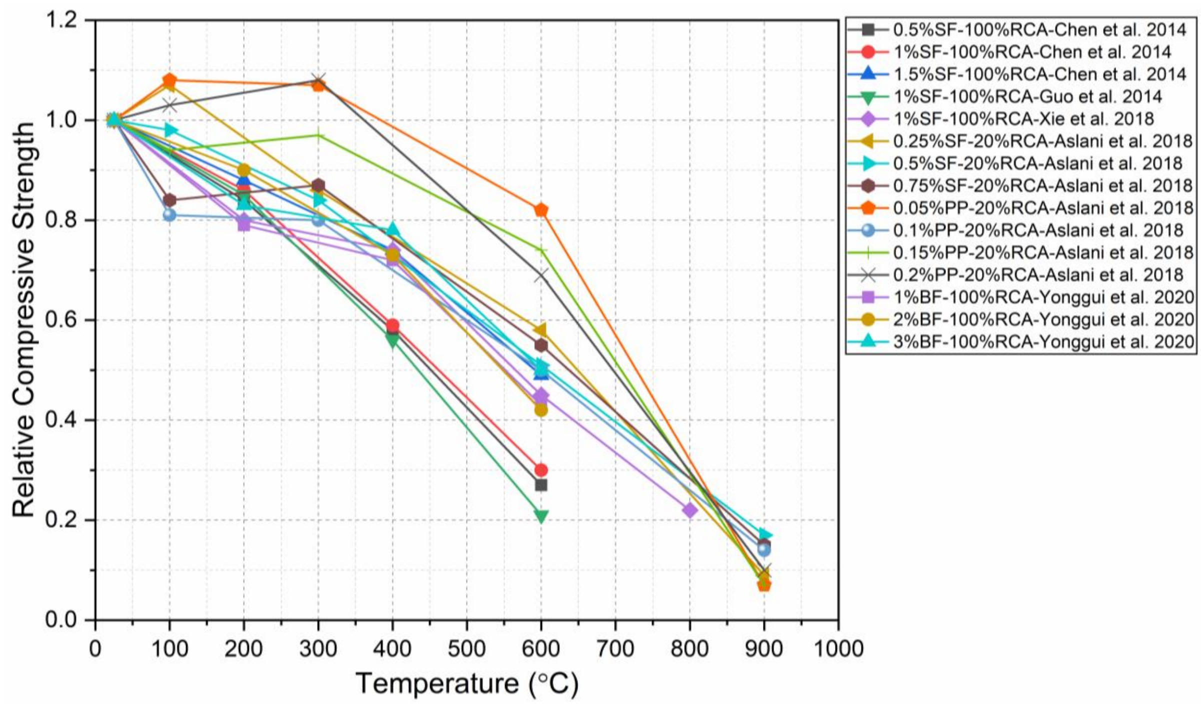

Figure 22. Influence of high temperatures and fiber quantities on relative residual compressive strength of FRAC [32,37,50,51,139].

Similarly, in the case of PP fiber, with the incorporation of 0.1, 0.15, and 0.2% dosages, the residual compressive strength of about 0.82, 0.95, and 1, respectively, was noted at elevated a temperature of 300 °C. Similarly, at 600 °C these dosages of PP fiber resulted in about 0.5, 0.72, and 0.67 residual compressive strength of FRAC [51]. Furthermore, with the increase in temperature, the compressive strength of FRAC reduces irrespective of the volume fractions and type of fiber. For instance, in the case of SF-reinforced FRAC, the previous experimental findings indicated a loss in the residual compressive strength from 0.84 to 0.21 when temperature was increased from 200 to 600 °C [32]. Other research studies also found a reduction in the residual compressive strength of FRAC in the range 1.0–0.22 when temperature was increased from 150 to 800 °C [52,139]. Similarly, in the case of PP-fiber-based FRAC, the residual compressive strength dropped significantly from 1.0 to 0.1 when temperature was raised from 300 to 900 °C [51]. In addition, unlike SF, the PP fiber was found to be less effective in preventing residual compressive strength loss at higher temperatures (beyond 600 °C) owing to its low melting point [108]. It has also been observed that with higher percentage replacement of RCA the relative residual compressive strength of concrete is reduced at elevated temperatures. For instance, for the equal volume fractions of SF (1%) the relative residual compressive strength of FRAC containing 25% and 100% RCA was 0.59 and 0.21, respectively [32,52]. Similarly, an increase in the dosage of BF shows a progressive increase in the values of relative strength. For instance, the 1%, 2%, and 3% content of BF shows residual strength of about 0.8–0.85 at 200 °C, 0.75–0.78 at 400 °C, and 0.42–0.46 at 600 °C [37].

5.2. Splitting Tensile Strength

The effects of varying volume fractions of fibers in conjunction with various replacement levels of RCA on the residual splitting tensile strength of FRAC at various elevated temperatures are shown in Figure 23. The relative residual splitting tensile strength was determined by taking the ratio of the splitting tensile strength of FRAC at elevated temperatures to the splitting tensile strength of FRAC at room temperature. It has been found that the addition of SF in the FRAC is greatly influential in the enhancement of residual tensile strength at elevated temperatures. The experimental study by [51] revealed that for the same elevated temperature (600 °C), the addition of SF dosage in the range 0.25–1% significantly improved the relative residual strength values of FRAC from 0.28 to 0.92. Similarly, at 900 °C the relative residual splitting tensile strength increased from 0.09 to 0.32 with increasing SF dosage in the range 0.25–1%. Similar trends in the residual tensile strength of FRAC were also found by [52]. However, it has also been noticed that like other mechanical properties of FRAC, the residual splitting tensile strength undergoes significant loss especially when exposed to 900 °C. On average, the FRAC reinforced with 1% volume fractions of SF and exposed to 900 °C depicted a strength loss of about 68% [51]. Unlike SF, the PP fiber is less effective in retaining the tensile strength of FRAC at elevated temperatures. Figure 23 depicts a significant drop in the relative residual splitting tensile strength of FRAC from 0.65 to 0.05 (with 0.05% of PP fiber), from 0.36 to 0.04 (with 0.1% of PP fiber), and from 0.78 to 0.042 (with 0.15% of PP fiber) when the temperature value is increased from 600 °C to 900 °C. Furthermore, the graph also suggests progressive improvements in the residual tensile capacity of FRAC in the case of BF. According to the research findings of [37], the FRAC showed about 0.82–0.97 residual tensile capacity at 400 °C, 0.4–0.6 at 600 °C, and 0.35–0.52 at 900 °C with the use of 1%, 2 %, and 3% content of BF. The findings of [103] also confirmed a similar increasing trend in the residual tensile capacity of FRAC with the use of BF.

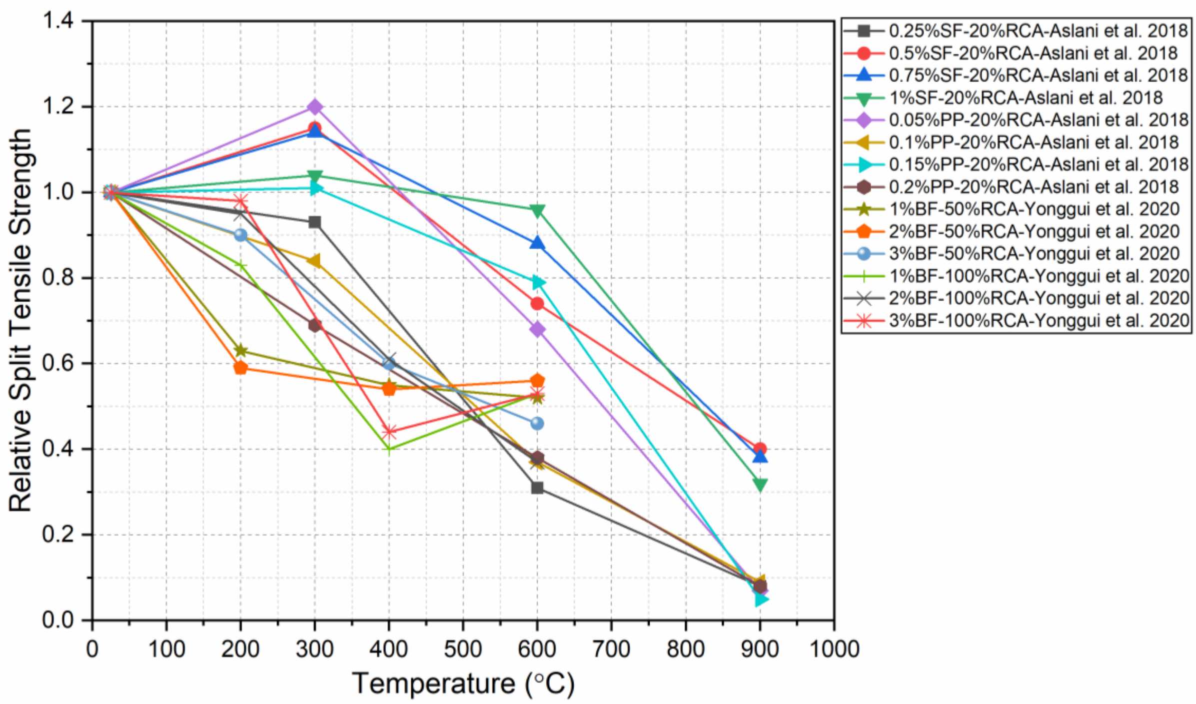

Figure 23. Effect of elevated temperatures and fiber dosages on relative residual splitting tensile strength of FRAC [37,51].

5.3. Modulus of Elasticity

The influence of varying volume fractions of fiber in conjunction with various proportions of RCA on the residual modulus of elasticity of FRAC at high temperatures is shown in Figure 23. The relative residual modulus of elasticity was determined by taking the ratio of modulus of elasticity of FRAC at elevated temperatures to the modulus of elasticity of FRAC at room temperature. It can be seen from the below figure (Figure 24) that the elastic modulus of FRAC is severely affected at high temperatures. With the increase in the temperature from 200 to 600 °C, the values of relative residual modulus of elasticity of FRAC containing 0.5, 1, and 1.5% volume fractions of SF reduced from 0.72 to 0.03, from 0.69 to 0.03, and from 0.78 to 0.09, respectively [50]. Similarly, the findings of [32] indicated that the residual modulus of elasticity of FRAC reinforced with 1% SF decreased from 0.51 to 0.04 when the temperature was increased from 200 to 800 °C.

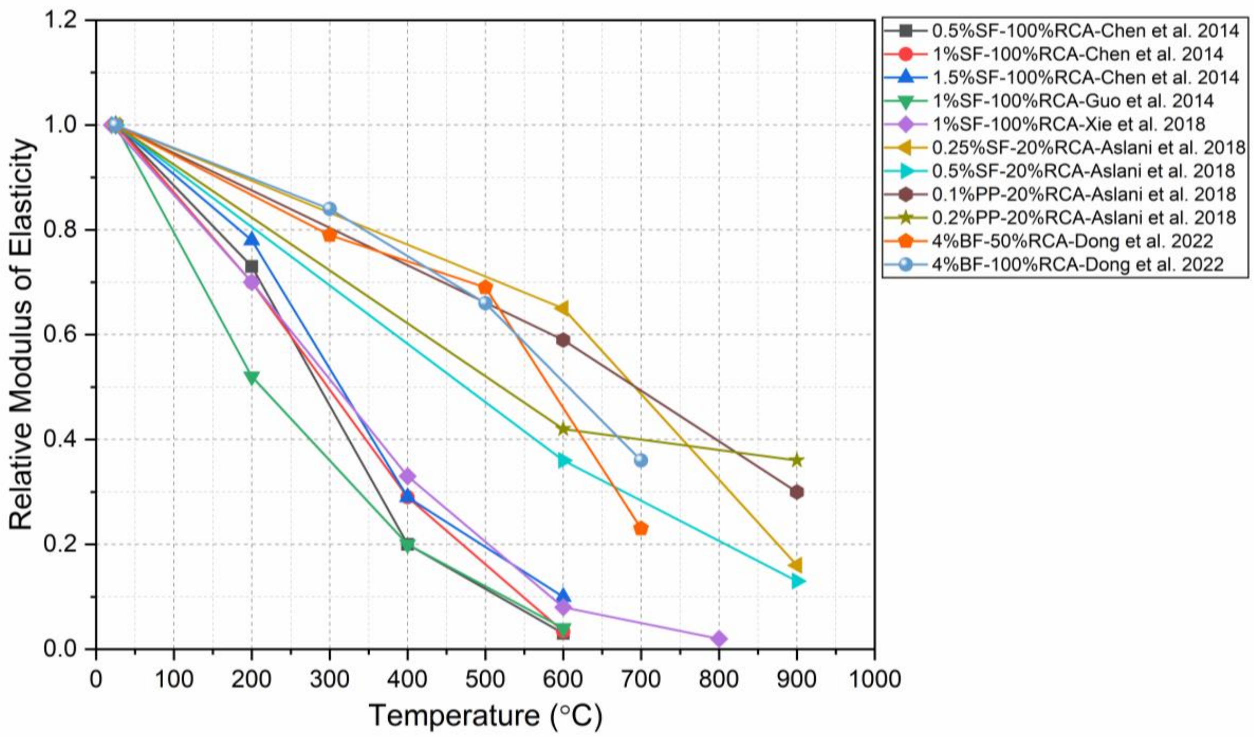

Figure 24. Influence of high temperatures and fiber dosages on the relative residual modulus of elasticity of FRAC [32,50,51,139,148].

In the case of PP-fiber-reinforced FRAC, a similar degradation trend in the residual modulus of elasticity was noticed with the increase in temperature. For instance, the experimental results of [108] showed a reduction in the relative residual modulus of elasticity of FRAC containing 0.1% PP fiber from 0.34 to 0.13 when the temperature was increased from 600 to 800 °C. Similarly, the outcomes of [51] showed about 0.62, 0.31, and 0.02 relative residual modulus of elasticity of FRAC reinforced with 0.1% volume fractions of PP fiber at elevated temperatures of 300, 600, and 900 °C, respectively. In the case of BF-based FRAC, a similar decreasing trend was noticed in the residual modulus of elasticity with an increase in temperature. However, due to the remarkable crack-arresting ability and thermally durable property of BFs in the host concrete matrix (Figure 20), the overall performance was better in comparison to SF and PP fiber. For instance, the findings of [148] reveal that the dosage of BF, i.e., 2 kg/m^3 and 6 kg/m^3 can retain about 87% of the residual modulus of elasticity of FRAC after exposure to high temperature, i.e., 500 °C.

6. Future Research Need

From the above technical discussion, it can be inferred that the use of SF up to 1.5% dosage is effective in improving residual compressive and splitting tensile strength of FRAC exposed to high temperatures (up to 800 °C). However, it is less effective in preventing an abrupt loss in the residual modulus of elasticity of FRAC. In terms of concrete spalling resistance, controversies in the results were found. For instance, the outcomes of some studies [32,50] revealed better resistance of FRAC against the spalling phenomenon, while other studies [164,165] argued that the presence of fiber could enhance the spalling chances in FRAC during high temperatures. Moreover, unlike other fibers, the thermal compatibility of SF and the concrete matrix is low, which leads to ineffective bonding of SF with the adjacent concrete matrix and thereby lowers the overall effectiveness of fiber [143]. Although SF is one of the most persuasive reinforcing fibers, due to high cost, high resource consumption, and unfavorable environmental effects its applications are limited in practical engineering. To overcome these challenges and promote the applications of this fiber material, further research exploration is required in this regard.

Unlike SF, the profitable effect of PP fiber diminishes at high temperatures especially above 600 °C, owing to its low melting point. However, it is highly effective in preventing excessive concrete spalling. Furthermore, the tensile strength of PP fiber is lower in comparison to that of SF, thus, it offers limited usefulness for FRAC in terms of residual strength improvement. Similarly, the PP fiber is also less effective in improving the post-fire durability of FRAC as it leads to unwanted pores and cavities in the concrete matrix. BF is a relatively new and environmentally friendly fiber that could soon replace the traditional fiber materials due to its high strength and excellent thermally durable nature. Some preliminary investigations showed remarkable improvements in the residual mechanical performance of FRAC with the use of BF. To date, only few studies have assessed the usefulness of BF as a reinforcing fiber in FRAC and found significant improvement in the mechanical performance of FRAC at elevated temperatures. Furthermore, some researchers [148] argued that the choice of optimum dosage of BF is highly essential for its effectiveness as the high content of BF could result in fragile ITZs and lower density of concrete. This phenomenon may compromise the overall effectiveness of BF in FRAC. With regards to the post-fire durability performance of BF-reinforced FRAC, no information is reported in the literature so far. Hence, to establish further knowledge about the influence of various dosages of BF in conjunction with varying proportions of RCA on the residual strength and durability of FRAC, further research exploration is inevitably required.

7. Conclusions

The current review article has produced a comprehensive summary and analysis of recently established studies pertinent to the mechanical properties and durability of FRAC reinforced with varying contents of SF, PP fiber, and BF and exposed to elevated temperatures. Based on the detailed discussions above, the following conclusions are drawn.

1. Unlike normal aggregate concrete, the microstructure of RAC consists of weaker interfacial transition zones owing to the adhered cement mortar to the surface of RCA, which results in lower residual properties of RAC. On average, RAC containing 100% of RCA displays a significant loss of about 1.0–0.30 in relative compressive strength, a loss of about 1.0–0.34 in relative splitting tensile strength, and a loss of about 1.0–0.10 in relative modulus of elasticity upon exposure to high temperatures (25 °C to 800 °C).
2. The concrete spalling, mass loss, and durability are essential indicators in assessing the mechanical performance of concrete at high temperatures. Generally, the RAC containing higher replacement levels of RCA depicts greater concrete spalling, high mass loss, and lower durability after exposure to elevated temperatures (25 °C to 800 °C), due to a great deal of microstructural physio-chemical changes.
3. Among the available strengthening techniques, fiber reinforcing is an effective and persuasive technique that prevents and retards the microcracks via crack-bridging ability in the weak matrix of RAC, and thereby results in improved residual mechanical properties and durability in comparison to conventional concrete.
4. The mechanical performance of FRAC at elevated temperatures depends on several factors, such as the selection of the type of reinforcing fiber (i.e., SF, PP fiber, BF, etc.) and its volume fractions, the quality and replacement levels of RCA, and the heating condition (i.e., heating and cooling rate, maximum value of temperature, etc.).
5. The use of high strength and thermally stable fiber such as SF and BF could improve the crack resistance and mechanical properties in FRAC, while the incorporation of low thermally stable fiber such as PP fiber may prevent severe concrete spalling in FRAC at elevated temperatures.
6. Among the commercially available fibers, SF is the most widely used fiber due to its high strength and melting point that significantly improves the mechanical performance of FRAC at both ambient and elevated temperatures. A dosage of SF (up

to 1.5% by volume) can retain an average of 50% of the residual compressive strength and 78% of the residual splitting tensile strength of FRAC, exposed to temperatures up to 600 °C.

7. The PP fiber has low tensile strength and melting point that offers limited usefulness in terms of residual mechanical properties of FRAC. However, due to its low melting point, it creates pathways for water vapor to escape and reduces the chances of microstructure damage due to internal pore pressure and temperature gradient, thus preventing the spalling phenomenon at elevated temperatures. An addition of PP fiber up to 0.5% could be effectively utilized in the FRAC for counteracting the adverse effects of elevated temperatures.
8. BF is widely known as an environmentally friendly and green fiber that possesses high tensile strength and excellent thermal stability. At room temperature, the dosage of BF up to 1.5% is found to remarkably improve the tensile capacity, flexural strength, and fracture toughness of FRAC. With regards to the mechanical response of FRAC at elevated temperatures, limited work has been conducted so far that reveals significant enhancements in the residual mechanical performance of FRAC. To know more about the effect of varying content of BF on the mechanical performance and durability of FRAC composites at high temperatures, further research is needed.

Funding: This research was funded by City University of Hong Kong (Project No. ARG 9667238).

Data Availability Statement: The data presented in this study are available upon request from the corresponding author.

Acknowledgments: The work described in this paper was supported by City University of Hong Kong (Project No. ARG 9667238).

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

BF	basalt fiber
C&D	construction and demolition
CF	carbon fiber
CO_2	carbon dioxide
CSH	calcium silicate hydrates
FRAC	fiber-reinforced recycled aggregate concrete
GF	glass fiber
GPa	gigapascal
HSC	high strength concrete
ITZs	interfacial transition zones
kPa	kilopascal
MPa	megapascal
NAC	normal aggregate concrete
NCA	normal concrete aggregate
PP	polypropylene
RAC	recycled aggregate concrete
RCA	recycled concrete aggregate
SEM	scanning electron microscope
SF	steel fiber
UPV	ultrasonic pulse velocity

References

1. Correal, J.F.; Carrillo, J.; Reyes, J.C.; Renjifo, A.E.; Herrán, C.A. Cyclic tests of full-scale fiber-reinforced concrete (FRC) walls with steel and hybrid fibers for low-rise buildings. *Eng. Struct.* **2022**, *256*, 113952. [CrossRef]
2. Affan, M.; Ali, M. Experimental investigation on mechanical properties of jute fiber reinforced concrete under freeze-thaw conditions for pavement applications. *Constr. Build. Mater.* **2022**, *323*, 126599. [CrossRef]

3. Frazão, C.; Barros, J.; Bogas, J.A.; García-Cortés, V.; Valente, T. Technical and environmental potentialities of recycled steel fiber reinforced concrete for structural applications. *J. Build. Eng.* **2022**, *45*, 103579. [CrossRef]
4. Zhang, G.; Ding, Z.; Zhang, R.; Chen, C.; Fu, G.; Luo, X.; Wang, Y.; Zhang, C. Combined Utilization of Construction and Demolition Waste and Propylene Fiber in Cement-Stabilized Soil. *Buildings* **2022**, *12*, 350. [CrossRef]
5. Pomponi, F.; Moncaster, A. Circular economy for the built environment: A research framework. *J. Clean. Prod.* **2017**, *143*, 710–718. [CrossRef]
6. Azua, G.; González, M.; Arroyo, P.; Kurama, Y. Recycled coarse aggregates from precast plant and building demolitions: Environmental and economic modeling through stochastic simulations. *J. Clean. Prod.* **2019**, *210*, 1425–1434. [CrossRef]
7. Akbar, A.; Liew, K.M. Assessing recycling potential of carbon fiber reinforced plastic waste in production of eco-efficient cement-based materials. *J. Clean. Prod.* **2020**, *274*, 123001. [CrossRef]
8. Del Vecchio, C.; Di Ludovico, M.; Balsamo, A.; Prota, A.; Cosenza, E. Experimental response and fiber-reinforced cement composites strengthening of real reinforced concrete columns with poor-quality concrete. *Struct. Concr.* **2019**, *20*, 1168–1181. [CrossRef]
9. Aghdasi, P.; Heid, A.E.; Chao, S.H. Developing ultra-high-performance fiber-reinforced concrete for large-scale structural applications. *ACI Mater. J.* **2016**, *113*, 559–569. [CrossRef]
10. Del Vecchio, C.; Di Ludovico, M.; Balsamo, A.; Prota, A. Seismic Retrofit of Real Beam-Column Joints Using Fiber-Reinforced Cement Composites. *J. Struct. Eng.* **2018**, *144*, 04018026. [CrossRef]
11. Nobili, A.; Lanzoni, L.; Tarantino, A.M. Experimental investigation and monitoring of a polypropylene-based fiber reinforced concrete road pavement. *Constr. Build. Mater.* **2013**, *47*, 888–895. [CrossRef]
12. Dagenais, M.-A.; Massicotte, B.; Boucher-Proulx, G. Seismic Retrofitting of Rectangular Bridge Piers with Deficient Lap Splices Using Ultrahigh-Performance Fiber-Reinforced Concrete. *J. Bridg. Eng.* **2018**, *23*, 04017129. [CrossRef]
13. Meda, A.; Rinaldi, Z.; Spagnuolo, S.; De Rivaz, B.; Giamundo, N. Hybrid precast tunnel segments in fiber reinforced concrete with glass fiber reinforced bars. *Tunn. Undergr. Sp. Technol.* **2019**, *86*, 100–112. [CrossRef]
14. Bailey, C. Holistic behaviour of concrete buildings in fire. *Proc. Inst. Civ. Eng. Struct. Build.* **2015**, *152*, 199–212. [CrossRef]
15. Li, Y.; Lu, X.; Guan, H.; Ying, M.; Yan, W. A Case Study on a Fire-Induced Collapse Accident of a Reinforced Concrete Frame-Supported Masonry Structure. *Fire Technol.* **2016**, *52*, 707–729. [CrossRef]
16. Hussain, H.K.; Abbas, A.M.; Ojaimi, M.F. Fiber-Type Influence on the Flexural Behavior of RC Two-Way Slabs with an Opening. *Buildings* **2022**, *12*, 279. [CrossRef]
17. Akbar, A.; Liew, K.M. Influence of elevated temperature on the microstructure and mechanical performance of cement composites reinforced with recycled carbon fibers. *Compos. Part B Eng.* **2020**, *198*, 108245. [CrossRef]
18. Zhou, Z.; Xie, R.; Qiao, P.; Lu, L. On the modeling of tensile behavior of ultra-high performance fiber-reinforced concrete with freezing-thawing actions. *Compos. Part B Eng.* **2019**, *174*, 106983. [CrossRef]
19. Ramesh, R.B.; Mirza, O.; Kang, W.H. Mechanical properties of steel fiber reinforced recycled aggregate concrete. *Struct. Concr.* **2019**, *20*, 745–755. [CrossRef]
20. Ahmed, W.; Lim, C.W. Coupling effect assessment of vacuum based pozzolana slurry encrusted recycled aggregate and basalt fiber on mechanical performance of fiber reinforced concrete. *Constr. Build. Mater.* **2021**, *300*, 124032. [CrossRef]
21. Das, C.S.; Dey, T.; Dandapat, R.; Mukharjee, B.B.; Kumar, J. Performance evaluation of polypropylene fibre reinforced recycled aggregate concrete. *Constr. Build. Mater.* **2018**, *189*, 649–659. [CrossRef]
22. Kachouh, N.; El-Maaddawy, T.; El-Hassan, H.; El-Ariss, B. Shear Behavior of Steel-Fiber-Reinforced Recycled Aggregate Concrete Deep Beams. *Buildings* **2021**, *11*, 423. [CrossRef]
23. Hanumesh, B.; Harish, B.; Venkata Ramana, N. Influence of polypropylene fibres on recycled aggregate concrete. *Mater. Today Proc.* **2018**, *5*, 1147–1155. [CrossRef]
24. Muhammad; Saleem, M.A.; Kazmi, S.M.S.; Munir, M.J. Experimental study of fibre-reinforced interlocking mud bricks under compressive test. *Proc. Inst. Civ. Eng.Constr. Mater.* **2018**, *173*, 181–189. [CrossRef]
25. Dong, J.F.; Wang, Q.Y.; Guan, Z.W. Material properties of basalt fibre reinforced concrete made with recycled earthquake waste. *Constr. Build. Mater.* **2017**, *130*, 241–251. [CrossRef]
26. Nitesh, K.J.N.S.; Rao, S.V.; Kumar, P.R. An experimental investigation on torsional behaviour of recycled aggregate based steel fiber reinforced self compacting concrete. *J. Build. Eng.* **2019**, *22*, 242–251. [CrossRef]
27. Gao, D.; Zhang, L. Flexural performance and evaluation method of steel fiber reinforced recycled coarse aggregate concrete. *Constr. Build. Mater.* **2018**, *159*, 126–136. [CrossRef]
28. Katkhuda, H.; Shatarat, N. Improving the mechanical properties of recycled concrete aggregate using chopped basalt fibers and acid treatment. *Constr. Build. Mater.* **2017**, *140*, 328–335. [CrossRef]
29. Liew, K.M.; Akbar, A. The recent progress of recycled steel fiber reinforced concrete. *Constr. Build. Mater.* **2020**, *232*, 117232. [CrossRef]
30. Guo, Y.C.; Zhang, J.H.; Chen, G.; Chen, G.M.; Xie, Z.H. Fracture behaviors of a new steel fiber reinforced recycled aggregate concrete with crumb rubber. *Constr. Build. Mater.* **2014**, *53*, 32–39. [CrossRef]
31. Xu, F.; Wang, S.; Li, T.; Liu, B.; Li, B.; Zhou, Y. Mechanical properties and pore structure of recycled aggregate concrete made with iron ore tailings and polypropylene fibers. *J. Build. Eng.* **2021**, *33*, 101572. [CrossRef]

32. Guo, Y.C.; Zhang, J.H.; Chen, G.M.; Xie, Z.H. Compressive behaviour of concrete structures incorporating recycled concrete aggregates, rubber crumb and reinforced with steel fibre, subjected to elevated temperatures. *J. Clean. Prod.* **2014**, *72*, 193–203. [CrossRef]
33. Rasoul, Z.M.R.A.; Radhi, M.S.; Alsaad, A.J. Case Studies in Thermal Engineering Elevated temperature performance of reinforced concrete beams containing waste polypropylene fibers. *Case Stud. Therm. Eng.* **2020**, *21*, 100705. [CrossRef]
34. Karimipour, A.; Rakhshanimehr, M.; Ghalehnovi, M.; de Brito, J. Effect of different fibre types on the structural performance of recycled aggregate concrete beams with spliced bars. *J. Build. Eng.* **2021**, *38*, 102090. [CrossRef]
35. Chen, G.M.; Yang, H.; Lin, C.J.; Chen, J.F.; He, Y.H.; Zhang, H.Z. Fracture behaviour of steel fibre reinforced recycled aggregate concrete after exposure to elevated temperatures. *Constr. Build. Mater.* **2016**, *128*, 272–286. [CrossRef]
36. Obaidat, Y.T.; Barham, W.S.; Abdelrahman, B.N. Effect of elevated temperature on the bond behavior between near Surface Mounted-Carbon Fiber Reinforced Polymers strips and Recycled Aggregate concrete. *Constr. Build. Mater.* **2020**, *251*, 118970. [CrossRef]
37. Yonggui, W.; Shuaipeng, L.; Hughes, P.; Yuhui, F. Mechanical properties and microstructure of basalt fibre and nano-silica reinforced recycled concrete after exposure to elevated temperatures. *Constr. Build. Mater.* **2020**, *247*, 118561. [CrossRef]
38. Zegardło, B.; Szeląg, M.; Ogrodnik, P. Concrete resistant to spalling made with recycled aggregate from sanitary ceramic wastes—The effect of moisture and porosity on destructive processes occurring in fire conditions. *Constr. Build. Mater.* **2018**, *173*, 58–68. [CrossRef]
39. Homoro, O.; Vu, X.H.; Ferrier, E. Experimental and analytical study of the thermo-mechanical behaviour of textile-reinforced concrete (TRC) at elevated temperatures: Role of discontinuous short glass fibres. *Constr. Build. Mater.* **2018**, *190*, 645–663. [CrossRef]
40. Wu, H.; Lin, X.; Zhou, A. A review of mechanical properties of fibre reinforced concrete at elevated temperatures. *Cem. Concr. Res.* **2020**, *135*, 106117. [CrossRef]
41. Cree, D.; Green, M.; Noumowé, A. Residual strength of concrete containing recycled materials after exposure to fire: A review. *Constr. Build. Mater.* **2013**, *45*, 208–223. [CrossRef]
42. Salahuddin, H.; Nawaz, A.; Maqsoom, A.; Mehmood, T.; Zeeshan, B.u.A. Effects of elevated temperature on performance of recycled coarse aggregate concrete. *Constr. Build. Mater.* **2019**, *202*, 415–425. [CrossRef]
43. Xie, J.; Huang, L.; Guo, Y.; Li, Z.; Fang, C.; Li, L.; Wang, J. Experimental study on the compressive and flexural behaviour of recycled aggregate concrete modified with silica fume and fibres. *Constr. Build. Mater.* **2018**, *178*, 612–623. [CrossRef]
44. Jang, H.-S.; So, H.-S.; So, S. The properties of reactive powder concrete using PP fiber and pozzolanic materials at elevated temperature. *J. Build. Eng.* **2016**, *8*, 225–230. [CrossRef]
45. Koushkbaghi, M.; Kazemi, M.J.; Mosavi, H.; Mohseni, E. Acid resistance and durability properties of steel fiber-reinforced concrete incorporating rice husk ash and recycled aggregate. *Constr. Build. Mater.* **2019**, *202*, 266–275. [CrossRef]
46. Poon, C.S.; Shui, Z.H.; Lam, L. Compressive behavior of fiber reinforced high-performance concrete subjected to elevated temperatures. *Cem. Concr. Res.* **2004**, *34*, 2215–2222. [CrossRef]
47. Choe, G.; Kim, G.; Yoon, M.; Hwang, E.; Nam, J.; Guncunski, N. Effect of moisture migration and water vapor pressure build-up with the heating rate on concrete spalling type. *Cem. Concr. Res.* **2019**, *116*, 1–10. [CrossRef]
48. Al Qadi, A.N.S.; Al-Zaidyeen, S.M. Effect of fibre content and specimen shape on residual strength of polypropylene fibre self-compacting concrete exposed to elevated temperatures. *J. King Saud Univ. Eng. Sci.* **2014**, *26*, 33–39. [CrossRef]
49. Ahmed, T.W.; Ali, A.A.M.; Zidan, R.S. Properties of high strength polypropylene fiber concrete containing recycled aggregate. *Constr. Build. Mater.* **2020**, *241*, 118010. [CrossRef]
50. Chen, G.M.; He, Y.H.; Yang, H.; Chen, J.F.; Guo, Y.C. Compressive behavior of steel fiber reinforced recycled aggregate concrete after exposure to elevated temperatures. *Constr. Build. Mater.* **2014**, *71*, 1–15. [CrossRef]
51. Aslani, F.; Kelin, J. Assessment and development of high-performance fibre-reinforced lightweight self-compacting concrete including recycled crumb rubber aggregates exposed to elevated temperatures. *J. Clean. Prod.* **2018**, *200*, 1009–1025. [CrossRef]
52. Mehdipour, S.; Nikbin, I.M.; Dezhampanah, S.; Mohebbi, R.; Moghadam, H.H.; Charkhtab, S.; Moradi, A. Mechanical properties, durability and environmental evaluation of rubberized concrete incorporating steel fiber and metakaolin at elevated temperatures. *J. Clean. Prod.* **2020**, *254*, 120126. [CrossRef]
53. Wang, J.; Du, B. Experimental studies of thermal and acoustic properties of recycled aggregate crumb rubber concrete. *J. Build. Eng.* **2020**, *32*, 101836. [CrossRef]
54. Baloch, W.L.; Khushnood, R.A.; Memon, S.A.; Ahmed, W.; Ahmad, S. Effect of Elevated Temperatures on Mechanical Performance of Normal and Lightweight Concretes Reinforced with Carbon Nanotubes. *Fire Technol.* **2018**, *54*, 1331–1367. [CrossRef]
55. Sancak, E.; Sari, Y.D.; Simsek, O. Effects of elevated temperature on compressive strength and weight loss of the light-weight concrete with silica fume and superplasticizer. *Cem. Concr. Compos.* **2008**, *30*, 715–721. [CrossRef]
56. Junak, J.; Sicakova, A. Effect of Surface Modifications of Recycled Concrete Aggregate on Concrete Properties. *Buildings* **2017**, *8*, 2. [CrossRef]
57. Abed, M.; de Brito, J. Evaluation of high-performance self-compacting concrete using alternative materials and exposed to elevated temperatures by non-destructive testing. *J. Build. Eng.* **2020**, *32*, 101720. [CrossRef]
58. Velardo, P.; Sáez del Bosque, I.F.; Matías, A.; Sánchez de Rojas, M.I.; Medina, C. Properties of concretes bearing mixed recycled aggregate with polymer-modified surfaces. *J. Build. Eng.* **2021**, *38*, 102211. [CrossRef]

59. Gales, J.; Parker, T.; Cree, D.; Green, M. Fire Performance of Sustainable Recycled Concrete Aggregates: Mechanical Properties at Elevated Temperatures and Current Research Needs. *Fire Technol.* **2016**, *52*, 817–845. [CrossRef]
60. Zhao, H.; Liu, F.; Yang, H. Residual compressive response of concrete produced with both coarse and fine recycled concrete aggregates after thermal exposure. *Constr. Build. Mater.* **2020**, *244*, 118397. [CrossRef]
61. Demirel, B.; Keleştemur, O. Effect of elevated temperature on the mechanical properties of concrete produced with finely ground pumice and silica fume. *Fire Saf. J.* **2010**, *45*, 385–391. [CrossRef]
62. Memon, S.A.; Shah, S.F.A.; Khushnood, R.A.; Baloch, W.L. Durability of sustainable concrete subjected to elevated temperature—A review. *Constr. Build. Mater.* **2019**, *199*, 435–455. [CrossRef]
63. Zega, C.J.; Di Maio, A.A. Recycled concrete exposed to high temperatures. *Mag. Concr. Res.* **2006**, *58*, 675–682. [CrossRef]
64. Castellote, M.; Alonso, C.; Andrade, C.; Turrillas, X.; Campo, J. Composition and microstructural changes of cement pastes upon heating, as studied by neutron diffraction. *Cem. Concr. Res.* **2004**, *34*, 1633–1644. [CrossRef]
65. Schneider, U.; Diederichs, U.; Ehm, C. Effect of temperature on steel and concrete for PCRV's. *Nucl. Eng. Des.* **1982**, *67*, 245–258. [CrossRef]
66. Vieira, J.P.B.; Correia, J.R.; De Brito, J. Post-fire residual mechanical properties of concrete made with recycled concrete coarse aggregates. *Cem. Concr. Res.* **2011**, *41*, 533–541. [CrossRef]
67. Abedalqader, A.; Shatarat, N.; Ashteyat, A.; Katkhuda, H. Influence of temperature on mechanical properties of recycled asphalt pavement aggregate and recycled coarse aggregate concrete. *Constr. Build. Mater.* **2021**, *269*, 121285. [CrossRef]
68. Pliya, P.; Hajiloo, H.; Romagnosi, S.; Cree, D.; Sarhat, S.; Green, M.F. The compressive behaviour of natural and recycled aggregate concrete during and after exposure to elevated temperatures. *J. Build. Eng.* **2021**, *38*, 102214. [CrossRef]
69. Li, B.; Zhang, Y.; Selyutina, N.; Smirnov, I.; Deng, K.; Liu, Y.; Miao, Y. Thermally-induced mechanical degradation analysis of recycled aggregate concrete mixed with glazed hollow beads. *Constr. Build. Mater.* **2021**, *301*, 124350. [CrossRef]
70. Pliya, P.; Cree, D.; Hajiloo, H.; Beaucour, A.L.; Green, M.F.; Noumowé, A. High-Strength Concrete Containing Recycled Coarse Aggregate Subjected to Elevated Temperatures. *Fire Technol.* **2019**, *55*, 1477–1494. [CrossRef]
71. Fernandes, B.; Carré, H.; Mindeguia, J.C.; Perlot, C.; La Borderie, C. Effect of elevated temperatures on concrete made with recycled concrete aggregates—An overview. *J. Build. Eng.* **2021**, *44*, 103235. [CrossRef]
72. Laneyrie, C.; Beaucour, A.L.; Green, M.F.; Hebert, R.L.; Ledesert, B.; Noumowe, A. Influence of recycled coarse aggregates on normal and high performance concrete subjected to elevated temperatures. *Constr. Build. Mater.* **2016**, *111*, 368–378. [CrossRef]
73. Zhu, Q.; Yuan, Y.-X.; Chen, J.-H.; Fan, L.; Yang, H. Research on the high-temperature resistance of recycled aggregate concrete with iron tailing sand. *Constr. Build. Mater.* **2022**, *327*, 126889. [CrossRef]
74. Beatriz da Silva, J.; Pepe, M.; Toledo Filho, R.D. High temperatures effect on mechanical and physical performance of normal and high strength recycled aggregate concrete. *Fire Saf. J.* **2020**, *117*, 103222. [CrossRef]
75. Sarhat, S.R.; Sherwood, E.G. Residual mechanical response of recycled aggregate concrete after exposure to elevated temperatures. *J. Mater. Civ. Eng.* **2013**, *25*, 1721–1730. [CrossRef]
76. Zega, C.J.; Di Maio, A.A. Recycled concrete made with different natural coarse aggregates exposed to high temperature. *Constr. Build. Mater.* **2009**, *23*, 2047–2052. [CrossRef]
77. Xiao, J.Z.; Zhang, C.Z. Fire Damage and Residual Strengths of Recycled Aggregate Concrete. *Key Eng. Mater.* **2007**, *348–349*, 937–940. [CrossRef]
78. Saberian, M.; Shi, L.; Sidiq, A.; Li, J.; Setunge, S.; Li, C.Q. Recycled concrete aggregate mixed with crumb rubber under elevated temperature. *Constr. Build. Mater.* **2019**, *222*, 119–129. [CrossRef]
79. Kou, S.C.; Poon, C.S.; Etxeberria, M. Residue strength, water absorption and pore size distributions of recycled aggregate concrete after exposure to elevated temperatures. *Cem. Concr. Compos.* **2014**, *53*, 73–82. [CrossRef]
80. Bravo, M.; De Brito, J.; Pontes, J.; Evangelista, L. Mechanical performance of concrete made with aggregates from construction and demolition waste recycling plants. *J. Clean. Prod.* **2015**, *99*, 59–74. [CrossRef]
81. Poon, C.S.; Kou, S.C.; Lam, L. Use of recycled aggregates in molded concrete bricks and blocks. *Constr. Build. Mater.* **2002**, *16*, 281–289. [CrossRef]
82. Maier, M.; Zeiml, M.; Lackner, R. On the effect of pore-space properties and water saturation on explosive spalling of fire-loaded concrete. *Constr. Build. Mater.* **2020**, *231*, 117150. [CrossRef]
83. Yang, H.; Lv, L.; Deng, Z.; Lan, W. Residual compressive stress-strain relation of recycled aggregate concrete after exposure to high temperatures. *Struct. Concr.* **2017**, *18*, 479–486. [CrossRef]
84. Shaikh, F.U.A. Mechanical properties of concrete containing recycled coarse aggregate at and after exposure to elevated temperatures. *Struct. Concr.* **2018**, *19*, 400–410. [CrossRef]
85. Senaratne, S.; Gerace, D.; Mirza, O.; Tam, V.W.Y.; Kang, W. The costs and benefits of combining recycled aggregate with steel fibres as a sustainable, structural material. *J. Clean. Prod.* **2016**, *112*, 2318–2327. [CrossRef]
86. Erdem, S.; Dawson, A.R.; Thom, N.H. Microstructure-linked strength properties and impact response of conventional and recycled concrete reinforced with steel and synthetic macro fibres. *Constr. Build. Mater.* **2011**, *25*, 4025–4036. [CrossRef]
87. Chaboki, H.R.; Ghalehnovi, M.; Karimipour, A.; de Brito, J.; Khatibinia, M. Shear behaviour of concrete beams with recycled aggregate and steel fibres. *Constr. Build. Mater.* **2019**, *204*, 809–827. [CrossRef]
88. Lau, A.; Anson, M. Effect of high temperatures on high performance steel fibre reinforced concrete. *Cem. Concr. Res.* **2006**, *36*, 1698–1707. [CrossRef]

89. Kazemi, M.; Hajforoush, M.; Talebi, P.K.; Daneshfar, M.; Shokrgozar, A.; Jahandari, S.; Saberian, M.; Li, J. In-situ strength estimation of polypropylene fibre reinforced recycled aggregate concrete using Schmidt rebound hammer and point load test. *J. Sustain. Cem. Mater.* **2020**, *9*, 289–306. [CrossRef]
90. Akbar, A.; Farooq, F.; Shafique, M.; Aslam, F.; Alyousef, R.; Alabduljabbar, H. Sugarcane bagasse ash-based engineered geopolymer mortar incorporating propylene fibers. *J. Build. Eng.* **2021**, *33*, 101492. [CrossRef]
91. Liu, H.; Yang, J.; Wang, X. Bond behavior between BFRP bar and recycled aggregate concrete reinforced with basalt fiber. *Constr. Build. Mater.* **2017**, *135*, 477–483. [CrossRef]
92. Xianggang, Z.; Junna, Y.; Fang, W.; Jianhui, Y. Experimental study on deformation performance of basalt fiber-reinforced recycled aggregate concrete. *J. Eng. Sci. Technol. Rev.* **2018**, *11*, 138–145. [CrossRef]
93. Borhan, T.M. Properties of glass concrete reinforced with short basalt fibre. *Mater. Des.* **2012**, *42*, 265–271. [CrossRef]
94. Akbar, A.; Liew, K.M. Multicriteria performance evaluation of fiber-reinforced cement composites: An environmental perspective. *Compos. Part B Eng.* **2021**, *218*, 108937. [CrossRef]
95. Mastali, M.; Dalvand, A.; Sattarifard, A.R. The impact resistance and mechanical properties of reinforced self- compacting concrete with recycled glass fi bre reinforced polymers. *J. Clean. Prod.* **2016**, *124*, 312–324. [CrossRef]
96. Ali, B.; Qureshi, L.A.; Shah, S.H.A.; Rehman, S.U.; Hussain, I.; Iqbal, M. A step towards durable, ductile and sustainable concrete: Simultaneous incorporation of recycled aggregates, glass fiber and fly ash. *Constr. Build. Mater.* **2020**, *251*, 118980. [CrossRef]
97. Hassanzadeh-Aghdam, M.K.; Mahmoodi, M.J.; Safi, M. Effect of adding carbon nanotubes on the thermal conductivity of steel fiber-reinforced concrete. *Compos. Part B Eng.* **2019**, *174*, 106972. [CrossRef]
98. Khaliq, W.; Kodur, V. Thermal and mechanical properties of fiber reinforced high performance self-consolidating concrete at elevated temperatures. *Cem. Concr. Res.* **2011**, *41*, 1112–1122. [CrossRef]
99. Chen, B.; Liu, J. Residual strength of hybrid-fiber-reinforced high-strength concrete after exposure to high temperatures. *Cem. Concr. Res.* **2004**, *34*, 1065–1069. [CrossRef]
100. Akbar, A.; Kodur, V.K.R.; Liew, K.M. Microstructural changes and mechanical performance of cement composites reinforced with recycled carbon fibers. *Cem. Concr. Compos.* **2021**, *121*, 104069. [CrossRef]
101. Mirza, F.A.; Soroushian, P. Effects of alkali-resistant glass fiber reinforcement on crack and temperature resistance of lightweight concrete. *Cem. Concr. Compos.* **2002**, *24*, 223–227. [CrossRef]
102. Ma, C.; Shi, T.; Ma, H.; Yang, S.; Xu, Y.; Chen, P.; Wang, L. Dynamic Mechanical Properties of Slag Mortar with Alkali-Resistant Glass Fiber. *Buildings* **2022**, *12*, 266. [CrossRef]
103. Hassani Niaki, M.; Fereidoon, A.; Ghorbanzadeh Ahangari, M. Experimental study on the mechanical and thermal properties of basalt fiber and nanoclay reinforced polymer concrete. *Compos. Struct.* **2018**, *191*, 231–238. [CrossRef]
104. Dal Lago, B.; Taylor, S.E.; Deegan, P.; Ferrara, L.; Sonebi, M.; Crosset, P.; Pattarini, A. Full-scale testing and numerical analysis of a precast fibre reinforced self-compacting concrete slab pre-stressed with basalt fibre reinforced polymer bars. *Compos. Part B Eng.* **2017**, *128*, 120–133. [CrossRef]
105. Tan, Y.; Xu, Z.; Liu, Z.; Jiang, J. Effect of Silica Fume and Polyvinyl Alcohol Fiber on Mechanical Properties and Frost Resistance of Concrete. *Buildings* **2022**, *12*, 47. [CrossRef]
106. Sanchayan, S.; Foster, S.J. High temperature behaviour of hybrid steel–PVA fibre reinforced reactive powder concrete. *Mater. Struct. Constr.* **2016**, *49*, 769–782. [CrossRef]
107. Zheng, W.; Zhou, X.; Yan, Y. Effect of Stress-Strength Ratio and Fiber Length on Creep Property of Polypropylene Fiber-Reinforced Alkali-Activated Slag Concrete. *Buildings* **2022**, *12*, 91. [CrossRef]
108. Ozawa, M.; Subedi Parajuli, S.; Uchida, Y.; Zhou, B. Preventive effects of polypropylene and jute fibers on spalling of UHPC at high temperatures in combination with waste porous ceramic fine aggregate as an internal curing material. *Constr. Build. Mater.* **2019**, *206*, 219–225. [CrossRef]
109. Heo, Y.S.; Sanjayan, J.G.; Han, C.G.; Han, M.C. Critical parameters of nylon and other fibres for spalling protection of high strength concrete in fire. *Mater. Struct. Constr.* **2011**, *44*, 599–610. [CrossRef]
110. Heo, Y.S.; Sanjayan, J.G.; Han, C.G.; Han, M.C. Synergistic effect of combined fibers for spalling protection of concrete in fire. *Cem. Concr. Res.* **2010**, *40*, 1547–1554. [CrossRef]
111. Bu, C.; Zhu, D.; Liu, L.; Lu, X.; Sun, Y.; Yan, Z.; Yu, L.; Wei, Q. A Study on the Mechanical Properties and Microcosmic Mechanism of Basalt Fiber Modified Rubber Ceramsite Concrete. *Buildings* **2022**, *12*, 103. [CrossRef]
112. Ozawa, M.; Morimoto, H. Effects of various fibres on high-temperature spalling in high-performance concrete. *Constr. Build. Mater.* **2014**, *71*, 83–92. [CrossRef]
113. Yan, L.; Su, S.; Chouw, N. Microstructure, flexural properties and durability of coir fibre reinforced concrete beams externally strengthened with flax FRP composites. *Compos. Part B Eng.* **2015**, *80*, 343–354. [CrossRef]
114. Khan, E.U.; Khushnood, R.A.; Baloch, W.L. Spalling sensitivity and mechanical response of an ecofriendly sawdust high strength concrete at elevated temperatures. *Constr. Build. Mater.* **2020**, *258*, 119656. [CrossRef]
115. Ahmed, W.; Khushnood, R.A.; Memon, S.A.; Ahmad, S.; Baloch, W.L.; Usman, M. Effective use of sawdust for the production of eco-friendly and thermal-energy efficient normal weight and lightweight concretes with tailored fracture properties. *J. Clean. Prod.* **2018**, *184*, 1016–1027. [CrossRef]
116. Khatib, M.; Baydoun, J.; Elkordi, S.; Assaad, A.; Machaka, M.; Khatib, J.; Baydoun, S.; Elkordi, A.; Assaad, J.J. The Effect of Adding Phragmites australis Fibers on the Properties of Concrete. *Buildings* **2022**, *12*, 278. [CrossRef]

117. Demir, I.; Gümüş, M.; Gökçe, H.S. Gamma ray and neutron shielding characteristics of polypropylene fiber-reinforced heavyweight concrete exposed to high temperatures. *Constr. Build. Mater.* **2020**, *257*, 119596. [CrossRef]
118. Zhang, C.; Wang, Y.; Zhang, X.; Ding, Y.; Xu, P. Mechanical properties and microstructure of basalt fiber-reinforced recycled concrete. *J. Clean. Prod.* **2020**, *278*, 123252. [CrossRef]
119. Lei, B.; Li, W.; Liu, H.; Tang, Z.; Tam, V.W.Y. Synergistic Effects of Polypropylene and Glass Fiber on Mechanical Properties and Durability of Recycled Aggregate Concrete. *Int. J. Concr. Struct. Mater.* **2020**, *14*, 37. [CrossRef]
120. Mo, J.; Zeng, L.; Liu, Y.; Ma, L.; Liu, C.; Xiang, S.; Cheng, G. Mechanical properties and damping capacity of polypropylene fiber reinforced concrete modified by rubber powder. *Constr. Build. Mater.* **2020**, *242*, 118111. [CrossRef]
121. Afroughsabet, V.; Ozbakkaloglu, T. Mechanical and durability properties of high-strength concrete containing steel and polypropylene fibers. *Constr. Build. Mater.* **2015**, *94*, 73–82. [CrossRef]
122. Ghavami, K. Bamboo as reinforcement in structural concrete elements. *Cem. Concr. Compos.* **2005**, *27*, 637–649. [CrossRef]
123. Banthia, N.; Gupta, R. Influence of polypropylene fiber geometry on plastic shrinkage cracking in concrete. *Cem. Concr. Res.* **2006**, *36*, 1263–1267. [CrossRef]
124. Qian, C.X.; Stroeven, P. Development of hybrid polypropylene-steel fibre-reinforced concrete. *Cem. Concr. Res.* **2000**, *30*, 63–69. [CrossRef]
125. Abraham, C.B.; Nathan, V.B.; Jaipaul, S.R.; Nijesh, D.; Manoj, M.; Navaneeth, S. Basalt fibre reinforced aluminium matrix composites—A review. *Mater. Today Proc.* **2020**, *21*, 380–383. [CrossRef]
126. Jamshaid, H.; Mishra, R. A green material from rock: Basalt fiber—A review. *J. Text. Inst.* **2016**, *107*, 923–937. [CrossRef]
127. Raj, S.; Kumar, V.R.; Kumar, B.H.B.; Iyer, N.R. Basalt: Structural insight as a construction material. *Sadhana Acad. Proc. Eng. Sci.* **2017**, *42*, 75–84. [CrossRef]
128. Fu, C.; Ye, H.; Wang, K.; Zhu, K.; He, C. Evolution of mechanical properties of steel fiber-reinforced rubberized concrete (FR-RC). *Compos. Part B Eng.* **2019**, *160*, 158–166. [CrossRef]
129. Hesami, S.; Salehi Hikouei, I.; Emadi, S.A.A. Mechanical behavior of self-compacting concrete pavements incorporating recycled tire rubber crumb and reinforced with polypropylene fiber. *J. Clean. Prod.* **2016**, *133*, 228–234. [CrossRef]
130. Chen, A.; Han, X.; Chen, M.; Wang, X.; Wang, Z.; Guo, T. Mechanical and stress-strain behavior of basalt fiber reinforced rubberized recycled coarse aggregate concrete. *Constr. Build. Mater.* **2020**, *260*, 119888. [CrossRef]
131. Ahmed, W.; Baloch, W.L.; Khushnood, R.A. Fire performance of concrete containing nano-fibers and graphite nano-particles. In *Smart Nanoconcretes and Cement-Based Materials*; Elsevier: Amsterdam, The Netherlands, 2020; pp. 297–311. ISBN 9780128178546.
132. Ali, B.; Qureshi, L.A. Influence of glass fibers on mechanical and durability performance of concrete with recycled aggregates. *Constr. Build. Mater.* **2019**, *228*, 116783. [CrossRef]
133. Gao, D.; Zhang, L.; Nokken, M. Mechanical behavior of recycled coarse aggregate concrete reinforced with steel fibers under direct shear. *Cem. Concr. Compos.* **2017**, *79*, 1–8. [CrossRef]
134. Jalilifar, H.; Sajedi, F.; Kazemi, S. Investigation on the mechanical properties of fiber reinforced recycled concrete. *Civ. Eng. J.* **2016**, *2*, 13–22. [CrossRef]
135. Vaishali, G.G.; Rao, H.S. Strength and permeability characteristics of fiber reinforced high performance concrete with recycled aggregates. *Asian J. Civ. Eng.* **2012**, *13*, 55–78.
136. Akca, K.I.R.; Cakir, O.; Ipek, M. Properties of polypropylene fiber reinforced concrete using recycled aggregates. *Constr. Build. Mater.* **2015**, *98*, 620–630. [CrossRef]
137. Alnahhal, W.; Aljidda, O. Flexural behavior of basalt fiber reinforced concrete beams with recycled concrete coarse aggregates. *Constr. Build. Mater.* **2018**, *169*, 165–178. [CrossRef]
138. Ahmed, W.; Lim, C.W. Production of Sustainable and Structural Fiber Reinforced Recycled Aggregate Concrete with Improved Fracture Properties: A Review. *J. Clean. Prod.* **2020**, *279*, 123832. [CrossRef]
139. Xie, J.; Zhang, Z.; Lu, Z.; Sun, M. Coupling effects of silica fume and steel-fiber on the compressive behaviour of recycled aggregate concrete after exposure to elevated temperature. *Constr. Build. Mater.* **2018**, *184*, 752–764. [CrossRef]
140. Eidan, J.; Rasoolan, I.; Rezaeian, A.; Poorveis, D. Residual mechanical properties of polypropylene fiber-reinforced concrete after heating. *Constr. Build. Mater.* **2019**, *198*, 195–206. [CrossRef]
141. Bencardino, F.; Rizzuti, L.; Spadea, G.; Swamy, R.N. Experimental evaluation of fiber reinforced concrete fracture properties. *Compos. Part B Eng.* **2010**, *41*, 17–24. [CrossRef]
142. Ibrahm, H.A. Mechanical behavior of recycled self-compacting concrete reinforced with polypropylene fibres. *J. Archit. Eng. Technol.* **2017**, *6*, 207. [CrossRef]
143. Nguyen, H.T.N.; Li, Y.; Tan, K.H. Shear behavior of fiber-reinforced concrete hollow-core slabs under elevated temperatures. *Constr. Build. Mater.* **2021**, *275*, 121362. [CrossRef]
144. High, C.; Seliem, H.M.; El-Safty, A.; Rizkalla, S.H. Use of basalt fibers for concrete structures. *Constr. Build. Mater.* **2015**, *96*, 37–46. [CrossRef]
145. Jiang, C.; Fan, K.; Wu, F.; Chen, D. Experimental study on the mechanical properties and microstructure of chopped basalt fibre reinforced concrete. *Mater. Des.* **2014**, *58*, 187–193. [CrossRef]
146. Asprone, D.; Cadoni, E.; Iucolano, F.; Prota, A. Analysis of the strain-rate behavior of a basalt fiber reinforced natural hydraulic mortar. *Cem. Concr. Compos.* **2014**, *53*, 52–58. [CrossRef]
147. Kabay, N. Abrasion resistance and fracture energy of concretes with basalt fiber. *Constr. Build. Mater.* **2014**, *50*, 95–101. [CrossRef]

148. Dong, J.F.; Wang, Q.Y.; Guan, Z.W.; Chai, H.K. High-temperature behaviour of basalt fibre reinforced concrete made with recycled aggregates from earthquake waste. *J. Build. Eng.* **2022**, *48*, 103895. [CrossRef]
149. Serrano, R.; Cobo, A.; Prieto, M.I.; González, M. de las N. Analysis of fire resistance of concrete with polypropylene or steel fibers. *Constr. Build. Mater.* **2016**, *122*, 302–309. [CrossRef]
150. Carneiro, J.A.; Lima, P.R.L.; Leite, M.B.; Toledo Filho, R.D. Compressive stress-strain behavior of steel fiber reinforced-recycled aggregate concrete. *Cem. Concr. Compos.* **2014**, *46*, 65–72. [CrossRef]
151. Mohseni, E.; Saadati, R.; Kordbacheh, N.; Parpinchi, Z.S.; Tang, W. Engineering and microstructural assessment of fibre-reinforced self-compacting concrete containing recycled coarse aggregate. *J. Clean. Prod.* **2017**, *168*, 605–613. [CrossRef]
152. Wang, Y.; Hughes, P.; Niu, H.; Fan, Y. A new method to improve the properties of recycled aggregate concrete: Composite addition of basalt fiber and nano-silica. *J. Clean. Prod.* **2019**, *236*, 117602. [CrossRef]
153. Chandar, S.P.; Gunasekaran, K.; Sandeep, N.S.; Manikandaprabhu, S. An experimental investigation on strength properties of steel fibres along with recycled aggregate in cement concrete. *Rasayan J. Chem.* **2017**, *10*, 528–533. [CrossRef]
154. Kumar, D.N.; Rao, T.V. An experimental study of recycled concrete with polypropylene fiber. *Int. J. Innov. Res. Adv. Eng.* **2014**, *1*, 67–75.
155. Gao, D.; Yan, D.; Li, X. Splitting strength of GGBFS concrete incorporating with steel fiber and polypropylene fiber after exposure to elevated temperatures. *Fire Saf. J.* **2012**, *54*, 67–73. [CrossRef]
156. Li, Y.; Tan, K.H.; Yang, E.H. Influence of aggregate size and inclusion of polypropylene and steel fibers on the hot permeability of ultra-high performance concrete (UHPC) at elevated temperature. *Constr. Build. Mater.* **2018**, *169*, 629–637. [CrossRef]
157. Noumowe, A. Mechanical properties and microstructure of high strength concrete containing polypropylene fibres exposed to temperatures up to 200 °C. *Cem. Concr. Res.* **2005**, *35*, 2192–2198. [CrossRef]
158. Zhang, P.; Kang, L.; Wang, J.; Guo, J.; Hu, S.; Ling, Y. Mechanical Properties and Explosive Spalling Behavior of Steel-Fiber-Reinforced Concrete Exposed to High Temperature—A Review. *Appl. Sci.* **2020**, *10*, 2324. [CrossRef]
159. Pliya, P.; Beaucour, A.L.; Noumowé, A. Contribution of cocktail of polypropylene and steel fibres in improving the behaviour of high strength concrete subjected to high temperature. *Constr. Build. Mater.* **2011**, *25*, 1926–1934. [CrossRef]
160. Heo, Y.S.; Sanjayan, J.G.; Han, C.G.; Han, M.C. Relationship between inter-aggregate spacing and the optimum fiber length for spalling protection of concrete in fire. *Cem. Concr. Res.* **2012**, *42*, 549–557. [CrossRef]
161. Zhang, D.; Dasari, A.; Tan, K.H. On the mechanism of prevention of explosive spalling in ultra-high performance concrete with polymer fibers. *Cem. Concr. Res.* **2018**, *113*, 169–177. [CrossRef]
162. Mahapatra, C.K.; Barai, S.V. Temperature impact on residual properties of self-compacting based hybrid fiber reinforced concrete with fly ash and colloidal nano silica. *Constr. Build. Mater.* **2019**, *198*, 120–132. [CrossRef]
163. Bangi, M.R.; Horiguchi, T. Pore pressure development in hybrid fibre-reinforced high strength concrete at elevated temperatures. *Cem. Concr. Res.* **2011**, *41*, 1150–1156. [CrossRef]
164. Yermak, N.; Pliya, P.; Beaucour, A.L.; Simon, A.; Noumowé, A. Influence of steel and/or polypropylene fibres on the behaviour of concrete at high temperature: Spalling, transfer and mechanical properties. *Constr. Build. Mater.* **2017**, *132*, 240–250. [CrossRef]
165. Sideris, K.K.; Manita, P.; Chaniotakis, E. Performance of thermally damaged fibre reinforced concretes. *Constr. Build. Mater.* **2009**, *23*, 1232–1239. [CrossRef]
166. Bilodeau, A.; Kodur, V.K.R.; Hoff, G.C. Optimization of the type and amount of polypropylene fibres for preventing the spalling of lightweight concrete subjected to hydrocarbon fire. *Cem. Concr. Compos.* **2004**, *26*, 163–174. [CrossRef]
167. Han, C.G.; Hwang, Y.S.; Yang, S.H.; Gowripalan, N. Performance of spalling resistance of high performance concrete with polypropylene fiber contents and lateral confinement. *Cem. Concr. Res.* **2005**, *35*, 1747–1753. [CrossRef]
168. Novak, J.; Kohoutkova, A. Mechanical properties of concrete composites subject to elevated temperature. *Fire Saf. J.* **2018**, *95*, 66–76. [CrossRef]
169. Mohammadhosseini, H.; Alyousef, R.; Abdul Shukor Lim, N.H.; Tahir, M.M.; Alabduljabbar, H.; Mohamed, A.M. Creep and drying shrinkage performance of concrete composite comprising waste polypropylene carpet fibres and palm oil fuel ash. *J. Build. Eng.* **2020**, *30*, 101250. [CrossRef]
170. Alaskar, A.; Albidah, A.; Alqarni, A.S.; Alyousef, R.; Mohammadhosseini, H. Performance evaluation of high-strength concrete reinforced with basalt fibers exposed to elevated temperatures. *J. Build. Eng.* **2021**, *35*, 102108. [CrossRef]
171. Li, Y.; Tan, K.H.; Yang, E.H. Synergistic effects of hybrid polypropylene and steel fibers on explosive spalling prevention of ultra-high performance concrete at elevated temperature. *Cem. Concr. Compos.* **2019**, *96*, 174–181. [CrossRef]
172. Kalifa, P.; Chéné, G.; Gallé, C. High-temperature behaviour of HPC with polypropylene fibres. *Cem. Concr. Res.* **2001**, *31*, 1487–1499. [CrossRef]
173. Khan, M.; Cao, M.; Chaopeng, X.; Ali, M. Experimental and analytical study of hybrid fiber reinforced concrete prepared with basalt fiber under high temperature. *Fire Mater.* **2021**, *46*, 205–226. [CrossRef]
174. Deshpande, A.A.; Kumar, D.; Ranade, R. Influence of high temperatures on the residual mechanical properties of a hybrid fiber-reinforced strain-hardening cementitious composite. *Constr. Build. Mater.* **2019**, *208*, 283–295. [CrossRef]
175. Booya, E.; Gorospe, K.; Ghaednia, H.; Das, S. Durability properties of engineered pulp fibre reinforced concretes made with and without supplementary cementitious materials. *Compos. Part B Eng.* **2019**, *172*, 376–386. [CrossRef]
176. Abdi Moghadam, M.; Izadifard, R.A. Effects of steel and glass fibers on mechanical and durability properties of concrete exposed to high temperatures. *Fire Saf. J.* **2020**, *113*, 102978. [CrossRef]

177. Afroz, M.; Patnaikuni, I.; Venkatesan, S. Chemical durability and performance of modified basalt fiber in concrete medium. *Constr. Build. Mater.* **2017**, *154*, 191–203. [CrossRef]
178. Zeiml, M.; Leithner, D.; Lackner, R.; Mang, H.A. How do polypropylene fibers improve the spalling behavior of in-situ concrete? *Cem. Concr. Res.* **2006**, *36*, 929–942. [CrossRef]
179. Bošnjak, J.; Ožbolt, J.; Hahn, R. Permeability measurement on high strength concrete without and with polypropylene fibers at elevated temperatures using a new test setup. *Cem. Concr. Res.* **2013**, *53*, 104–111. [CrossRef]