Article

Residual Mechanical Properties of Fiber-Reinforced Lightweight Aggregate Concrete after Exposure to Elevated Temperatures

Chao-Wei Tang ^{1,2,3}

¹ Department of Civil Engineering & Geomatics, Cheng Shiu University, No. 840, Chengching Rd., Niasong District, Kaohsiung 83347, Taiwan; tangcw@gcloud.csu.edu.tw; Tel.: +886-7-735-8800

² Center for Environmental Toxin and Emerging-Contaminant Research, Cheng Shiu University, No. 840, Chengching Rd., Niasong District, Kaohsiung 83347, Taiwan

³ Super Micro Mass Research & Technology Center, Cheng Shiu University, No. 840, Chengching Rd., Niasong District, Kaohsiung 83347, Taiwan

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Abstract: In this study, the effects of individual and mixed fiber on the mechanical properties of lightweight aggregate concrete (LWC) after exposure to elevated temperatures were examined. Concrete specimens were divided into a control group (ordinary LWC) and an experimental group (fiber-reinforced LWC), and their compressive strength, elastic modulus, and flexural strength after heating to high temperatures of 400–800 °C were investigated. The four test parameters included concrete type, concrete strength, fiber type, and targeted temperature. The test results show that after exposure to 400–800 °C, the variation in mechanical properties of each group of LWC showed a trend of increasing first and then decreasing. After exposure to 400 °C, the residual mechanical properties of all specimens did not attenuate due to the drying effect of the high temperature and the more sufficient cement hydration reaction. However, after exposure to 800 °C, the residual mechanical properties significantly reduced. Overall, the mixed fiber-reinforced LWC showed a better ability to resist the loss of mechanical properties caused by high temperature. Compared with the loss of compressive strength, the flexural strength was relatively lost.

Keywords: fiber-reinforced lightweight aggregate concrete; residual mechanical properties; elevated temperatures

1. Introduction

Aggregates used in cement concrete are generally classified into three categories: light-, normal-, and heavy-weight. Lightweight aggregate (LWA) is a general term for natural or artificial aggregates with a bulk density less than 1200 kg/m³ [1]. Due to the increasing demand for LWAs and the unavailability of natural LWAs worldwide, techniques have been developed to produce them in modern factories [2]. LWA can be used to produce lightweight aggregate concrete (LWC) [1,2], which has a lower unit weight and can significantly reduce the cross-section of load-bearing members, thereby reducing the size of the foundation and making it more suitable for structural engineering [2,3]. Compared with normal weight aggregate concrete (NWC), LWC has practical advantages, such as good seismic performance, fire resistance, and durability [2]. Therefore, in recent years, LWC has become an important structural material, and the demand for it is increasing [1,2]. However, LWC generally has higher brittleness and lower mechanical properties than NWC with the same compressive strength [4,5]. Many studies showed that the use of fibers in LWC is a solution to resolving these problems [6–8]. In fiber-reinforced concretes, the fiber acts as a crack arrester that can dissipate the local internal stress and cut off the cracks caused by the internal stress and the propagation path of the original

crack to prevent plastic dry shrinkage cracks in the initial solidification of concrete. The addition of fibers to LWC can improve its mechanical properties and significantly increase its toughness, ductility performance, and energy absorption, while decreasing its workability [5,9,10].

High temperatures cause the deterioration of concrete materials, which is a special failure type of concrete structures and considerably impacts on the overall safety of the structure. Thermal degradation of concrete mechanical properties is critical in assessing the fire resistance and post-fire capacity of reinforced concrete structures. Once concrete is exposed to fire and high temperature, the microstructure and properties of the cement hydration product change with temperature, which directly or indirectly destroys the macroscopic properties of the matrix, thereby affecting the overall behavior of the concrete at high temperatures [11]. When the firing temperature reaches 200 °C or above, the decomposition of cement hydrate and the destruction of aggregates gradually occur in the concrete. The difference in thermal deformation between the cement matrix and the aggregate leads to stress concentration, which causes the concrete strength to decline significantly, and the degree of strength reduction mainly depends on the characteristics of the aggregate and the temperature to which the concrete is subjected [8]. Especially in environments where the temperature rises rapidly, high strength concrete (HSC) is more susceptible to explosive spalling due to the combined effect of pore pressure and thermal stress caused by temperature gradients during heating [12,13]. The structural integrity of a reinforced concrete structure is severely damaged. Therefore, the spalling behavior of HSC at high temperatures has attracted the interest of many researchers [14–21]. With fiber concrete, the thermal interface between the fiber and the concrete matrix can lead to thermal cracking at high temperatures. Xiong and Liew's research [14] pointed out that even if the added amount is 1.0% (volume), steel fiber cannot effectively prevent the spalling of ultra-high performance concrete. It was found that polypropylene fibers with a dosage of 0.1% can be effective at temperatures up to 800 °C because the polypropylene fibers melted and then left voids to release steam. Seitllari and Naser [17], through a comprehensive data-driven inspection of actual fire tests, proved that artificial intelligence technology can provide an attractive tool capable of predicting fire-induced spalling phenomenon with high precision. Chen and Liu [19] studied the residual strength of HSC after exposure to high temperatures. The test results showed that HSC is prone to exploding after exposure to high temperatures, and the first spalling occurred when the temperature was close to 400 °C. For HSC doped with high melting point fibers, the first spalling occurred when the temperature reached about 800 °C; the HSC with low melting point polypropylene (PP) fibers did not explode when exposed to high temperatures. The properties of HSC mixed with a high melting point fiber (carbon or steel fiber) and a low melting point fiber (polypropylene fiber) can be considerably improved after exposure to high temperature. Zhang et al. [20] reviewed the mechanical properties of steel fiber-reinforced concrete (SFRC) subjected to high temperature, including its residual compressive strength, flexural strength, tensile strength, elasticity, fracture characteristics, and stress–strain relationship. The residual mechanical properties of the SFRC and the mechanism of action of steel fibers were reviewed in detail. The results showed that, in general, SFRC exhibited better residual mechanical properties than plain concrete when exposed to high temperatures and can more effectively prevent the risk of explosive spalling. Kodur and Dwaikat [21] confirmed that concrete spalling is directly related to its permeability and has an adverse effect on the fire resistance of RC beams. Due to spalling caused by fire in concrete, the fire resistance of HSC beams with extremely low permeability can be significantly reduced by more than 50%.

Many researchers [3–5,9,10,17,22–32] studied the residual mechanical properties of LWC at room temperature after exposure to high temperatures because, to some extent, they represent conditions present after a fire event. Compared with ordinary aggregates, LWA has a larger porosity, so its water absorption is relatively higher. Jiang et al. [26] found that under normal circumstances, when the moisture content of NWC is less than 75%, spalling caused by high temperature does not occur. However, when the moisture content of the LWC is higher than 25%, spalling at high temperatures may occur. This shows that LWC spalling at high temperatures is much more sensitive to moisture than NWC. In practice, to minimize the water absorption of LWA and its effect on the workability

and subsequent setting and hardening of the concrete produced, LWA is usually pre-saturated before mixing. However, this treatment allows excess water to enter the concrete to increase its moisture content, thereby increasing the possibility of spalling at high temperatures. To improve the spalling resistance of LWC at high temperatures, He et al. [27] used two types of modified materials to modify the LWA using surface coating modifications. During the temperature increase, the spalling behavior of concrete samples formed with modified aggregates was observed. Their test results showed that the modified concrete specimen remained intact at 1200 °C, and retained about 25% to 38% of the residual compressive strength at this temperature. Huang et al. [31] investigated the mechanical behavior and microstructure of a new type of ultra-lightweight cement composite (ULCC), which used cenospheres as the LWA and was exposed to high temperatures up to 900 °C. To prevent the spalling of ULCC material at high temperatures, synthetic fibers were used, with different contents of polypropylene fiber, steel fiber, mixed fiber, and fly ash instead of cement. ULCC containing a small amount of PP fiber was found to improve the fire resistance of ULCC and eliminate the explosive spalling behavior of ULCC for temperatures up to 900 °C. After high temperature exposure, hybrid fibers improve concrete fire resistance and ductility. However, the effects of polypropylene fibers on the mechanical degradation of various fiber-reinforced LWCs are not fully understood. Due to the large variation in LWC composition, mix design, testing apparatus, and experimental protocols, the rate of degradation of LWC mechanical properties with temperature varies widely.

As such, a series of experiments were conducted in this study to investigate the residual mechanical properties of various fiber-reinforced LWCs after exposure to high temperatures to further understand the efficacy of individual and mixed fiber in fire resistance of LWC.

2. Experimental Procedure

2.1. Experimental Programs

Test variables included concrete type (control group: ordinary LWC; experimental group: fiber reinforced LWC), concrete strength (30 and 50 MPa), fiber type (steel fiber and polypropylene fiber), and targeted temperature (400, 600, and 800 °C). The bottom range of strength of various concrete varies with time and geographical location [33–35]. In the study, medium-strength concrete is tentatively defined as the concrete having the strength of 40–60 MPa, while low-strength is defined as the concrete having the strength of less than 40 MPa. The details of each experimental variable are shown in Table 1. The percentage of steel fibers in the literature is generally 0.25%–1.5% of the volume fraction of concrete. Most studies showed that when the steel fiber content is 1%, the effect is more significant [20]. To enable comparison, the percentage of steel fiber in this study was 1%. Polypropylene fiber is very fine and its specific surface area is large, which leads to an increase in the viscosity of concrete and a decrease in workability [14]. Therefore, the amount of polypropylene fiber was only 0.1% (volume percentage). For all investigated concrete mixtures, the specimens were tested in ambient temperature conditions as well as in residual conditions after exposure to a predetermined elevated temperature and cooling to room temperature. As for the thermal degradation of concrete's mechanical properties, the following properties were investigated: compressive strength, stress versus strain curve, elastic modulus, flexural strength, and load–deflection curve.

Table 1. Planning of experimental variables.

Group	Mix No.	Specified Concrete Strength (MPa)	Fiber Content (Volume %)	Targeted Temperature (°C)
Control group	C30	30	0	400, 600, and 800
	C50	50	0	400, 600, and 800
Experimental group	E30-S	30	Steel fiber (1%)	400, 600, and 800
	E50-S	50	Steel fiber (1%)	400, 600, and 800
	E50-P	50	Polypropylene fiber (0.1%)	400, 600, and 800
	E50-M	50	Steel fiber (1%) + Polypropylene fiber (0.1%)	400, 600, and 800

2.2. Materials

Materials used included cement, slag, fine and coarse aggregates, fiber, and superplasticizer. Local Portland cement with a specific gravity of 3.15 and a fineness of 3400 cm²/g, complying with ASTM C150/C150M (ASTM C150/C150M-15 2015) [36], was used as binding material. Local slag with a specific gravity of 2.9 and a fineness of 6000 cm²/g was used. The fine aggregate was a locally available natural river sand that meets ASTM C33/C33M (ASTM C33/C33M-13 2013) [37]. The specific weight, water absorption, and fineness modulus of the fine aggregate are shown in Table 2. The coarse LWA used was locally produced from reservoir sludge. Its dry specific weight, water absorption, unit weight, and crushing strength are listed in Table 3. Local steel fibers and polypropylene fibers were used, as shown in Figure 1. The basic properties of these two fibers are listed in Table 4. The reason for using wavy steel fiber is that the wavy shape can produce a strong mechanical bonding force to improve the shear strength of concrete. A superplasticizer called Sikament-1250 (Sika Taiwan Ltd.) was used to enhance the workability of the concrete mixtures.

Table 2. Physical properties of fine aggregate.

Aggregate Type	Specific Weight (SSD)	Water Absorption (SSD) (%)	FM
Fine aggregate	2.60	1.25	2.70

Notes: SSD, saturated surface dry condition; FM, fineness modulus.

Table 3. Physical and mechanical of lightweight aggregates.

Dry Specific Weight	1-h Water Absorption (%)	Unit Weight (Dry-Rodded) (kg/m ³)	Crushing Strength (MPa)
1.2	4.9	707.5	3.6

(a)

(b)

Figure 1. Appearance of fibers: (a) wavy steel fibers and (b) polypropylene fibers.

Table 4. Basic properties of fibers.

Type of fiber	Length (mm)	Diameter (mm)	Density (g/cm ³)	Elastic Modulus (GPa)	Tensile Strength (MPa)	Melting Point (°C)
Wavy Steel Fibers	30	0.8	7.8	200	2000	-
Polypropylene Fibers	12	0.05	0.9	-	300	165

2.3. Concrete Mix Design

In this study, ordinary LWC and fiber-reinforced LWC were prepared, the former serving as the reference concrete. To analyze the effect of concrete strength on its residual mechanical properties, each group of concrete was cast with low- and medium-strength specimens, and the specified 28-day compressive strengths were 30 and 50 MPa, respectively. Through a series of trial mixing, the concrete mixture was designed to achieve the target strength at 28 days of age and had a proper workability of 150 to 200 mm. The concrete mixing design used is shown in Table 5. The abbreviations for identifying each concrete indicate the type of concrete: control group (C) or experimental group (E), the strength of concrete (30 or 50 MPa), and the type of fiber (S: steel fiber, P: polypropylene fiber, M: hybrid fiber).

Table 5. Concrete mix design composition.

Group	Mix No.	W/B	Cement (kg/m ³)	Slag (kg/m ³)	Water (kg/m ³)	Aggregate (kg/m ³)		SP (kg/m ³)	Steel Fiber (kg/m ³)	PP (kg/m ³)
						FA	CA			
Control group	C30	0.50	315	105	210	824	418	2.9	-	-
	C50	0.32	412	138	176	957	348	7.7	-	-
Experimental group	E30-S	0.50	315	105	210	824	418	2.9	78	-
	E50-S	0.32	412	138	176	957	348	7.7	78	-
	E50-P	0.32	412	138	176	957	348	7.7	-	0.9
	E50-M	0.32	412	138	176	957	348	7.7	78	0.9

Note: C, ordinary LWC; E, fiber-reinforced LWC; digits, strength level; W/B, water/binder ratio; FA, fine aggregate; CA, lightweight coarse aggregate; SP, superplasticizer; PP, polypropylene fiber.

Before mixing, the aggregates were cured indoors until the required saturated surface-dry condition was reached. In the mixing process, the cement, slag, fiber, fine aggregates, and lightweight coarse aggregates were generally blended first, and then water and superplasticizer were added. The mixing operation was continued until a uniform and homogeneous concrete without any segregation was obtained.

2.4. Fabrication of Specimens

Following the mixing procedure, the slump and unit weight of each mixture were measured. Concrete specimens for each test were then cast from each mixture and compacted using an external vibrator. Along with each mixture, 12 100-mm-diameter and 200 mm tall cylindrical specimens were cast for compressive strength test and elastic modulus test; twelve prism specimens (360 mm long × 100 mm wide × 100 mm thick) were cast for flexural strength of concrete. Immediately after casting, all the specimens were covered with wet hessian and polyethylene sheets for a period of 24 h, at which time they were then demolded. Following demolding, all specimens were placed in a laboratory water bath. After curing, the specimens were removed from the water bath one day before the test. Then, the specimens were placed in an oven at 100 °C for 24 h to avoid spalling during the subsequent fire test.

2.5. Testing Methods

The compressive strength, flexural strength, and elastic modulus of the concrete were tested according to the ASTM C39 [38], ASTM C78 [39], and ASTM C469 [40]. The specimens were heated at a prescribed rate (10 °C/min). As soon as the target maximum temperature was reached, the furnace

temperature was maintained at this temperature for 60 min to achieve thermal stability throughout the specimen (Figure 2). Afterwards, the furnace power switch was turned off and the specimens were allowed to cool slowly in the furnace with the door opened. Upon the specimens cooling to room temperature, the residual strength tests were conducted. In these tests, the average value was calculated using the recordings from three specimens.

Figure 2. Schematic diagram of specimens heating and cooling in the furnace.

3. Results and Discussion

3.1. Fresh Properties of Concrete

The fresh properties of concrete were recorded for each batch. The tested fresh properties of the concrete included slump and unit weight, as shown in Figure 3. The slump value ranged from 16 to 21 cm. In the control group, the slump values of the C30 and C50 mixes were 20 and 21 cm, respectively. These results showed that the mixtures of the control group had good workability. In the experimental group, the slump value of the E30-S and E50-S mixes with steel fiber was 18 cm, and the slump value of the E50-P mix with polypropylene fiber was 20 cm, but the slump value of the E50-M mix with steel fiber and polypropylene fiber was only 16 cm because the amount of fiber used in the E50-M mix was higher, resulting in a stiffer mixture and leading to reduced workability. For low strength LWC, the unit weights of the C30 and E30-S mixes were 1875 and 1953 kg/m³, respectively, which are not much different. For medium-strength LWC, the unit weight of the C50, E50-S, E50-P, and E50-M mixes with the addition of fiber ranged from 2039 to 2118 kg/m³, which meets the limit of unit weight for structural LWC.

Figure 3. Results of slump and unit weight test of lightweight aggregate concretes.

3.2. Compressive Strength

At a test age of 28 days, the cylinders of investigated concrete mixtures were capped with gypsum capping compound and tested in compression to determine the compressive strength of concrete. As shown in Figure 4, the 28 day compressive strength of each concrete mixture at room temperature was higher than the designed 28 day compressive strength. Comparing the strength of the concrete

with low strength C30 and E30-S mixes, the incorporation of steel fiber did not significantly contribute to the increase in the 28 day compressive strength of the concrete; it rather decreased slightly by 2.1%. As for the medium-strength concrete, the compressive strength of the experimental group (E50-S, E50-P, and E50-M mixes) was 9.6%–11.7% lower than that of the control group (the C50 mix). The strength of the E50-S mix was slightly lower than that of the E50-P mix, whereas the strength of the E50-M mixture was the lowest. These results showed that regardless of whether the concrete is low- or medium-strength, the control group had higher strength. Although it was fully stirred during the mixing, the decrease in the compressive strength of the experimental group may be due to difficulties in scattering and condensing the fibers in the concrete. This phenomenon has been discussed elsewhere [5].

Figure 4. Results of compressive strength test.

The residual compressive strength of investigated LWC mixtures after exposure to different elevated temperatures is shown in Figure 4. Taking the control group as an example, the residual compressive strength of the C30 and C50 mixes at different fire temperatures was 16.5–34.4 and 33.2–60.8 MPa, respectively. For the experimental group, the residual compressive strengths of the E30-S, E50-S, E50-P, and E50-M mixes at the different fire temperatures were 19.1–35.4, 29.6–54.1, 28.5–54.7, and 32.8–52.8 MPa, respectively. Overall, the variation in the compressive strength of each group of LWC showed a trend of increasing first and then decreasing. After exposure to the lowest target temperature (400 °C), the residual compressive strength of all mixtures increased relative to the initial values determined at room temperature. The reason for the increase in strength is the drying effect of the concrete specimen due to the increase in temperature [41]. Chen et al. [42] confirmed that a significant gap between the internal temperature of the specimen and the furnace temperature, which was only about half that of the furnace temperature. In other words, despite maintaining the furnace temperature for one hour, the temperature inside the concrete was still far below 400 °C. Therefore, under the action of high temperature drying, the water vapor in the specimen remained, which contributed to the improvement of strength. Li and Bu [43] also demonstrated that the compressive strength of concrete after 200–300 °C increased with increasing temperature. Drzymala et al. [44] showed that the compressive strength of fiber concrete after 300 °C was also higher than the initial value measured at 20 °C. Some scholars found that when the temperature range is between room temperature and 400 °C, high temperatures cause the cement hydration reaction to occur more fully, thus increasing the strength [20]. From this point of view, a small increase in temperature can produce favorable chemical changes inside the concrete microstructure and can even improve concrete's performance [45]. However, once the temperature exceeded a certain threshold, the mechanical properties of the two groups of concrete tended to deteriorate. After exposure to 600–800 °C, the residual compressive strength of each concrete mixture decreased significantly because the strength loss was mainly caused by physical changes below 400 °C. However, at 600–800 °C, the decrease in strength was mainly due to chemical degradation in hydrated products and aggregates, which was basically unrelated to the amount and type of fiber [46]. Kong et al. [47] showed that after exposure to 800 °C, the

residual strength of LWC decreased to 40% of the room temperature strength. However, in this study, the residual strength of the two groups of LWC after exposure to 800 °C was about 50%–66% of the initial strength.

The degree of variation in strength after exposure to high temperatures can be understood through the residual compressive strength ratio of the specimen, which is defined as the ratio of the strength after exposure to the target temperature to the original strength at room temperature. Figure 5 shows that the variation in the residual compressive strength ratio of different LWC mixtures is a function of temperature. Notably, the residual compressive strength ratio of the two series of concrete after exposure to 400 °C significantly improved, as shown in Figure 5. In the case of low-strength LWC, Figure 5a shows that the residual compressive strength ratio of the experimental group after exposure to high temperatures was higher than that of the control group. Similarly, for medium-strength LWC, Figure 5b shows that the residual compressive strength ratio of the experimental group after exposure to 400–600 °C was higher than that of the control group due to the bridging effect of the fibers. Figure 5b, in the experimental group, shows that the residual compression of the specimens with steel fibers (E50-S and E50-M) produced obvious changes in the residual compressive strength ratio with increasing temperature between 400 and 600 °C. By comparison, specimens with polypropylene fiber (E50-P) underwent a moderate change in the residual compressive strength ratio with increasing temperature because the addition of polypropylene fibers in concrete led to improved retention of compressive strength at moderately high temperatures due to the melting of polypropylene fibers, which created pathways within the concrete microstructure for the release of water. As can be seen in Figure 5b, the residual compressive strength ratio of the E50-P mix was lower than that of the control group after exposure to 800 °C. After this temperature, the specimens with polypropylene fibers had the lowest residual compressive strength ratio among all tested concretes because the pyrolysis process of polypropylene fibers destroyed the internal structure of the material [13]. In other words, the burning of polypropylene fibers led to creating additional voids that further weakened the microstructure, which could facilitate collapse. In contrast, the residual compressive strength ratio of the E50-M mix was higher than that of the control group because the inherent high melting temperature of the steel fiber guaranteed its good performance under high temperature conditions, thus allowing the concrete to retain better residual compressive strength. According to the above results, the effect of the added fiber on the residual compressive strength of different grades of the LWC was also different. Overall, the hybrid fiber reinforced concrete showed better ability to resist the loss of compressive strength caused by high temperature. This is consistent with the test results reported by Babuji and Varghese [48].

Figure 5. Comparison of residual compressive strength ratio of LWC specimens: (a) low-strength and (b) medium-strength concrete.

3.3. Stress–Strain Curve

The stress–strain curves for low- and medium-strength LWC after exposure to different temperatures are shown in Figures 6 and 7, respectively. At room temperature, the ascending branch of the stress–strain curve of the low-strength LWC exhibited a linear relationship, as shown in Figure 6. After exposing the specimen to temperatures above 400 °C, the stress–strain curve was characterized by atypical non-linearities in the elastic region, that is, at the beginning of loading, which formed a concave-up curve. This is consistent with the results of Chang et al. [49]. During the period of pre-elastic hardening, the specimen stiffened as it approached the linear elastic region. As the exposure temperature increased, this behavior became more apparent. Chang et al. confirmed that the closing of pre-existing cracks due to heating and cooling can cause this phenomenon. Dehydration of calcium hydroxide can lead to cracking, which led to the shrinkage of the matrix, thermal incompatibility between the aggregate and cement paste, and the expansion of steel fibers [50]. After exposure to 400 °C, as mentioned above, due to the high temperature drying effect, the ascending branches of the stress–strain curves of each concrete group were approximately linear, and the slope was steeper than that at room temperature. However, after exposure to 600–800 °C, the ascending branch of the stress–strain curve of the experimental group was approximately linear and the slope was relatively small, which was caused by the difference in expansion between the fiber and the matrix during the heating process, resulting in interface peeling. In this case, the position where the fiber was located became a potential crack. As a result, as the temperature increased, the stiffness of the concrete specimens gradually decreased. After being exposed to 800 °C, the slope of the descending branch of the stress–strain curve reduced, and the ultimate strain value markedly increased, that is, the stress–strain curve became quite gentle. As a whole, the residual stress–strain curve of the experimental group exposed to high temperatures was relatively flat due to the incorporation of fibers. This also confirmed that the residual stress–strain behavior of the experimental group was superior to that of the control group.

Figure 6. Stress versus strain curves of low-strength LWC specimens: (a) control group C30 and (b) experimental group E30-S.

Figure 7. Stress versus strain curves of medium-strength LWC specimens: (a) control group C50 and (b) experimental group E50-M.

As for the medium-strength LWC, taking the E50-M mix as an example, as shown in Figure 7, a linear relationship was found with the ascending branch of the stress–strain curve before the fire damage, and the slope was quite steep. Similarly, after exposing the specimen to temperatures above 400 °C, the stress–strain curve was also characterized by atypical non-linearities in the elastic region. The ascending branch of the stress–strain curves after exposure to high temperatures still remained linear, but the slope decreased significantly with increasing temperature. Within 400 to 600 °C, the damage caused by high temperature was not obvious, but within 600 to 800 °C, the effect of high temperature was more pronounced. The reason may be that in the case of low temperature damage, the temperature was transmitted through pore water, colloids, and the crystal skeleton. As a result, the transfer of heat energy to the center of the concrete to attenuate its strength was slow. However, in the case of high temperature fire, the transmission of heat energy mainly occurred through radiation, and the heat transfer was relatively rapid, so cracks formed faster inside the concrete.

The test results of the elastic modulus of each LWC specimen at 28 days of age are depicted in Figure 8. It shows that at room temperature, the elastic modulus of the control group and the experimental group of low-strength LWC were 13.62 and 11.64 GPa, respectively. For medium-strength LWC, the elastic modulus of the control group was 27.86 GPa and the elastic modulus of the experimental group was between 22.18 and 28.39 GPa (the highest was the E50-S mix). The residual elastic modulus of each LWC mixture after exposure to elevated temperatures of 400–800 °C is also shown in Figure 8. In the control group, the residual elastic modulus of the C30 mix was between 4.51 and 13.92 GPa; the residual elastic modulus of the C50 mix was between 8.79 and 29.51 GPa. In the experimental group, the residual elastic modulus of the E30-S, E50-S, EC50-P, and E50-M mixes at different fire temperatures were 6.15–12.13, 9.32–30.06, 6.52–22.96, and 11.24–24.74 GPa, respectively. In addition, the test results of the low-strength LWC (the C30 and E30-S mixes) indicated that the use of steel fiber slightly reduced the modulus of elasticity at 28 days of age. For medium-strength LWC (C50, E50-S, E50-P, and E50 M mixes), the elastic modulus of the E50-S mix was higher than that of the control group, but the difference between the specimens of the experimental group had no certain tendency. Figure 8 shows that when the temperature was 400 to 600 °C, the elastic modulus of both groups of LWC decreased slightly. However, after exposure to 800 °C, the residual elastic modulus of each group of LWC decreased significantly. This is mainly attributed to the increase in the volume

of the porous and the cracking of the interface zone between the paste and the aggregate after high temperature exposure.

Figure 8. Results of elastic modulus.

Figure 9 shows the residual elastic modulus ratios of each LWC mixture at different temperatures. The residual elastic modulus ratio tended to rise first and then fell as the temperature increased. Figure 9a shows that the residual elastic modulus ratios were only slightly reduced when the temperature was 400 to 600 °C. However, at 800 °C, the residual elastic modulus ratios attenuated sharply. In the control group, the residual elastic modulus ratio was 0.33. For the experimental group, the residual elastic modulus ratio was maintained at 0.53. Figure 9b shows that the residual elastic modulus ratios of the medium-strength LWC increased after exposure to 400 °C. When the temperature was 600 °C, the elastic modulus of the control group and the experimental group declined slightly. After exposure to higher temperatures (600 to 800 °C), the residual elastic modulus ratios of the control group and the experimental group significantly attenuated. Notably, as the temperature rose, the decreasing trend of the residual elastic modulus ratio was more obvious than that of the residual compressive strength because the elastic modulus is more sensitive to cracks at the macroscopic or microscopic scale induced by high temperatures [51]. At normal temperature, the higher the compressive strength, the higher the elastic modulus of concrete. The relationship in which the modulus of elasticity is proportional to the compressive strength has long been accepted. However, the test results showed that the aforementioned relationship should not be applied unconditionally to concrete affected by high temperature. Therefore, it is necessary to be particularly cautious when estimating the elastic modulus of concrete after fire based on the measured compressive strength [13]. This also specifically confirms that the parameter has a high sensitivity to heating at high temperatures.

Figure 9. Comparison of residual elastic modulus ratio of LWC specimens: (a) low- and (b) medium-strength concrete.

3.4. Flexural Strength

The flexural strengths at 28 days of age of each group of LWC specimens at room temperature were higher than 5 MPa, as shown in Figure 10. Of them, the flexural strength of the E50-M specimen with hybrid fibers was the largest (6.54 MPa). For the low-strength LWC, the addition of steel fiber did not increase its flexural strength. For the medium-strength LWC, due to the bridging effect of the steel fibers, the flexural strength of the steel fiber-added experimental group was higher than that of the control group. This is consistent with the test results reported by Lau and Anson [52]. However, the flexural strength of the polypropylene fiber-added experimental group was less than that of the control group. With the increase in temperature, taking the specimens mixed with steel fiber as an example, although the thermal energy generated by high temperature led to the formation of cracks between the cement paste and the steel fiber, the steel fiber still prevented the crack from propagating and maintained the flexural strength to a certain extent. As for the specimens mixed with polypropylene fiber, at 400–600 °C, the pores formed by the melting of the polypropylene fiber dissipated the water vapor pressure, thereby maintaining the flexural strength. However, above 800 °C, due to the melting of polypropylene fibers, additional voids were created that further weakened the microstructure and increased the likelihood of collapse. The residual flexural strengths of each LWC mixture after exposure to temperatures of 400–800 °C are also shown in Figure 10. In the control group, the residual flexural strengths of the C30 mix and C50 mix were between 2.14 and 5.71 MPa and 2.85 and 5.51 MPa, respectively. In the experimental group, the residual flexural strength of the E30-S, E50-S, EC50-P, and E50-M mixes at different fire temperatures were 2.54–5.36, 3.15–5.83, 2.48–5.17, and 3.89–6.72 MPa, respectively.

Figure 10. Results of flexural strength.

Figure 11 depicts the residual flexural strength ratio of each LWC mixture at different temperatures. This parameter is an important property from the viewpoint of fire resistance due to the significant influence of tensile strength on concrete cracking. Figure 11 shows that the flexural strength of each group of LWC was not influenced by the temperature rising up to 400 °C. However, after exposure to an elevated temperature of 600 °C, the flexural strength of each group of concrete decreased, but the residual flexural strength ratio after exposure to elevated temperatures can still be maintained above 0.8. After exposure to 800 °C, a dramatic loss was observed in the flexural strength of each group of LWC, and the residual flexural strength ratio after high temperatures was between 0.38 and 0.59. In the low-strength LWC (Figure 11a), when the temperature was 600 to 800 °C, the residual flexural strength ratio of the control group and the experimental group decreased sharply as the temperature increased, and the difference between the two was quite obvious. In the medium-strength LWC (Figure 11b), the residual flexural strength ratio of both groups slightly increased after exposure to 400 °C. At 600 °C, the residual flexural strength ratio of the control group and the experimental group significantly reduced. Of them, the residual flexural strength ratios of the experimental group and control group were between 0.90 and 0.91, and 0.83, respectively. Since steel fibers do not melt at temperatures

below 1300 °C, they maintain their beneficial effects of bridging cracks over a wide temperature range. The results of this study showed that after being subjected to 600 °C, the residual flexural strengths of the E50-S and E50-M specimens increased by 7%–8% compared with the control group. Lau and Anson [52] reported that after being subjected to 600 °C, the use of 1% steel fiber (based on the volume of the composite material) increased the residual flexural strength by about 15% compared to similar concrete with no steel fiber. After exposure to an elevated temperature of 800 °C, the residual flexural strength ratio of the control group and the experimental group significantly reduced; the residual flexural strength ratio of the E50-P mix was the lowest. This was attributed to polypropylene fibers melting at a relatively low temperature of 165 °C, so the crack-bridging ability was not maintained at higher temperatures. This is the same as the result of the compressive strength because the pyrolysis process of the polypropylene fiber damages the internal structure of the material. Overall, compared with the loss of compressive strength, the loss of flexural strength was relatively obvious because the flexural strength is more sensitive to macroscopic or microscopic cracks caused by high temperatures.

Figure 11. Comparison of residual flexural strength ratio of LWC specimens: (a) low-strength concrete and (b) medium-strength concrete.

The relationship between flexural load and midspan deflection of the low-strength LWC is shown in Figure 12. When the load reached the peak, the test was stopped immediately. Therefore, the post-peak behavior cannot be captured. At all temperatures, the flexural load of concrete specimens increased almost linearly with the increase in displacement, and sharply decreased after reaching the peak. Figure 12 shows that the peak load of the control group did not change significantly after exposure to 400 °C, whereas the peak load of the experimental group slightly increased. As mentioned above, this was attributed to the LWC specimen increasing in strength due to the drying effect of high temperatures. With high temperature drying, removing the evaporable water (capillary water, adsorbed water, and interlayer water) first was easier. The pore pressure formed by the high temperature thus lowered and the flexural load of the specimen increased. At different temperatures, the midspan deflection of the low-strength LWC specimens was relatively small, and the value was about 0.6–1.0 mm.

The load–deflection curves of medium-strength LWC specimens at room temperature and each fire temperature are shown in Figure 13. Figure 13 demonstrates that the load–deflection curve of the experimental group was relatively ductile at room temperature or at various firing temperatures. Figure 13a shows that at room temperature, due to the bridging effect of the fibers, the experimental group generally showed better ductility than the control group. After being exposed to 400 °C, the slope of the ascending branch of the load–deflection curve of the C50 specimen in the control group had no obvious attenuation, whereas that of the E50-M sample in the experimental group significantly increased, as shown in Figure 13b. In addition, after exposure to 600 °C, the initial slopes of ascending branches of the load–deflection of each specimen reduced but still maintained a certain degree (Figure 13c). However, after exposure to 800 °C, the slope of the ascending branch of the

load–deflection curve of the experimental group significantly reduced. Figure 13d shows that the failure deflection of the control group was quite close to the crack deflection; in contrast, the failure deflection of the E50-S and E50-M specimens reached several times the crack deflection, that is, the ductility of the load–deflection curve was more pronounced. Based on the above results, although polypropylene fibers had better strength and ductility at low to moderately elevated temperatures, steel fibers could provide fiber bridging effects at higher temperatures, allowing the E50-S and E50-M specimens to retain a large proportion of flexural strength and ductility.

Figure 12. Load–deflection curves of low-strength LWC specimens: (a) control group C30 and (b) experimental group E30-S.

Figure 13. Load–deflection curves of medium-strength LWC specimens: (a) room temperature, (b) 400 °C, (c) 600 °C, and (d) 800 °C.

4. Conclusions

In this study, steel fiber and polypropylene fiber were used to investigate the effects of individual and mixed fiber on the residual mechanical properties of low- and medium-strength LWC after exposure to elevated temperatures. On the basis of the above experimental results and discussion, the following conclusions were drawn:

- Overall, the residual mechanical properties of each group of LWC decreased with increasing temperature. After exposure to 400 °C, the residual mechanical properties of all specimens did not attenuate due to the drying effect of high temperature. Then, after exposure to 800 °C, the residual mechanical properties significantly reduced.
- Due to the bridging effect of steel fibers and their inherent high melting temperature, the residual mechanical properties of LWC with steel fibers exposed to high temperatures significantly improved. Compared with individual fiber-reinforced LWC, the residual mechanical properties of mixed fiber-reinforced LWC were the best of the mixes tested.
- The elastic modulus of each group of LWC changed with increasing temperature. After exposure to 800 °C, the residual elastic modulus decreased significantly and the residual elastic modulus ratio was lower than 0.53. As the temperature rose, the decreasing trend of the residual elastic modulus ratio was steeper than that of the residual compressive strength.
- After exposure to 400 °C, the flexural strength of each group of LWC did not attenuate. After exposure to 600 °C, the residual flexural strength of each group of LWC reduced, but the residual flexural strength ratio can be maintained above 0.83. After exposure to 800 °C, the residual flexural strength of each group of LWC was significantly attenuated, and the residual flexural strength ratio was between 0.38 and 0.59. Compared with the loss of compressive strength, the loss of flexural strength was relatively obvious.

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