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Effect of Elevated Temperatures on Compressive and Tensile Strengths of Reactive Powder Concrete

Asst. Lec. Sana Taha Abdul-Hussain
Civil Engineering Department, College of Engineering, Al-Mustansiriya University

Abstract

An experimental investigation was conducted on the effect of elevated temperatures on mechanical properties of reactive powder concrete (RPC), mainly on compressive strength, flexural strength and splitting tensile strength. RPC was prepared using cement, silica fume, fine sand and steel fibers to cast and test 128 specimens (cubes, cylinders and prisms) with various steel fibers ratios of 0%, 1%, 2% and 3% at temperatures of 20°C, 200°C, 400°C and 600°C. Results generally show that the decrease in compressive strength, flexural strength and splitting tensile strength become larger when temperature exceeds 400°C. At 600°C the decreasing ratios were 17.8%, 38.87% and 58.58% for compressive strength, flexural strength and splitting tensile strength, respectively. Explosive spalling of RPC at elevated temperatures was also observed and discussed.

Key Words: *Reactive Powder Concrete, elevated temperatures, spalling.*

تأثير ارتفاع درجات الحرارة على مقاومة الأنضغاط ومقاومة الشد لخرسانة المساحيق الفعالة

م.م سنا طه عبد الحسين
قسم الهندسة المدنية، كلية الهندسة
الجامعة المستنصرية

الخلاصة

تم اجراء تحريات عملية على تأثير الأرتفاع في درجات الحرارة على الخصائص الميكانيكية لخرسانة المساحيق الفعالة و بشكل رئيسي على مقاومة الأنضغاط، مقاومة الأنثناء و مقاومة شد الأنفلاق. خرسانة المساحيق الفعالة المستخدم فيها السمنت،أبخرة السليكا، الرمل الناعم و ألياف الحديد لصب و فحص 128 نموذجا (مكعبات ، أسطوانات ومواشير) مع نسب مختلفة من ألياف الحديد هي0 %، 1 %، 2 %و 3 % عند درجات حرارة 20 °م، 200°م، 400°م و600°م. بشكل عام ،النتائج اظهرت ان مقدار الأنخفاض في مقاومة الأنضغاط، مقاومة الأنثناء و مقاومة شد الأنفلاق يكون أكبر عندما تتجاوز درجات الحرارة 400°م. عند درجة حرارة600°م نسبة الانخفاض17.8 %، 38.87 % و 58.57 % لمقاومة الانضغاط، مقاومة الانثناء و مقاومة شد الانفلاق على التوالي. كذلك تم ملاحظة و مناقشة التشظي الأنفجاري لخرسانة المساحيق الفعالة عند ارتفاع درجات الحرارة.

الكلمات المرشدة: خرسانة المساحيق الفعالة، درجات الحرارة المرتفعة، التشظي.

1. Introduction

Reactive Powder Concrete (RPC) is a new generation concrete it was developed through microstructure enhancement techniques for cementitious materials. As compared to ordinary cement-based materials, the primary improvements of RPC include the particle size homogeneity, porosity, and microstructures [1].

In general, RPC is characterized by very low water/binder (W/B) ratio below 0.2, and very dense microstructure formed by using a series of powders including cement, silica fume, and ground quartz sand. Cured under hot water condition, RPC may have compressive strength between 100 and 800 MPa [2].

Fire resistance is the property of a material or assembly to withstand fire or to give protection from it; as applied to elements of building, it is characterized by the ability to confine a fire or to continue to perform a given structural function, or both. (Defined in ASTM E176) [3].

With the gradual expansion of applications, more attention has been drawn to the mechanical properties of RPC structures or their components and the stability when subjected to high temperature or after high temperature. One of the important reasons is the phenomenon of strength reduction and explosive spalling commonly observed in high strength concrete (HSC) and high performance concrete (HPC) subjected to high temperature [4], which severely threatens the safety and durability of concrete structures in high temperature environment. How to avoid or mitigate the hazards caused by explosive spalling has become a very important research topic in application of HSC and HPC.

As a newly developed concrete with ultra-high strength and outstanding performance, it is difficult to ensure the safety of RPC structures and promotion and application of RPC would be impeded if the thermophysical properties and failure mechanism of RPC under high temperature or after high temperature are not well understood. In recent years, researches have been carried out on the properties of RPC under high temperature and the differences between RPC and normal HSC and HPC were revealed.

Tai et al. [5] investigated the residual strength and the stress-strain relationship of RPC under quasi-static loading after high temperature. It was found that compared with RPC under room temperature, the residual strength increased when the temperature rose to 200-300°C and then decreased remarkably after 300°C, and that the residual peak strain increased during 400-500°C and decreased gradually after 500°C.

Yang et al. [6] investigated the performance of RPC with steel fibers under dynamic compression in normal temperature and after being heated in temperatures of 400 and 800°C, respectively. It was shown that the peak stress and elastic modulus decreased remarkably after high temperature, which significantly affected the failure mode of RPC.

The research on HSC and HPC shows that explosive spalling under high temperature is related to many factors, such as the concrete strength, moisture content, heating rate, moisture migration ability, heat conductivity, specimen size, curing method, original material properties, etc.[7].

Liu et al. [8] found that the spalling of RPC occurred when the temperature at the core of the cubic specimen was about 250°C under a certain heating rate. Addition of steel fibers did not improve the spalling temperature significantly, but reduced the extent of the spalling. This effect became more prominent with higher fiber volume. However, due to the short history of development and application of RPC and the difficulty in loading tests under high temperature, few studies on the performance of RPC at high temperature have been reported.

The concrete compressive strength reduces after exposure to high temperatures (except at 150 °C) where at this temperature a little increase of about (4.45%) takes place. The percentage reduction in compressive strength after exposure to (300°C, 600°C and 800°C) is about (22%, 40% and 73%) respectively [9].

The concrete compressive strength and tensile strength are reduced after exposure to high temperature to a certain extent depending on the exposing temperature. For high strength concrete, the percentage reduction in strength for the 150mm×300mm cylinders with strength of 60 MPa after exposure to 150°C, 250°C, 400°C and 500°C were about 16%, 14%, 28% and 39%, respectively for the splitting tensile strength [10].

2. Experimental Program

2.1 Materials

2.1.1 Cement

Ordinary Portland cement (type I Tasluja-Bazian) which is produced in Iraq by the United Cement Company (UCC) was used in all test specimens. The chemical analysis and physical test results of the cement are given in **Tables (1)** and **(2),** respectively. They conform to the Iraqi specification No. 5/1984[11].

2.1.2 Silica Fume

Silica fume is a highly reactive material that is used in relatively small amounts to enhance the properties of concrete. The chemical composition and properties of silica fume are given in **Table (3).** The chemical analysis gives in **Table (3)** as in product catalog.

Table (1) Chemical composition of cement*

Compound Composition	Chemical Composition	Percent by weight	Iraqi specification No. 5/1984
Lime	CaO	61.19	-
Silica	SiO_2	21.44	-
Alumina	Al_2O_3	4.51	-
Iron Oxide	Fe_2O_3	3.68	-
Magnesia	MgO	2.31	Maximum 5
Sulfate	SO_3	2.7	Maximum 2.8
Loss on ignition	L.O.I	2.39	Maximum 4.0
Insoluble residue	I.R	1.18	Maximum 1.5
Lime saturation factor	L.S.F	0.87	0.66-1.02
Tricalcium aluminates	C_3A	6.06	-
Tricalcium silicate	C_3S	Not available	-
Dicalcium silicate	C_2S	Not available	-
Tricalcium alumina ferrite	C_4AF	Not available	-

*All tests were made at the National Center for Construction Laboratories and research.

Table (2) Physical composition of cement*

Physical Properties	Test Results	Iraqi specification No. 5/1984
Fineness using Blain air permeability apparatus(cm^2/gm)	4050	Minimum 2300
Soundness using autoclave method	Not available	Minimum 0.8%
Setting time using Vicat's instruments Initial (min.) Final (hr)	135 3:25	Maximum 45 Minimum 10
Compressive strength for cement Paste Cube(70.7mm) at: 3days (MPa) 7days (MPa) 28days (MPa)	24.4 32.3 47.2	Minimum 15 Minimum 23

*All tests were made at the National Center for Construction Laboratories and research.

Table (3) Composition and Properties of Silica Fume*

Composition (%) - property	Silica fume
SiO_2	98.87
Al_2O_3	0.01
Fe_2O_3	0.01
CaO	0.23
MgO	0.01
K_2O	0.08
Na_2O	0.00
Blaine fineness (m^2/kg)	200000

*Manufacturer Properties.

2.1.3 Steel Fibers

The characteristics of steel fibers used in the experimental program are given in **Table (4). Figure (1)** shows a sample of the used steel fibers.

Figure (1) Steel Fibers used in RPC

Table (4) Characteristics of steel fiber used*

Type of steel	Hooked
Relative Density	7860 kg/m^3
Yield strength	1130 MPa
Modulus of Elasticity	200 000 MPa
Strain at proportion limit	$5650*10^{-6}$
Poisson's ratio	0.28
Average length (L)	30 mm
Nominal diameter (d)	0.375
Aspect Ratio(L/d)	80

*Manufacturer Properties

2.1.4 Fine Aggregate

Fine aggregate from Al-najaf Al-ashraf region has been used. It is yellowish brown colored sand with rounded shaped particles and the grading and the properties of this sand shown in **Table (5).**

Table (5) Grading of the separated fine sand*

Sieve size (mm)	Cumulative passing %	Iraqi Specification No.45/1984/Zone 4 [12]
9.5	100	100
4.75	100	100-95
2.36	100	95-100
1.18	100	90-100
0.600	88	80-100
0.300	20	15-50
0.150	5	0-15

*The test has been performed in the Structural Material Laboratory of Engineering College of Al-Mustansyiria University.

2.1.5 Superplasticizer

A superplasticizer type which is known commercially as (Sika Visco Crete-PC 20) was used in this work. Sika ViscoCrete-PC 20 is a third generation superplasticizer for concrete and mortar. **Table (6)** indicates the technical description of aqueous solution of the superplasticizer used. It is free from chlorides and complies with ASTM C494 types A and F [13].

Table (6) Technical description of the used superplasticizer*

Main action	Concrete superplasticizer
Appearance/Colures	Light brownish liquid
Chemical base	Modified polycarboxylates based polymer
Density	1.09 kg/l, at 20 °C
PH	7
Chloride ion content%	Free
Effect on setting	Non-retarding

*Manufacturer Properties.

2.1.6 Water

Tap water has been used for concrete mixing and curing of specimens.

2.2 Mix Proportions

In most basic form, reactive powder concrete contains high content of Portland cement as main cementitious materials beside silica fume as a second supplementary cementitious component. Both sand to cement ratio (S/C) and water cement ratio (W/C) are low. The superplasticizer has been used in an appropriate ratio to give flowable concrete. In addition steel fibers are also added to enhance its properties. Many mix proportions were tried in this study to get maximum compressive strength. The variable used in the RPC mix was the volume ratio of steel fibers (four volume ratios were considered 0%, 1%, 2% and 3%). The mix proportions of RPCṡ are shown in **Table (7).**

Table (7) Mix proportions of reactive powder concrete mixes

Mixture description	RPC 0%	RPC 1%	RPC 2%	RPC 3%
Portland cement (C) (kg/m^3)	900	900	900	900
Silica fume (SF) (kg/m^3)	225	225	225	225
*Silica fume %	25	25	25	25
Fine sand (FS) (kg/m^3)	900	900	900	900
Steel fibers (kg/m^3)	0	78	156	234
**Steel fiber % (by volume)	0	1	2	3
Sika viscocrete (Kg/m^3)	56.25	56.25	56.25	56.25
***Sika viscocrete %	5.5	5.5	5.5	5.5
Water (W) (kg/m^3)	180	180	180	180
W/C	0.2	0.2	0.2	0.2
W/(C+SF)	0.16	0.16	0.16	0.16

*Percent of cement weight.
**Percent of mix volume.
***Percent of binder (cement + silica fume) weight.

2.3 Mixing Procedure

Mixing procedure proposed by Wille et al [14] was used in this research to obtain RPC in a simpler way without any accelerated curing regimes. Pan mixer of 0.056 m^3 capacity was used to prepare the concrete. Sand and silica fume were first mixed for 4 minutes, then cement was added and the dry component (cement, sand and silica fume) were mixed for 5 minutes. Superplastcizer was added to the water and stirred, then the blended liquid was added to the dry mix during the mixer rotation and the mixing process continues for 3 minutes. Then the mixing process was stopped to shovel the mix by hand and then restarted for 2 additional minutes. Finely, steel fibers were all added by hand within 2 minutes. The total mixing time was about 15 minutes.

2.4 Specimens preparation and casting procedure

Specimen's molds were cleaned thoroughly, tightened well and the internal surfaces were oiled with thin car engine oil to prevent the hardened Concrete adhesion with molds, various concrete specimens (128 specimens) are casted as follows: three (50mm×50mm×50mm) cubes for compressive strength, three (40mm×40mm×160mm) prisms for flexural strength, and two (70mm×140mm) cylinders for splitting tensile strength. A vibrating table is used for consolidation of RPC into the molds. After being molded, all the specimens are covered by polyethylene sheets for about 24 hours in a laboratory environment to prevent evaporation of water.

2.5 Curing

For each mix, various concrete specimens have been casted and cured. After 24 hours of casting the specimens were stripped from molds and placed in water containers in the laboratory to be cured at room temperature. Heat curing at elevated temperature was not used in this research in order to gain an advantage of producing RPC of exceptional mechanical properties using conventional curing method without any additional provisions.

3. Testing of Specimens and Experimental Results

The results are presented and discussed. They include the results of compressive strength, flexural and splitting tensile strength of (RPC) with different volume fraction percent of steel fiber at elevated temperatures of 200 °C, 400 °C and 600 °C. Some of specimens were put in the furnace as a dry state (after 3 days from curing) and some of these specimens were put as a moisture state (immediately after 28 days curing). The specimens are heated by an electrical furnace (Type Wanger) which has a capacity of 1300°C. The furnace internal dimensions are (500mm×600mm×750mm). The specimens are heated with slow heating rate. Once the required temperature level is attained, the specimens are thermally saturated for 60 minutes at the level. Then the furnace is switched off and the air cooling openings are opened. The specimens are left inside the furnace for about three hours and then after they are removed from the furnace they are stored in the laboratory to be cooled in air for about 24 hours before testing.

3.1 Compressive Strength

Three cubes of (50mm×50mm×50mm) for each mix are casted to determine the compressive strength and an average value is obtained according to ASTM C109/C109.02 [15]. Compressive strength test is performed by using universal testing machine (sans) of 1000 kN capacity in the Structural Material Laboratory of Engineering College of Al-Mustansyiria University.

3.1.1 Effect of Temperatures

The results of compressive strength tests for RPC are illustrated in Table (8) and Figure (2 and 3). Figure (2) shows that temperatures can be divided into two ranges in terms of effect on RPCṡ strength, namely 20°C-200°C and 200°C-600°C.

At 200°C the compressive strengths f_{cu} of all RPC mixes are slightly higher than the corresponding compressive strength for 20°C. The increasing ratios are 1.22%, 3.88%, 3.45% and 1.22% for RPC-0%, RPC-1%, RPC-2% and RPC-3% respectively as shown in Figure (3). The increase in compressive strength in the range of 20-200 °C this might be due to further hydration of cement residues or reaction between calcium hydroxide and minerals such as silica fume, and might be due to that RPC was cured normally.

At both 400°C and 600°C the compressive strength decreases. The decreasing ratio at 400°C are 5.49%, 2.47%, 1.41% and 0.32% for RPC-0%, RPC-1%, RPC-2% and RPC-3% respectively. The reason for this is the loss of water from the hydrated cement paste and possibly internal collapse [19]. While at 600°C the decreasing ratios are 10.94%, 13.45%, 13.69% and 17.8% for RPC-0%, RPC-1%, RPC-2% and RPC-3% respectively, as shown in Figure (3). This may be attributed to the decomposition of calcium hydroxide [16].

The results clearly show that the deterioration become greater when temperature rises after 400°C. However, the maximum decrease is only 17.8% at 600°C for RPC-3% but the risk of spalling at higher temperature become larger as will be discussed later.

3.1.2 Effect of Steel Fibers

Table (8) and Figures (4 and 5) show the effect of steel fibers ratio on compressive strength. Results show that the compressive strength increases with the increase of steel fiber ratio at all temperatures. When steel fibers ratio increases from 0% to 3%, compressive strength $f_{cu}/f_{cu(Vf=0\%)}$ increases by 25.51%, 25.5%, 32.37% and 15.84% at temperatures of 20°C, 200°C, 400°C and 600°C respectively.

These results show clearly that the increasing in compressive strength when steel fibers ratio increases, is higher at 400°C than other temperatures, while the less increase in compressive strength is observed at 600°C **(Figure 5).** As mentioned in previous section, the above results also indicate that the compressive strength of RPC shows faster deterioration when temperatures exceeds 400°C.

Table (8) Results of compressive strength

mix \ Temperatures		20 °C	200 °C	400 °C	600 °C
RPC-0%	f_{cu}	97.6	98.8	92.25	86.93
	$f_{cu}/f_{cu(T=20°C)}$ %	100	101.22	94.51	89.06
	$f_{cu}/f_{cu(Vf=0\%)}$ %	100	100	100	100
RPC-1%	f_{cu}	105.6	109.7	103	91.4
	$f_{cu}/f_{cu(T=20°C)}$ %	100	103.88	97.53	86.55
	$f_{cu}/f_{cu(Vf=0\%)}$ %	108.19	111.03	111.65	105.14
RPC-2%	f_{cu}	114	117.94	112.4	98.4
	$f_{cu}/f_{cu(T=20°C)}$ %	100	103.45	98.59	86.31
	$f_{cu}/f_{cu(Vf=0\%)}$ %	116.8	119.37	121.84	113.19
RPC-3%	f_{cu}	122.5	124	122.12	100.7
	$f_{cu}/f_{cu(T=20°C)}$ %	100	101.22	99.68	82.20
	$f_{cu}/f_{cu(Vf=0\%)}$ %	125.51	125.5	132.3	115.84

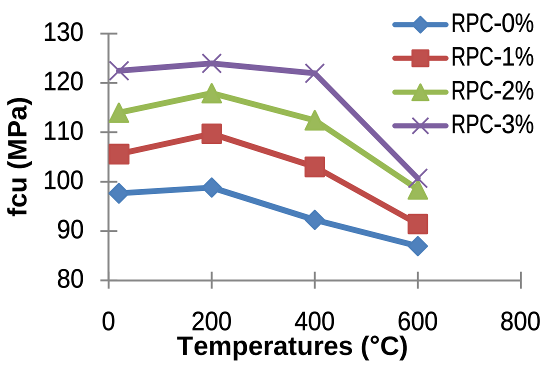

Fig. (2) Relationship between compressive strength and temperatures

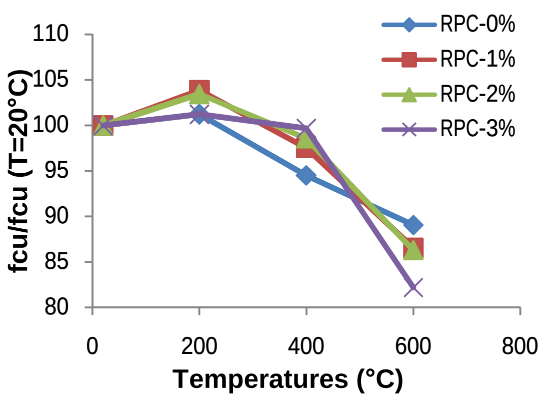

Fig. (3) Effect of temperatures on compressive strength ratios

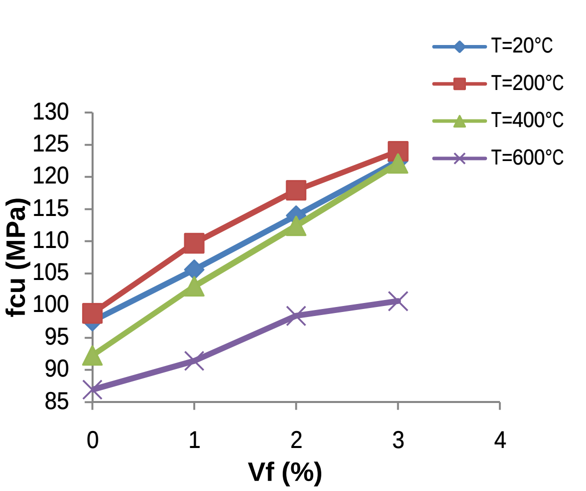

Figure (4) Relationship between compressive strength and steel fibers ratio

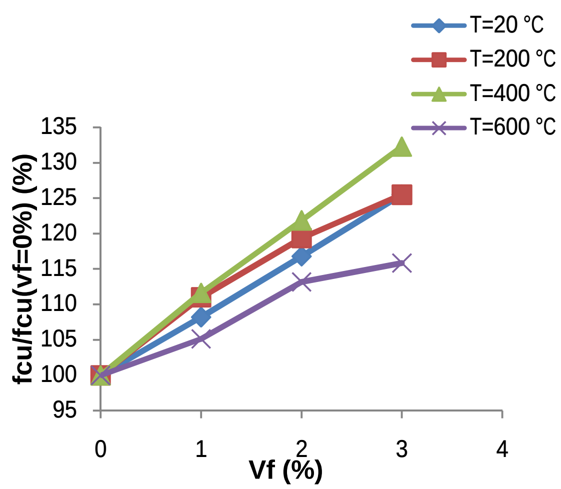

Figure (5) Effect of steel fibers ratios on compressive strength

3.2 Flexural Strength

The flexural strength is tested at the age of 28 days on prisms of (40mm×40mm×160mm) with one point loading according to ASTM C348-02 [17] on prisms with 100 mm span using a hydraulic testing machine (ELE) of 50 kN capacity in the Structural Material Laboratory of Engineering College of Al-Mustansyiria University.

3.2.1 Effect of Temperatures

The results of flexural strength tests for RPC are illustrated in **Table (9)** and Figure **(6 and 7). Figure (6)** shows that temperatures also can be divided into two ranges in terms of effect on RPCṡ strength, namely 20°C-200°C and 200°C-600°C.

At 200°C the flexural strengths f_r of all RPC mixes are slightly higher than the corresponding flexural strength for 20°C. The increasing ratios $f_r/f_{r(T=20°C)}$ are 37.11%, 49.61%, 19.5% and 11.8% for RPC-0%, RPC-1%, RPC-2% and RPC-3% respectively as shown in **Figure (7).**

At both 400°C and 600°C the flexural strength f_r decreases. The decreasing ratio $f_r/f_{r(T=20°C)}$ at 400°C are 9.91%, 4.03%, 3.24% and 16.14% for the mixes RPC-0%, RPC-1%, RPC-2% and RPC-3% respectively, while at 600°C the decreasing ratios are 58.02%, 25.77%, 32.17% and 38.87% for RPC-0%, RPC-1%, RPC-2% and RPC-3% respectively, as shown in **Figure (7).**

These results clearly show that the deterioration become greater when temperature rises after 400°C. However, the maximum decrease is 58.02% for RPC-0% at 600°C as shown in **Figure (7).**

3.2.2 Effect of Steel Fibers

Table (9) and **Figures (8 and 9)** show the effect of steel fiber ratio on flexural strength. Results show that the flexural strength increases with the increase of steel fibers ratio at all temperatures. When steel fibers ratio increases from 0% to 3%, flexural strength ratio $f_r/f_{r(Vf=0\%)}$ increases by 314.41%, 238.1%, 285.8% and 503.43% at temperatures of 20°C, 200°C, 400°C and 600°C respectively.

These results show clearly that the increasing in flexural strength when steel fibers ratio increases, is higher at 600°C than other temperatures, while the less increase in flexural strength is observed at 200°C (**Figure 9).** As mentioned in previous section, the above results also indicate that the compressive strength of RPC shows faster deterioration when temperatures exceeds 400°C.

Table (9) Results of flexural strength

Mix \ Temperatures		20 °C	200 °C	400 °C	600 °C
RPC-0%	f_r	**5.55**	**7.61**	**5.0**	**2.33**
	$f_r/f_{r(T=20°C)}$ %	100	137.11	90.09	41.98
	$f_r/f_{r(Vf=0\%)}$ %	100	100	100	100
RPC-1%	f_r	**10.44**	**15.62**	**10.02**	**7.75**
	$f_r/f_{r(T=20°C)}$ %	100	149.61	95.97	74.23
	$f_r/f_{r(Vf=0\%)}$ %	188.1	205.25	200.4	332.6
RPC-2%	f_r	**17.63**	**21.08**	**17.06**	**11.96**
	$f_r/f_{r(T=20°C)}$ %	100	119.5	96.76	67.83
	$f_r/f_{r(Vf=0\%)}$ %	317.65	277	341.2	513.3
RPC-3%	f_r	**23**	**25.73**	**19.29**	**14.06**
	$f_r/f_{r(T=20°C)}$ %	100	111.8	83.86	61.13
	$f_r/f_{r(Vf=0\%)}$ %	414.41	338.1	385.8	603.43

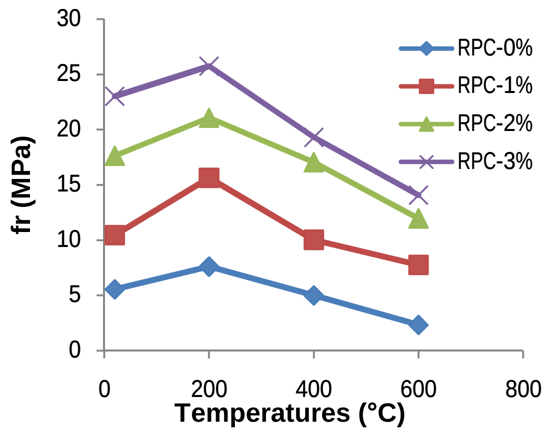

Fig. (6) Relationship between flexural strength and temperatures

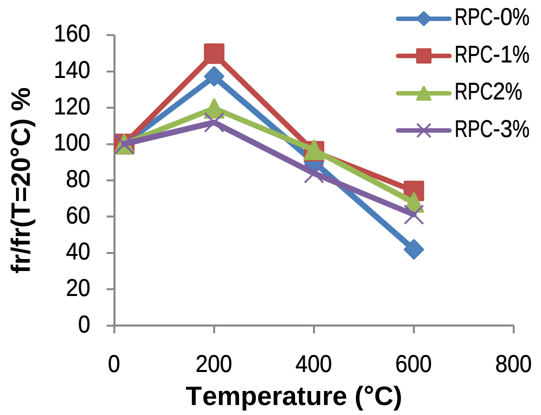

Fig. (7) Effect of temperaturs on flexural strength ratios

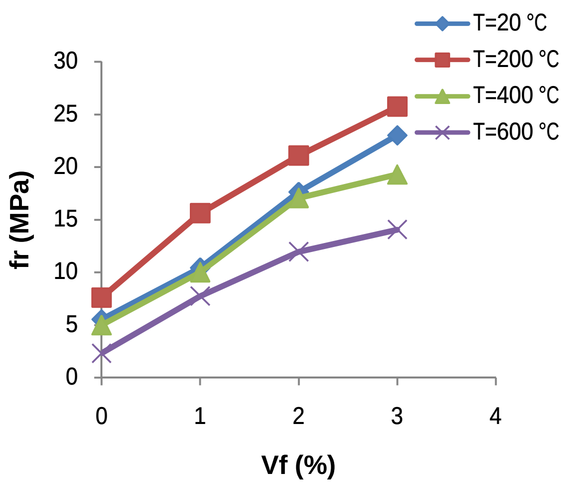

Fig. (8) Relationship between flexural strength and steel fibers ratios

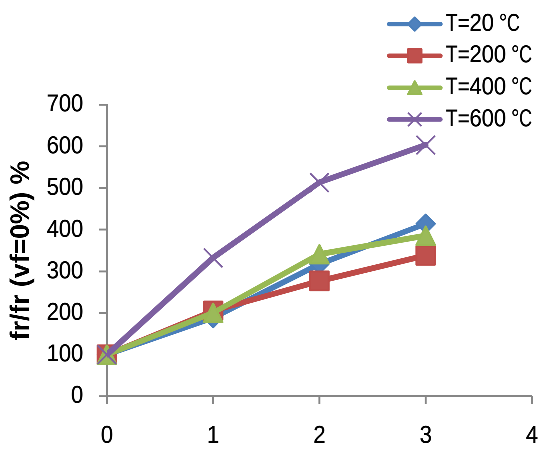

Fig. (9) Effect of steel fibers ratios on flexural strength ratios

3.3 Splitting Tensile Strength

The splitting tensile strength test was performed according to ASTM C496-04[18] on cylinder of (70mm×140mm) using universal testing machine (sans) of 1000 kN capacity in the Structural Material Laboratory of Engineering College of Al-Mustansyiria University. Average of two cylinders was used to obtain splitting tensile strength of each group.

3.3.1 Effect of Temperatures

The results of splitting tensile strength tests for RPC are illustrated in Table (10) and **Figure (10 *and* 11). Figure (10)** shows that temperatures can be divided into two ranges in terms of effect on RPCs̊ strength, namely 20°C-200°C and 200°C-600°C.

At 200°C the splitting tensile strengths f_s of all RPC mixes are slightly higher than the corresponding compressive strength for 20°C. The increasing ratios $f_s/f_{s(T=20\%)}$ are 6%, 4.4%, 13.7% and 8.2% for RPC-0%, RPC-1%, RPC-2% and RPC-3% respectively, as shown in **Figure (11).**

At both 400°C and 600°C the splitting tensile strength decreases. The decreasing ratio at 400°Care 3.2%, 22.72%, 3.99% and 7.09% for RPC-0%, RPC-1%, RPC-2% and RPC-3% respectively, while at 600°C the decreasing ratios are 82%, 83.76%, 71.3% and 58.57% for RPC-0%, RPC-1%, RPC-2% and RPC-3% respectively, as shown in **Figure (11).**

These results clearly show that the deterioration become greater when temperature rises after 400°C. The maximum decrease is 83.76% at 600°C for RPC-1%.

3.3.2 Effect of Steel Fibers

Table (10) and **Figures (12** and **14)** show the effect of steel fibers ratio on splitting tensile strength. Results show that the splitting tensile strength increases with the increase of steel fibers ratio at all temperatures. When steel fibers ratio increases from 0% to 3%, splitting tensile strength $f_s/f_{s(Vf=0\%)}$ increases by 190.6%, 196.79%, 178.92% and 568.88% at temperatures of 20°C, 200°C, 400°C and 600°C respectively.

These results show clearly that the increasing in splitting tensile strength when steel fibers ratio increases, is higher at 600°C than other temperatures, while the less increase in compressive strength is observed at 400°C (**Figure 13).**

Table (10) Results of splitting tensile strength

Mix / Temperatures		20 °C	200 °C	400 °C	600 °C
RPC-0%	f_s	**5**	**5.3**	**4.84**	**0.9**
	$f_s/f_{s(T=20°C)}$ %	100	106	96.8	18
	$f_s/f_{s(Vf=0\%)}$ %	100	100	100	100
RPC-1%	f_s	**7.88**	**8.23**	**6.09**	**1.28**
	$f_s/f_{s(T=20°C)}$ %	100	104.4	77.28	16.24
	$f_s/f_{s(Vf=0\%)}$ %	157.6	155.28	125.82	142.22
RPC-2%	f_s	**11.53**	**13.11**	**11.07**	**3.31**
	$f_s/f_{s(T=20°C)}$ %	100	113.7	96.01	28.7
	$f_s/f_{s(Vf=0\%)}$ %	230.6	247.35	228.7	367.77
RPC-3%	f_s	**14.53**	**15.73**	**13.5**	**6.02**
	$f_s/f_{s(T=20°C)}$ %	100	108.2	92.91	41.43
	$f_s/f_{s(Vf=0\%)}$ %	290.6	296.79	278.92	668.88

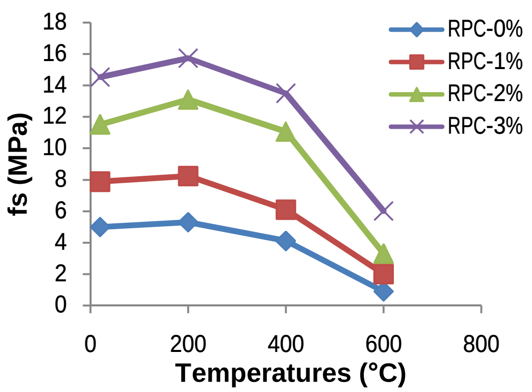

Fig.(10) Relationship between splitting tensile strength and temperatures

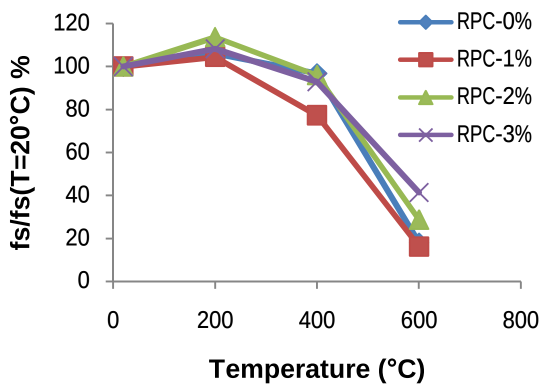

Fig. (11) Effect of temperatures on splitting tensile strength ratios

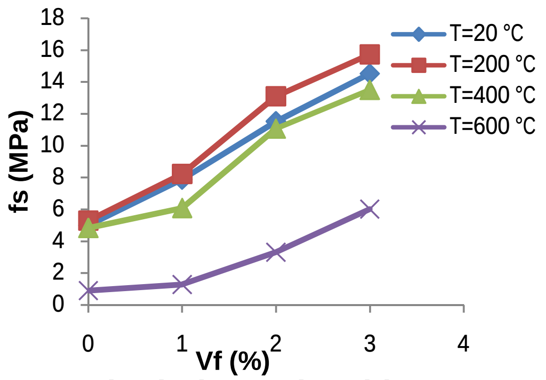

Fig. (12) Relationship between splitting tensile strength and steel fibers ratios

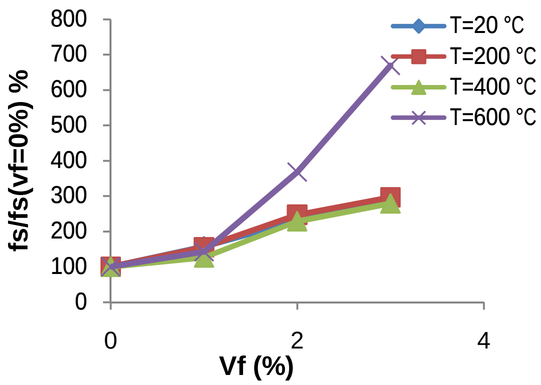

Fig. (13) Effect of steel fibers ratios on splitting tensile strength ratios

3.4 Explosive Spalling

In this section observations on spalling of RPC under elevated temperature will presented and discussed.

Explosive spalling of high-performance concrete under high temperature is related to many factors, such as the concrete strength, moisture content, heating rate, moisture migration ability, heat conductivity, specimen size, curing method, original material properties, etc.[7]. During testing of wet specimens (specimens' subjected to elevated temperatures immediately after removal from water) of RPC, it is found that moisture content plays a major role in explosive spalling. At 400°C, among the four types of RPC, the mix of 3% fraction volume suffered less spalling damage, as shown in **Figures (14).**

Wet specimens of RPC mixes with 0% steel fibers at 600°C were found to show greater degree of explosive spalling which means that more broken pieces were formed by spalling of this mix. However, the addition of steel fibers to RPC limited the explosive spalling and prevented the concrete specimens from separation into pieces as shown in **Figure (15).**

This result is according to the pore pressure mechanism, the microstructures of RPC are very compact with small and discontinuous pores. The vapor inside concrete can hardly escape as the temperature increases, which result in increasing pore pressures and temperature gradient. When the pore pressure in the matrix reaches the tensile strength of concrete, explosive spalling occurs [7]. This can leads to deterioration of the concrete structure.

For dry specimens (specimens that air dried for 3 days after removal from water) the pore pressure will be less than that of wet specimens which may reduce the risk of spalling as observed in this research. However, the study of spalling in RPC is not the major aim of this research and further investigations focused on the effect of the factors mentioned above on the spalling (especially the effect of moisture content).

Fig.(14-a) Explosive spalling of wet RPC-0% at 400°C.

Fig. (14-b) Explosive spalling of wet RPC-1% at 400°C

Fig. (14-c) Explosive spalling of wet RPC-2% at 400°C

Fig.(14-d) Explosive spalling of wet RPC-3% at 400°C

Fig. (15-a) Explosive spalling of wet RPC-1% at 600°C

Fig.(15-b) Explosive spalling of wet RPC-2% at 600°C

Fig. (15-c) Explosive spalling of wet RPC-3% at 600°C

4. Conclusions

Based on the experimental results in this research, the following conclusions can be drawn:

1. It is possible to produce reactive powder concrete with compressive strength 122.5MPa, flexural strength 23MPa and splitting tensile strength 14.53MPa using normal curing at room temperature. So with the mixing procedure adopted in this research, there is no need to use heat curing to produce reactive powder concrete (at least of the levels of strengths obtained in this research).

2. At relatively low fire temperature 200°C there is no deterioration in mechanical properties of RPC. Furthermore, there is a slight increase in mechanical properties. This may be attributed to the further hydration of cement residues or reaction between calcium hydroxide and minerals such as silica fume under this temperature.

3. At higher fire temperatures 400°C and 600°C, mechanical properties of RPC show a clear decrease. At 400°C, the loss of water from the hydrated cements paste and possibly internal

collapse. At 600°C, the deterioration may be attributed to the decomposition of calcium hydroxide.

4. The mechanical properties of RPC are increased as steel fibers ratio increased from 0% to 3% at all temperatures. A greater effect of steel fibers ratio on flexural strength and splitting tensile strength is recorded at 3% steel fibers especially at higher temperatures (600°C) where the increasing ratio of flexural strength and splitting tensile strength are 503.4% and 568.88% respectively. This reflects the importance of higher steel fibers ratio at higher temperatures.

5. The risk of explosive spalling was observed to be more in wet specimens than in dry specimens. This can be attributed to the higher pore pressure in wet specimens.

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