FLEXURAL PROPERTIES OF REACTIVE POWDER CONCRETE AFTER HIGH TEMPERATURE

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Reactive powder concrete (RPC) is characterized by the ultra-high strength and excellent durability, so it has widely application prospects in the fields of oil, nuclear power, municipal works, marine engineering and military facilities. This paper will focus on the flexural properties of RPC after high temperature. To do this, 300 specimens with the size of 40×40×160mm were tested after exposure to 20~900℃. The effect of the fiber type and dosage change on the spalling of RPC is investigated through high-temperature test. By bending experiments, the degradation of RPC flexural strength with heating temperature, fiber type and fiber content are studied. The results indicate that, with the increase of steel fiber and polypropylene fiber dosage, RPC spalling probability reduces significantly. The flexural strength decreases with increasing temperature, and the incorporation of steel fibers exhibits positive impact on flexural strength, but the polypropylene fibers exhibit adverse effect. Formulas are proposed to express the decay of the flexural strength with increasing temperature, and the results are compared with normal strength concrete (NSC) and high strength concrete (HSC).

Keywords: *reactive powder concrete (RPC); high temperature; flexural strength; spalling; steel fiber; polypropylene fiber*

1. Introduction

The mechanical properties of concrete after high temperature are very important for the evaluation of the residual behavior of concrete structures after exposure to high temperature. Up to now, a lot of research works have been performed to determine the mechanical properties of normal strength concrete (NSC) and high strength concrete (HSC) after exposure to elevate temperatures. It is found that the flexural and tensile strength both of NSC and HSC substantially decrease linearly with increasing temperature [1,2]. The incorporation of steel fibers can effectively improve the tension properties of concrete after high temperature [3~5], whereas the polypropylene fibers exhibit no obvious effect on the tension properties [5,6]. Ding [7] studied the residual behavior and flexural toughness of fiber cocktail reinforced self-compacting high performance concrete (SCHPC) after exposure to high temperature, and found that the mechanical properties of hybrid fiber reinforced SCHPC after heating are better than that of mono fiber reinforced SCHPC. The changes of flexural strength with heating temperature for HSC with or without steel and polypropylene fibers were studied by Pliya [8], and the research shows that the residual tensile strength of HSC mixed with steel and polypropylene fibers improved significantly compared with plain concrete.

Reactive Powder Concrete (RPC) is an ultra high strength cement-based composite material made of ultra-fine reactive powder, cement, fine aggregate, high-strength steel fiber and other components [9]. It has widely application prospects in the fields of oil, nuclear power, municipal works, marine engineering, mechanical engineering, aviation and military facilities due to its ultra-high strength, high toughness, high durability and excellent volume stability. So it is a very promising building material in the field of civil engineering. Currently, many studies have been completed on the mechanical properties of RPC at room temperature, and the studies show that the mechanical properties of RPC are better than NSC and HSC [10,11]. The steel fiber mixed in RPC can greatly improve its tensile strength and toughness [12]. Few studies have been performed on the mechanical properties of RPC after high temperature, especially on its flexural properties. For elimination of coarse aggregate, RPC has a denser internal structure than HSC [13]. Therefore, RPC is more prone to spalling than HSC under the heating treatment. The same with HSC, the incorporation of steel fibers and polypropylene fibers can also inhibit the spalling of RPC [14]. Tai

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[15] showed that the mechanical properties of steel fiber-reinforced RPC increased firstly and then decreased with increasing temperature. Xiong [16] has made a comparative study on the mechanical properties of an ultra-high strength concrete (UHSC) and the normal/high strength concretes, and the comparisons showed that the compressive strength and elastic modulus of the UHSC were generally reduced less than those of normal/high strength concretes at the elevated temperatures. Ju [17] proposes a conceptual model to explain the mechanism that induces the progressive spalling failure of RPC based on the numerical and experimental results, and the numerical simulation results are in good agreement with the experimental observations.

As seen from above analysis, it is necessary to study the mechanical properties of RPC after exposure to elevated temperatures. In this paper, to study the flexural properties of RPC after exposure to 20℃、120℃、200℃、300℃、400℃、500℃、600℃、700℃、800℃ and 900℃, the bending tests were carried out on the specimens of 40×40×160mm prisms. The effect of fiber type, fiber content and temperature on the flexural strength is studied. Formulas are established to express the decay of the flexural strength with increasing temperature.

2 Experimental program

2.1 Raw materials and mix proportion

RPC was prepared by the following ingredients: cementitious materials contain ordinary Portland cement with grade of 42.5 (Chinese cement grading system), silica fume with specific surface area of 20780m^2/kg and SiO_2 mass fraction of 94.5% and slag with the 28 days activity index of 95% and specific surface area of 475m^2/kg; quartz sand with SiO_2 mass fraction of higher than 99.6%, and diameter range of 600-360μm and 360-180μm; concentrated naphthalene water reducer with form of brown powder; high-strength steel fiber with diameter of 0.22mm and length of 13mm; polypropylene fiber (PPF) with melting point of 165℃ and length of 18-20mm. The physical and chemical properties of the cementitious materials are listed in Table 1. The type of water reducer, steel fiber and polypropylene fiber are shown in Figure1. Through preliminary tests on the mix design, ten mix proportions were selected, as given in Table 2.

2.2 Specimen design and fabrication

The RPC preparation has to follow certain requirements. Firstly, the pre-weighed quartz sand, cement, slag, silica fume and water reducer were

Table 1

Physical and chemical properties of cement, silica fume and slag (%)

Cementitious materials	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Loss of ignition
Cement	21.40	5.45	3.50	64.48	1.46	2.51
Silica fume	94.50	0.50	0.45	0.60	0.70	0.80
Slag	34.90	14.66	1.36	37.57	9.13	0.30

Table 2

Mix proportion of RPC

Series	Binding materials (kg/m^3)			Quartz sand (kg/m^3)	Water reducer (kg/m^3)	Water (kg/m^3)	Steel Fiber (%)	PPF (%)
	Cement	Silica fume	Slag					
RPC0	816.87	245.06	122.53	980.25	47.38	236.89	0	0
SRPC1	808.70	242.61	121.31	970.44	46.90	234.52	1	0
SRPC2	800.53	240.16	120.08	960.64	46.43	232.15	2	0
SRPC3	792.37	237.71	118.85	950.84	45.96	229.79	3	0
PRPC1	816.05	244.82	122.41	979.27	47.33	236.66	0	0.1
PRPC2	815.24	244.57	122.29	978.28	47.28	236.42	0	0.2
PRPC3	814.42	244.33	122.16	977.30	47.24	236.18	0	0.3
HRPC1	799.72	239.92	119.96	959.66	46.38	231.92	2	0.1
HRPC2	798.90	239.67	119.84	958.68	46.34	231.68	2	0.2
HRPC3	807.07	242.12	121.06	968.48	46.81	234.05	1	0.2

Notes: 1. RPC0, SRPC, PRPC and HRPC on behalf of RPC without fiber, with only steel fiber, with only polypropylene fiber and with both steel fiber and polypropylene fiber representatively; 2. Steel fiber and polypropylene fiber content are the volume dosage.

(a) Water reducer (b) Steel fiber (c) Polypropylene fiber

Fig. 1 - The water reducer, steel fiber and polypropylene fiber.

poured into concrete mixer and mixed for 3 minutes. Then, the pre-weighed water was poured into mixer and the mixing continued for another 5 minutes. Next, the polypropylene fibers and steel fibers were threw into mixer and stirred for 5 minutes. Then, the mixture was poured into molds and vibrated on high-frequency vibration table. After being stored for 1 day in standard conditions, the specimens were demoulded and cured for 3 days at 90℃ in the concrete accelerated curing box. Next, the specimens were moved into standard curing room and cured for 60 days. Before heating treatment, the specimens were taken out of standard curing room and exposed to air for 2 months.

Specimens used for bending test were 40×40×160mm prisms. According to mix proportion in Table 2, for each mix proportion, ten groups of specimens were prepared. Each group consisted of three specimens, a total of 300 specimens were prepared, and the final results are taken as the average of three test data.

2.3. Experiment regime

The high-temperature experiment was performed using an electric furnace when the specimens were cured to the required age by considering. Ten target temperatures are: 20℃, 120℃, 200℃, 300℃, 400℃, 500℃, 600℃, 700℃, 800℃ and 900℃. The heating rate was 4℃/min. The target temperature was maintained for 2 hours so that the temperature inside and outside of the specimen could be consistent. Through opening the furnace door, the specimens were cool down to room temperature. The temperature-time curves of furnace at different target temperatures are given in Figure 2.

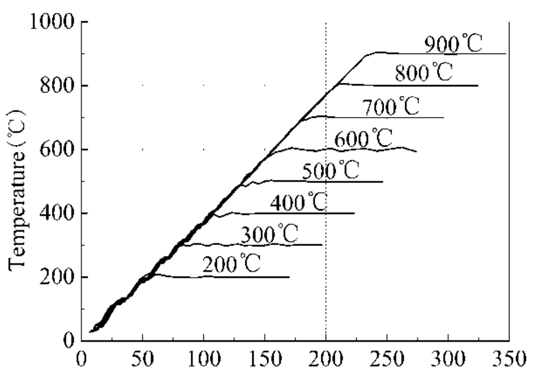


Fig. 2 - Temperature-time curves of furnace at different target temperatures.

The bending experiment was carried out when the specimens were placed indoors for 3 days after high temperature experiment. According to GB/T 17671-1999 [18], the bending experiment was performed on the YAW-300 microcomputer automatic press-fold cement testing machine by means of an in-house fixture as shown in Figure 3. The advantage of this fixture is that the distance between the two lower supporting points of specimen remains unchanged, avoiding the extra adjustments each time when the specimen is installed. In order to improve the test accuracy, the middle grooves of the fixture are ground into smooth semicircle, and a steel bar with diameter of 10mm was placed on the specimen surface in contact with the testing machine platen. The tests were controlled by load, and the loading rate was 0.5kN/s.

3 Results and discussions

3.1 Appearance and spalling

RPC shows different appearances after heating to different temperatures, as shown in Figure 4. The specimens appear to change in color with heating temperatures as: slate-gray (200℃ and below) → grayish brown (300~400℃) → darkish brown (500℃) → darkish gray (600℃) → grayish white (700℃) → pinkish white (800~900℃).

RPC adding with different fibers and dosage

Fig. 3 - Loading devices for bending experiment.

SRPC1, 400℃ SRPC2, 900℃ SRPC3, 900℃

(a) Appearance and spalling of RPC with steel fibers

PRPC1, 300℃ PRPC2, 600℃ PRPC3, 900℃

(b) Appearance and spalling of RPC with polypropylene fibers

HRPC1, 900℃ HRPC2, 900℃ HRPC3, 900℃

(c) Appearance and spalling of RPC with hybrid fibers

Fig. 4 **- C**hange of RPC spalling with different fiber types and exposure temperatures.

shows different spalling phenomena and crack propagation, as shown in Figure 4. The maximum tolerable temperatures under the premise of specimens not spalling according to different RPC mix proportions are also given in Figure 4. As can be seen from Fig.4a, the maximum tolerable temperature is 400℃ when the added steel fibers volume fraction is 1%. When the steel fibers volume fraction increases to 2% or 3% the specimens are not spalling until up to 900℃. The spalling temperature range of RPC single-doped with steel fibers is 360℃~ 550℃. The adding of steel fibers can reduce the spalling of RPC, and the reduction is more obvious when the steel fibers volume fraction increases to 2%. The reason is the steel fibers can improve the tensile strength of RPC, which is the similar to other observations from the scientific literarure [19].

Fig.4b shows that the maximum tolerable temperatures are 300℃ and 600℃ respectively when the added polypropylene fibers volume fraction is 0.1% and 0.2%. The maximum tolerable temperature can achieve to 900℃ when the polypropylene fibers volume fraction increases to 0.3%. The reason for the analysis is the melting point of polypropylene fibers which is 165℃. When RPC is heated to temperatures higher than the melting point, the polypropylene fibers melt and the melt holes communicating with each other provide channels for the steam overflow, which suppresses the occurrence of RPC spalling. The spalling inhibition effect of polypropylene fibers is not obvious in this experiment, which is slightly different from the conclusions from [20]. In this experiment, the integrity of the specimen can be ensured when the polypropylene fibers volume content increases to 0.3%. The spalling temperature range of RPC single-doped with polypropylene fibers is 450℃~580℃.

For RPC mixed with hybrid fibers (both steel fibers and polypropylene fibers), the maximum tolerable temperatures are all achieve to 900℃ according to three different mix proportion. As seen in Fig.4c**.** Because the steel fibers can increase the tensile strength of RPC on the one hand, the polypropylene fibers can ease the internal vapor pressure of RPC on the other hand. So the combined effect of both fibers exhibits significant reduction of RPC spalling.

3.2. Flexural failure mode

Figure 5 shows the flexural failure modes. For specimens of RPC without steel fibers (RPC0 and PRPC), they fractured immediately when the load reached the maximum, then the load decreased to zero rapidly, and the specimen was broken into two sections. The fracture surface was uniform and neat, and the failure mode was brittle failure

(a) RPC without steel fibers

(b) RPC with steel fibers

Fig.5 - Flexural failure modes of RPC after elevated temperatures

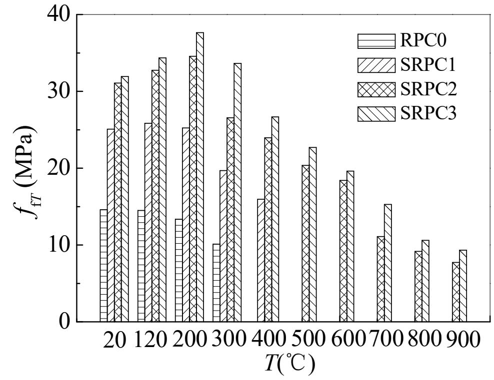
(Fig.5a). For specimens with steel fibers (SRPC and HRPC), with load increasing, a clear crack appeared first in the tension zone of the specimen. Meanwhile, the steel fibers crossing the crack came into play. As the load increased continually, the crack began to open. The tensile stresses were carried over by the steel fibers bridging the two sides of the crack. Finally, the specimen damaged but did not break, and the failure mode presented obviously toughness (Fig.5b).

3.3 Flexural strength

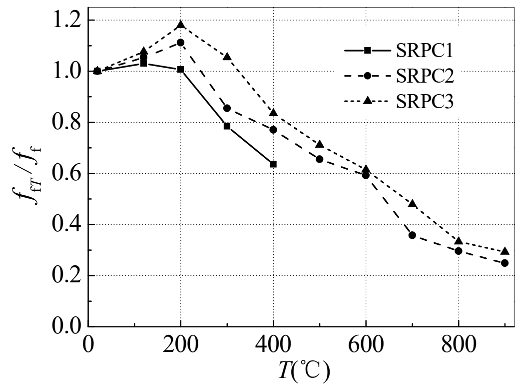
The absolute and relative values of flexural strength for RPC after different temperatures are given in Figures 6 -8. In the figures, f_{fT} represents the flexural strength of RPC specimen after high temperature of T, and f_f represents the flexural strength of RPC specimen at room temperature. When the specimens are more than one, the values shown in the figures are the average values.

3.3.1 Flexural strength of steel fiber-reinforced RPC

As seen from Figure 6, the flexural strength decreases gradually with increasing temperature. At room temperature, the flexural strength of RPC0, SRPC1, SRPC2 and SRPC3 are 14.60MPa, 25.09MPa, 31.08MPa and 31.92MPa respectively. Which means the steel fiber can effectively improve the flexural strength of RPC at room temperature. With increasing temperature, the residual flexural strength of RPC0 decreases gradually, but the residual flexural strength of steel fiber-reinforced RPC increases first and then decreases, and the critical temperature is 200 ℃. After heating to 200℃, the flexural strength of SRPC2 and SRPC3 increase by 11.20% and 17.95% relative to at the room temperature, respectively. The reason is flexural strength depends on the bond properties between steel fiber and RPC matrix, when subjected to a temperature lower than 200℃, the cement hydration reaction is more fully and the

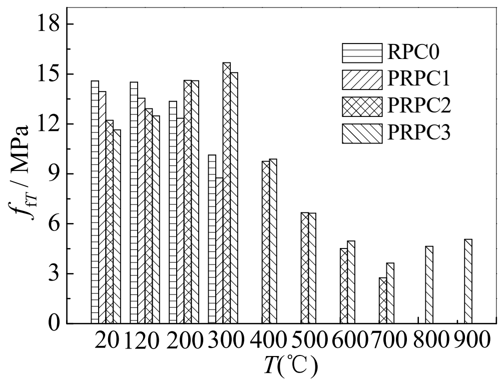


(a) Absolute value

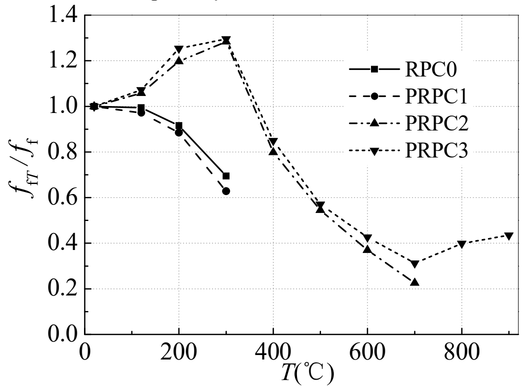


(b) Relative value

Fig. 6 -Flexural strength of steel fiber-reinforced RPC after high temperature.



(a) Absolute value



(b) Relative value

Fig. 7 - Flexural strength of PPF-reinforced RPC after high temperature.

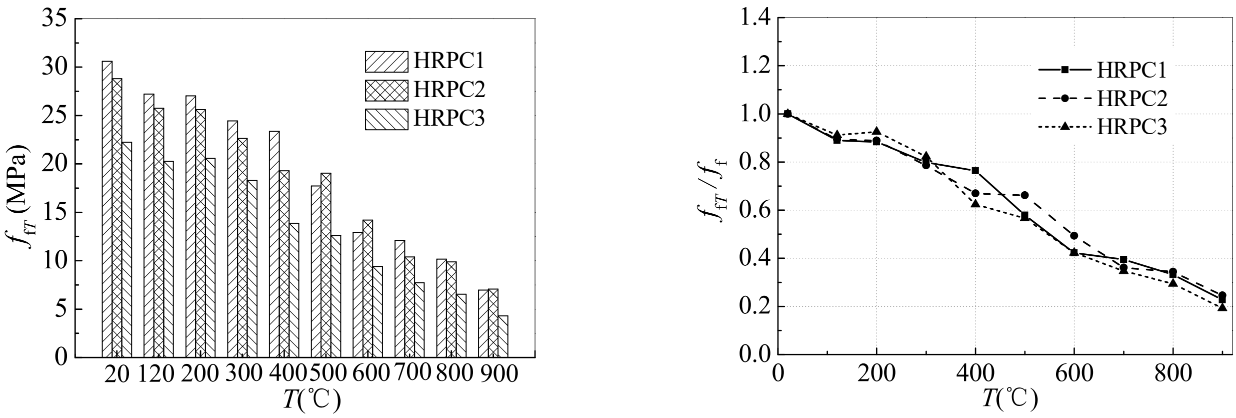


Fig. 8 - Flexural strength of hybrid fiber-reinforced RPC after high temperature

bond between steel fiber and RPC matrix is higher, so the flexural strength increases. After heating to 200~900℃, the bond between the steel fiber and matrix deteriorates due to high temperature, meanwhile, the strength of steel fiber itself degrades, so the flexural strength decreases.

3.3.2 Flexural strength of PPF-reinforced RPC

As can be seen from Figure 7, when the temperature is lower than 200℃, the polypropylene fibers have not yet melted, so the flexural strength decreases with increasing PPF content due to the lower elastic modulus of PPF.

When subjected to a temperature higher than 200℃, the PPF melt holes in communication with each other provide channels for the steam escaping and improve the integrity of RPC, so the flexural strength of RPC increases with improving PPF content after heating to the same temperature. With the temperature increases, the residual flexural strength of RPC0 and PRPC1 decreases following a parabolic law, whereas the residual flexural strength of PRPC2 and PRPC3 increases first and then decreases, with the critical temperature being 300℃. When subjected to 300℃, the residual flexural strength of PRPC2 and PRPC3 increases by 28.32% and 29.51% relative to at the room temperature, respectively. After heating to 800~ 900℃, the RPC flexural strength exhibits a little rebound because of concrete sintering. The reason is that when the temperature is lower than 300℃, the cement hydration reaction is more complete, and the internal structure of RPC is more compact, so the flexural strength increases. After heating to 300~900℃, the increased high-temperature damage has become a dominant factor affecting the performance of concrete, so the flexural strength decreases.

3.3.3 Flexural strength of hybrid fiber-reinforced RPC

As seen from Figure 8, the residual flexural strength of three hybrid fiber-reinforced RPC decreases gradually with increasing temperature and the flexural strength of HRPC1, HRPC2 and HRPC3 decreases to 22.74%, 24.55% and 19.28% of at the room temperature after heating to 900℃. The reason is hybrid fiber-reinforced RPC contains both steel fiber and polypropylene fiber. When the heating temperature is relatively low (200℃~300℃), the positive effect of secondary cement hydration reaction is still exist, but the bond properties of steel fiber and the RPC matrix are weakened by PPF and its melted holes, and this weakening is considered as a negative effect. The bond between steel fiber and RPC matrix has a greater effect on the flexural strength, so the residual flexural strength of hybrid fiber-reinforced RPC decreases linearly with increasing temperature. For the same heating treatment, the residual flexural strength of HRPC1 and HRPC2 with the same steel fiber content of 2% is almost similar, but much higher than HRPC3 with steel fiber content of 1%. This means that the steel fibers can effectively improve the flexural strength of RPC after high temperature and the PPF has little effect on improving flexural strength. Its incorporation provides a positive impact on flexural strength only when the temperature is higher than 500℃.

3.4 Statistical analysis of residual flexural strength of RPC

By polynomial regression, the experimental results of RPC residual flexural strength are summarized as shown in **Figure 9**. For SRPC1, SRPC2 and SRPC3, the relationship between the relative flexural strength f_{fT}/f_f and the temperature *T* is expressed as **Eq.1**.

For RPC0 and PRPC1, the relationship between f_{fT}/f_f and the temperature *T* is given as **Eq.2**.

For PRPC2 and PRPC3, the relationship between f_{fT}/f_f and the temperature *T* is given as **Eq.3**.

For HRPC1, HRPC2 and HRPC3, the relationship between f_{fT}/f_f and the temperature *T* is expressed as **Eq.4**.

$$\frac{f_{fT}}{f_f}=\begin{cases}0.99+0.55\left(\frac{T}{1000}\right), & 20°C\le T\le 200°C\ (R^2=0.998)\\ 1.47-2.01\left(\frac{T}{1000}\right)+0.75\left(\frac{T}{1000}\right)^2, & 200°C<T\le 900°C\ (R^2=0.988)\end{cases} \quad (1)$$

$$\frac{f_{fT}}{f_f}=0.99+0.75\left(\frac{T}{1000}\right)-6.11\left(\frac{T}{1000}\right)^2,\ \ 20^{\circ}C\le T\le 300^{\circ}C\ (R^2=0.999) \quad (2)$$

$$\frac{f_{fT}}{f_f}=\begin{cases}0.98+1.06\left(\frac{T}{1000}\right), & 20^{\circ}C\le T\le 300^{\circ}C\ (R^2=0.999)\\ 3.26-8.28\left(\frac{T}{1000}\right)+5.76\left(\frac{T}{1000}\right)^2, & 300^{\circ}C<T\le 900^{\circ}C\ (R^2=0.996)\end{cases} \quad (3)$$

$$\frac{f_{fT}}{f_f}=1.02-0.88\left(\frac{T}{1000}\right),\ \ 20°C\le T\le 900°C\ (R^2=0.996) \quad (4)$$

Where f_{fT} and f_f are the flexural strength of RPC specimen after high temperature and at room temperature respectively (MPa); T is the heating temperature (℃); R^2 is the correlation coefficient to evaluate simulation result.

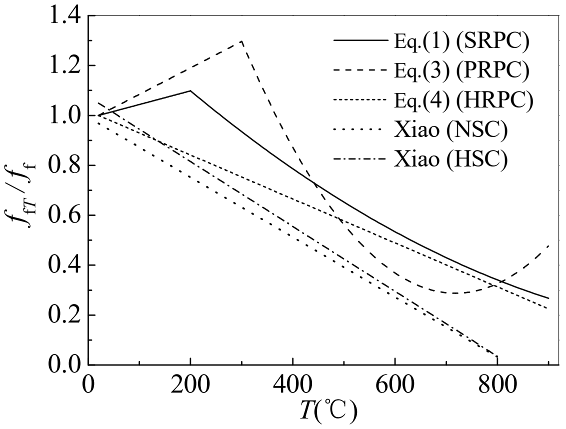


Fig. 9 - Flexural strength curves of RPC after high temperature.

4. Contrast of flexural strength for RPC, NSC and HSC

As shown in Figure 9, NSC is on behalf of the linear regression curve of normal strength concrete and HSC stands for the curve of high-strength concrete [21]. As can be seen from Figure 9, with increasing temperature, the residual flexural strength curves of NSC, HSC and HRPC decrease linearly, while the curves of SRPC and PRPC first increase and then decrease, and the curves of SRPC and HRPC decrease lower than the NSC and HSC. Because RPC does not contain coarse aggregate and incorporate with steel fibers, the internal cracks emerge and expand slowly when heating to a high temperature.

5. Conclusions

Through experimental research on the flexural strength of RPC after heating for temperatures up to 900℃, the following conclusions can be drawn.

(1) The incorporation of steel fibers can effectively reduce the damage and improve the residual flexural strength of RPC after heating to high temperature, and this effect is more obvious when the steel fibers volume dosage is up to 2%. The inhibition of polypropylene fibers to RPC spallig is not obvious, and the integrity of specimens can be ensured when the polypropylene fibers volume content of 0.3%.

(2) For specimens of RPC without steel fibers, the failure mode is brittle failure. On the contrary, for specimens with steel fibers, the failure mode presents obviously toughness because of the adding of steel fibers.

(3) The flexural strength of RPC with only steel fibers increases first and then decreases. The residual flexural strength of RPC with polypropylene fibers is lower than prime RPC when the temperature is not higher than 200℃, but greater than prime RPC when higher than 200℃. The residual flexural strength mixed with both steel fibers and polypropylene fibers decreases linearly with increasing temperature.

(4) Through regression analysis, formulas are proposed to express the decay of the flexural strength with increasing temperature, and the degradation of residual flexural strength is slow compared with NSC and HSC.

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