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Elevated Temperatures Impact on the Mechanical Behavior of Reactive Powder Concrete Containing Hybrid Fibers

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ABSTRACT

Reactive Powder Concrete (RPC) is a combined material that will allow the concrete industry to enhance material consumption, produce economic benefits, be more durable, and be more environmentally friendly. Due to the highly dense microstructure of RPC, it performs poorly at high temperatures due to the formation of high pore pressure, which causes material breakdown. This paper demonstrates the outcomes of an investigational study of the behavior of six RPC mixes incorporating hybrid steel and plastic waste (polypropylene) fibers after being subjected to high temperatures of up to 500 ºC. Residual compressive strength, residual splitting strength, and density were performed for all the RPC mixes. The results demonstrate that the drop in the compressive strength of RPC is greater than the reduction in their corresponding splitting strength. Furthermore, within a temperature range of about 500 ºC, this mechanical strength showed a noticeable decrease. The decrement of splitting strength ranged between about 8% to 33% . Steel and polypropylene fibers also improve the residual strength of RPC samples. On the basis of these results, a mix containing mixed fibers (25 % steel and 75 % polypropylene) is recommended as appropriate for extreme temperature applications.

تأثير الحرارة المرتفعة على الخواص الميكانيكية لخرسانة المساحيق الفعالة الحاوية على الياف مختلطة

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الملخص

خرسانة المساحيق الفعالة عبارة عن مادة مركبة ستسمح لصناعة الخرسانة بتحسين استهلاك المواد، وتحقيق فوائد اقتصادية، وتكون أكثر متانة، وتكون أكثر صديقة للبيئة. بسبب البنية المجهرية الكثيفة لخرسانة المساحيق الفعالة، فإنها أداءها يكون سيئ في درجات الحرارة المرتفعة بسبب تكوين ضغط عالي في المسامات، مما يؤدي إلى انهيارها. يوضح هذا البحث نتائج دراسة عملية لسلوك ستة خلطات من مختلفة من خرسانة المساحيق الفعالة تحتوي على ألياف مختلطة من الفولاذ والبلاستيك (البولي بروبلين)، بعد التعرض لدرجة حرارة عالية تصل إلى 500 درجة مئوية. تم حساب مقاومة الانضغاط المتبقية وقوة الانشطار المتبقية والكثافة لجميع خلطات توضح النتائج أن الانخفاض في مقاومة الضغط لخرسانة المساحيق الفعالة أكبر من الانخفاض في قوة الانشطار المقابلة. إضافة الى ذلك، في درجة حرارة حوالي 500 درجة مئوية، كما أظهرت خواص المقاومة الميكانيكية انخفاضًا ملحوظًا. تراوحت نسبة الانخفاض في مقاومة الانشطار من8% الى 33%. تعمل ألياف الفولاذ والبولي بروبلين أيضًا على تحسين المقاومة المتبقية لنماذج خرسانة المساحيق الفعالة. يوصى باستخدام مزيج يحتوي على ألياف مختلطة (25٪ فولاذ و 75٪ البولي بروبلين) مناسب لتطبيقات درجات الحرارة العالية على أساس هذه النتائج.

الكلمات المفتاحية:
الحرارة المرتفعة
الحريق
الياف البولي بروبلين
خرسانة المساحيق الفعالة
الياف الفولاذ
خواص المقاومة

Introduction

Over the last several decades, continuous growth in the construction sector has led to the implementation of several forms of concrete to

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serve diverse structural applications with a considerably better grade of strength and durability. Richard and Cheyrezy at Bouygues, France, produced one of the most recent concrete kinds, reactive powder concrete (RPC), in the early 1990s. RPC is a cementitious material made mainly of cement, fine sand, silica fume, steel fibers, superplasticizer, and water. RPC categorized as ultra-high performance concretes with compressive strength greater than 150 MPa. RPC was improved on the basis of the assumption that a material with minimum interior voids will have preferred structural behavior [1–3]. Dissimilar other concrete preparations, RPC omit coarse aggregates, and this causes denser microstructure, greater homogeneity, and superior mechanical characteristics besides improved durability. Moreover, the enhancement of 'granular packaging' and the employ of high range water reducing admixtures may acquire high workability properties. Even though the RPC's excellence in durability and strength, it exhibited inadequate performance under elevated temperature conditions. RPC can be a worthy choice to accomplish the practical requirements for many constructions such as wide arched towers, reactors, furnaces, and nuclear waste storage, but the opportunity of rapid exposure to fire is extremely limiting such application [4,5].

There is a variety of information available on the high temperature behavior of conventional concretes. Moreover, studies on the behavior of high-performance concretes are limited, much less the on Ultra High Performance Concrete (UHPC) like RPC. When exposed to high temperatures, dense concretes may develop a failure mechanism known as explosive spalling. During high temperatures environments, water in the concrete evaporates, and the dense morphology of RPC, combined with its low thermal conductivity, makes vapor escape difficult, resulting in high thermal stresses and high pore pressures. Since RPC's ductility is decreased as compressive strength increases, limiting its applicability in constructions, fibers are added to the concrete to mitigate brittleness. The fibers enhance the strength and ductility properties of the concrete. Spalling lowers the cross sectional area of sections and can result in higher temperatures of traditional steel strengthening. The usage of polypropylene and metallic fibers had been adopted to solve the situation of spalling of concrete at elevated temperature [6–8]. Hiremath and Yaragal [9] exhibited that the adding of polypropylene fiber was operative in restraining spalling of RPC at elevated temperature up to 800 ºC. Zheng et al. [10] demonstrated that 2% volumetric increments of steel fibers may prevent explosive spalling and improve the strength properties of the RPC. For steel fibers, when subjected to elevated temperatures, the dangerous or little degree of destruction that can lead to the cementitious matrix in RPC is supported by steel fibers. While utilizing polypropylene plastics fibers, they thaw out at about 185 ºC, and accordingly mist, can discharge concrete over the intersected holes.

Despite the fact that the residual compressive strength of high followability RPC declines with expanding fire duration, Liu and Huang [11] demonstrated that RPC has a better fire endurance temperature than normal concrete and high performance concrete, as well as a higher residual strength afterward a fire. The influence of steel fibers and elevated temperature on the mechanical characteristics of RPC was investigated by Abdelrahim et al. [12], According to the results of the tests, the Output temperature rises. When all samples were heated to 400 ºC, the compressive and splitting tensile strengths of RPC specimens were reduced.

Furthermore, the utilization of various waste materials, such as steel fibers, polypropylene (PP) fibers, and a hybrid of steel and PP fibers, is beneficial in preventing explosive spalling [13]. Steel fibers improve concrete's resistance to fire-induced spalling by enhancing its tensile capacity. Thus, the introduction of hybrid steel and PP fibers improves RPC performance at increased temperatures while avoiding the possibility of explosive spalling [14].

The intention of this investigation was to inspect some mechanical properties (initial and residual properties) of diverse mixes of RPCs (incorporating steel fibers, waste polypropylene fibers, and a conjunction of steel and waste polypropylene fibers) when exposed to high temperatures up to 500 ºC. The examined properties involved compressive strength, and splitting tensile strength, density.

Experimental work

1. Materials

The details and description of the materials used in this study are as follows:

Cement, In the present study, KERSTA ordinary Portland cement type was used. The chemical and physical properties were agreed upon as ASTM C-150 [15].

Silica fume, A micro silica fume with the brand Sika was used in this study. It fills the voids between cement particles, creating a very dense, less permeable concrete. The requirements for silica fume conform to ASTM C-1240 [16].

Fine aggregate, Natural sand was used in this study. Sand that passes through a 600mm sieve maximum size is used as fine aggregate in concrete mixes. The results indicated that the fine aggregate grading was within the requirements of the Iraqi specification ASTM C-33 [17].

The straight brass-coated steel fiber produced by Changhong Company in Anshan, Liaoning Province, was used. The average length was 13 mm, the average diameter was 0.22 mm, the tensile strength was 2850 MPa, and the elastic modulus was 200 GPa.

The plastic waste fiber utilized in this study was obtained from plastic rope (polypropylene twisted rope) and was cut into a small length (13 mm) and diameter (45 m). The tensile strength was 33 MPa, and the elastic modulus was 2.2 GPa, with a melting point of 170 ºC, as shown in Fig. (1). This would make the pervasion of plastic fiber inside the mix much easier.

Chemical Admixture, the chemical admixture utilized in this study is a third generation super plasticizer for concrete and mortar. It is an aqueous solution of modified polycarboxylates, which is known commercially as SikaViscocrete-5930, and a high-performance superplasticizer concrete additive. It was imported from the Sika company, and conformed to ASTM C494 [18].

Water, Potable water is used as a mixing water for all concrete mixes.

2. Mix proportion

The experimental program included two groups (one subjected to elevated temperatures and the other not subjected), each with five mixes as well as a reference mix prepared. The volumetric ratio of fiber (1%) was used, with five combinations (0 percent, 100% SF, 75% SF+25% WPF, 50% SF+50% WPF, 25% SF+75% WPF, and 100% WPF). The percentage mix of the reference mix was based on earlier local studies [19–22]. Table 1 shows the proportions for all mixtures.

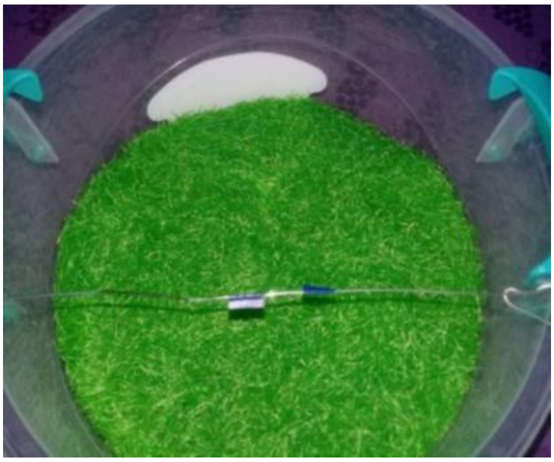

Fig. (1): Waste polypropylene plastic fiber.

Table 1: Mixes Proportions (kg/m^3)

Mixes	Cement	Sand	Silica Fume	W/C*	Sp.**%	Steel Fiber (SF)	Plastic Fiber (WPF)	Ratio of Fiber (1%)
Mix.1	880	970	220	0.175	5%	0	0	0
Mix.2	880	970	220	0.175	5%	78	0	100% SF
Mix.3	880	970	220	0.175	5%	58.5	2.2	75% SF+25%WPF
Mix4	880	970	220	0.175	5%	39	4.4	50% SF+50%WPF
Mix.5	880	970	220	0.175	5%	19.5	6.6	25% SF+75% WPF
Mix.6	880	970	220	0.175	5%	0	8.8	100% WPF

* water to cementitious materials ratio, ** Superplasticizer ratio.

3. Specimens preparation

After mixing preparation according to the method used in the previous studies, the mixture was cast into six steel mold cubes with a dimension of 50 mm and four mold cylinders with a dimension of 100 mm in diameter and 100 mm in height for each mix. Next, all specimens were vibrated, then covered with nylon for 24 hours. After that, the specimens were put in a water tank to cure at a temperature of 25–30 ºC. At the end of the period of curing, after 28 days, all specimens were taken out of the water tank and left to dry. The compressive, splitting strength, and density of all specimens were tested for six mixes of group one without being exposed to high temperatures. While all the specimens in group two were mixed into six mixes, they were placed in the burning furnace, which was made from fiber glass material and ceramic fiber plates, with an internal dimension of (64 ×64×100 cm). The burning furnace contains special plates made of carbon silicate to withstand high temperatures up to (1400 ºC) and weights up to 100 kg, with dimensions of 45 cm, as shown in Fig. (2). The temperature inside the burning furnace was controlled manually and was measured using thermocouples. The temperature was gradually raised to 500 ºC within around 2 hours (the program of burning was adapted from previous works [23,24]), and when it reached the required temperature, some specimens collapsed. After that, the furnace was left to cool for the rest of the day. After the burning was completed and the specimens were cooled, the compressive and splitting strengths were tested for the specimens.

Fig. (2): Burning Furnace.

Rustles and discussion

1. Compressive Strength:

In order to study the effect of mixed fiber (steel fiber (SF) and waste polypropylene fiber (WPF)) on the compressive strength of reactive powder concrete with and without exposure to high temperatures, twelve mixes were tested at the age of (28) days. They were divided into two groups (group one involved six mixes without exposure to high temperatures and group two involved the other six mixes exposed to high temperatures). Three cubes (50 mm) are used in this test. The results of compressive strength for six mixes without being exposed to high temperatures (group one) are shown in Fig. (3). From Fig. (3), the compressive strength for all mixes is greater than the control mix (Mix1) except for the mix containing (100%WPF). The percentages of increase for compressive strength, compared to control mix, are 39.6%, 25.06%, 12.5%, 5.45%, and -4.43%, respectively. These results were accepted with the results established by [25, 26]. While the results of compressive strength for mixes in group two are not recorded due to all specimens being collapsed, except the compressive strength of Mix5 was very low, at approximately 26 MPa. These results are similar to results obtained by previous researchers [27] after the specimens were subjected to a temperature of 500 ºC. The cause of the destruction of specimens might be the small surface area subjected to high temperatures for a long time.

2. Splitting Strength:

The splitting tensile strength test was performed according to ASTM C496-11 [28]. The average of two cylinders (100 mm in diameter and 100 mm in height) was used to determine the splitting tensile strength for each mix. Fig. (4) explains the outcomes of splitting strength for all mixes in group one. It is obvious from Fig. (4) that the values of splitting strength for all mixes are higher than the splitting strength for the reference mix. The increment percentage of splitting strength for all mixes compared with the reference mix is (36.21%, 21.21%, 13.41%, 8.53%, and 3.65%) respectively. This tendency to some extent was reported by previous authors [29,30]. It can be noted from the results that reducing the percentage of steel fiber causes a decrease in splitting strength. Fig. (5) shows the results of specimens for Mix2, Mix5, and Mix6 in group two after being exposed to a high temperature, while the specimens in other mixes (Mix1, Mix3, and Mix4) were distorted. It can be concluded that the size of surface area effects the failure of a specimen after being exposed to high temperatures. When comparing the results in groups one and two, the effect of temperature can be seen in the high reduction in splitting strength in Mix2. The mix contains a percent of steel fiber (100%), and the ratio reaches 33.39%. While the reduction ratios for Mix5 and Mix6 are equal to 8.98% and 8.35%, respectively, due to the increased ratio of waste polypropylene fiber.

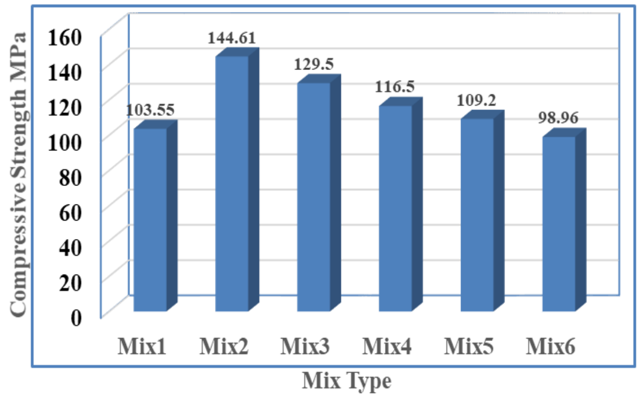

Fig. (3): The effect of fibers on the compressive strength (Group One: without heating).

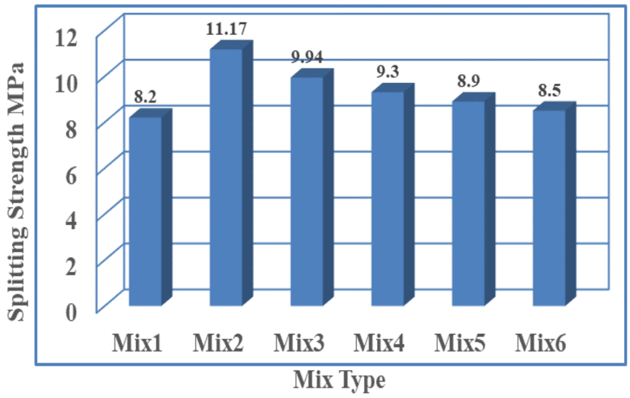

Fig. (4): The effect of fibers on the splitting strength (Group One: without heating).

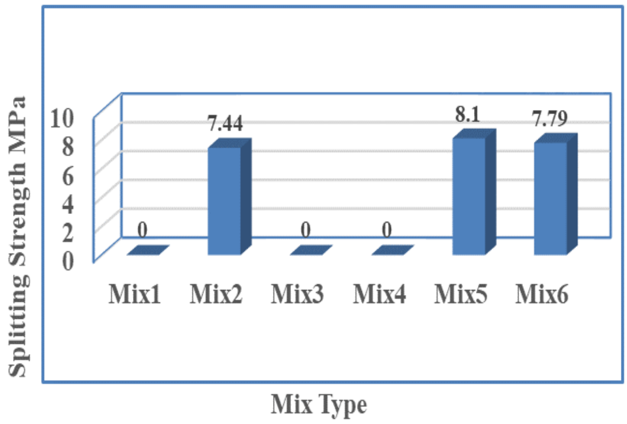

Fig. (5): The effect of mix fiber on the splitting strength (Group Two: with heating).

3. Density

Because the samples in group two were distorted, the density was only measured for the samples in group one. The average of three cubes and two cylinders for each mix was used for the density test. Fig. (6) illustrates the values of density for all mixes in group one, measured from cubes and cylinder samples. It can be seen from the results that the density for all mixes is higher than the density for control mix and the density value increased as the ratio of steel fiber increased and waste polypropylene fiber was reduced. This is because of the high density of steel fiber.

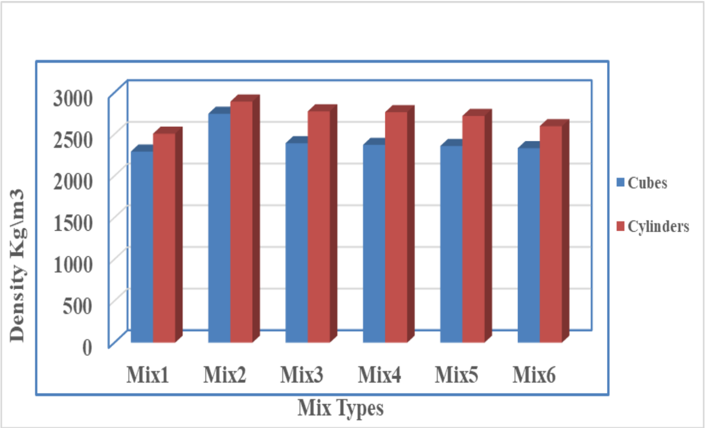

Fig. (6): The effect of mix fiber on density value (Group One: without heating).

Conclusions

The conclusions obtained from this study are summarized as follows:

1. The hybrid fiber contributed by improving the compressive strength of RPC mixes relative to non-fiber RPC mixes (group one) without being exposed to high temperatures. This improvement increased with the increasing steel fiber volume fraction. However, the effect of hybrid fiber on mixes in group two (exposed to high temperatures) was not seen because all specimens were exploded.
2. The positive effect of hybrid fiber on the splitting strength of all RPC mixes compared to the reference RPC mix (group one). While the behavior of splitting strength in group two improves with waste plastic fiber.
3. The effect of fiber on the density shows that these increased when the percentage value of steel fiber increased because of the high density of steel fiber.
4. The effect of high temperatures is clear on the results of splitting strength. When comparing some specimens in group one with those in group two, it can be seen that the ratios of splitting strength decrease when the waste plastic fiber is increased.

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