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# EFFECT OF ELEVATED TEMPERATURE ON DEGRADATION BEHAVIOUR OF REACTIVE POWDER CONCRETE MADE WITH RUBBER TIRE WASTES AS AN AGGREGATE REPLACEMENT

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## ABSTRACT

The recycling of the solid wastes (such as rubber tire wastes) is one of the major problems that represent a global challenge with the large population growth due to their environmental impact. Reactive powder concrete (RPC) has gained worldwide attention due to its superior strength, notable deformation, and excellent durability. Due to the low permeability of reactive powder concrete, at elevated temperature, free water is prevented from escaping, causing a high internal pressure and leading to spalling. Thus, this study was executed to explore the behaviour of reactive powder concrete made with rubber tire wastes (RW) as a partial replacement of fine aggregate (by volume) under elevated temperature. In addition to the control, nine RPC mixes divided into three groups were cast. The first group included replacing of aggregate with 15%, 25% and 50% of RW. Steel fibres in proportions 0.5%, 1% and 2% by weight of cement were used in the second group. In the third group, polypropylene fibres in the percentages 0.5%, 0.75% and 1% by volume of concrete were utilized. The fine aggregate for each mix in the second and third groups was substituted with 15% of RW. After 28 days of curing, the hardened specimens were air-dried and placed in a controlled oven. The considered temperature rates were 25, 200, 300 and 400 °C. The specimens remained at the target temperature for 2 hours then their behaviour was observed by compressive strength, weight loss, ultrasonic pulse velocity and visual inspection tests. Results showed that RW reduced the compressive strength of RPC compared to plain specimens (without RW) at ambient temperature. At elevated temperature, it was revealed that all specimens were broken at 400 °C except for 50% substitution of rubber tire wastes which had noticeable residual strength.

**Keywords:** reactive powder concrete, rubber tire wastes, elevated temperature, compressive strength.

## 1. INTRODUCTION

Reactive powder concrete (RPC) has gained worldwide attention due to its superior strength, notable deformation, and excellent durability. To date, it has many applications in various engineering fields, such as underground tunnels, infrastructure, and transportation [1]. The main ingredients of reactive powder concrete include cement, quartz sand, silica fume, and so forth. The coarse aggregate is removed in the reactive powder concrete [2, 3]. Despite its excellent performance, there are some weaknesses in RPC, such as the high cost of materials and the high cement content (800-1000 kg) [4]. As a result of their excellent mechanical properties, it is possible to reduce the thickness of RPC elements and thus reduce the cost of materials. Cement content can also be decreased in the mixture by using supplementary cementitious materials [5]. The RPC is recognized by dense microstructure and very low water content [6]. Due to the low permeability of reactive powder concrete, at elevated temperature, free water is prevented from escaping, causing a high internal pressure that leading to the spalling [7]. Therefore, appropriate solutions should be considered to address this problem.

The recycling of the solid wastes is one of the major problems that represent a global challenge with the large population growth. Rubber tire residues (wastes) are an important part of these solid wastes and pose a threat to the environment. In some countries, rubber tires are burned for use as a fuel and therefore result in additional health risks [8]. In addition, it is not easy to decompose the organic rubber residues even after a long period of time. Tires are durable and chemically stable materials, but they contain water-soluble compounds can seep into groundwater and are toxic to aquatic organisms [9]. Incorporating the rubber tire wastes in the concrete was discussed by many previous works.

Topçu and Demir [10] studied the behaviour of rubberized mortar and concrete under freeze-thaw, seawater, and high temperature. The rubber tire wastes were used in proportions 10%, 20%, 30% and 40% as a replacement of the fine aggregate volume. The temperature range was 20 ºC to 400 ºC. It was found that the compressive strength decreased with the increasing of rubber ratio in the mix. Additionally, the compressive strength values of the burned specimens were increased at 300 ºC then decreased at 400 ºC. The optimum rubber substitution ratio among different durability properties of that study was 10%.

Khaloo *et al* [11] explore the influence of rubber tire wastes in the range 12.5%-50% as an aggregate replacement (by volume). Results indicated that rubberized concrete appeared large reduction in tangential modulus of elasticity and compressive strength related to plain concrete.

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Based on the above, it is believed that the introduction of rubber tire wastes in the concrete industry as a partial replacement of aggregate is a worthwhile issue in terms of improving the environment and reducing the depletion of natural resources. This paper aims to study the effect of the use of rubber tire wastes as a partial replacement of the fine aggregate up to 50% on the degradation behaviour of the reactive powder concrete exposed to the elevated temperature with/without steel or polypropylene fibres.

## 2. MATERIALS AND METHODS

The ingredients used to manufacture the reactive powder concrete (RPC) in this study were: cement, sand, micro silica (silica fume), rubber tire wastes (RW), superplasticizer, steel fibres (StF) and polypropylene fibres (PP). Limestone cement type CEM II/A-L 42.5R conforms to the Iraqi specifications IQS NO 5/1984 [12] was used. The chemical composition of the cement is shown in Table-1. Natural sand with grading range 0.15-1.18 mm (see Figure-1) and an average density of 1525 ±10 Kg/m3 was used as fine aggregate. To adjust the workability of the fresh RPC, Glenium 54 (G54) superplasticizer which conforms to type A and F of ASTM C494 [13] was employed. In order to be used as partial replacement of the natural sand, the rubber tire wastes (Figure-2a) were brought from AL-Najaf Tires Factory (south of Iraq), where the old tires were washed and cut into different sizes. The RW (average density of 440 ±5 Kg/m3) were sieved to be within the range 0.15-1.18 mm, as seen in Figure-1. Densified micro silica commercially called MS610 purchased from BASF company was utilized as a cement replacement. The fineness, unit weight and purity of the micro silica were, respectively, 20000 m2/kg, 2300 kg/m3 and > 90%. Steel and polypropylene fibres (see Figure-2b) were also employed to investigate their influence on the behaviour of the RPC. The properties of steel and polypropylene fibres are illuminated in Table-2.

Ten mixes were carried out for this study. One control mix and three groups each one consists of three mixes. In the first group, the natural sand was replaced (by volume) with the RW in proportions 15%, 25% and 50%. Steel fibres were added in three percentages (0.5%, 1% and 2% by weight of cement) in the second group. While, in the third group, polypropylene fibres were added up to the RPC in three ratios 0.5%, 0.75% and 1% by concrete volume. In the second and third group mixes, the fine aggregate was replaced by 15% of the RW. The cement for all mixes was replaced by a fixed proportion of micro silica (20% of cement weight). The details of all mixes can be seen in Table-3. A planetary mixer with 10-liter capacity and two-speed rates (110 rpm and 360 rpm) was used to mix the RPC materials. The only slow speed (110 rpm) were taken into account for mixing. The depended mixing procedure was as follow:

- All dry materials were fed into the mixer and allowed to operate for two minutes;
- After that, the mixer was stopped, then the mixing water and the superplasticizer (which were mixed previously) were added and all ingredients were mixed for two minutes;
- The mixer, afterward, was rested for one minute;
- Thereafter, the RPC materials were mixed for five minutes; and
- The fibres (if any) then added while the mixer is working and the mixing time was extended for additional three minutes.

So, the total mixing time was ten minutes in the absence of fibres and thirteenth minutes in the presence of fibres.

**Table-1.** The chemical composition of cement.

| Oxides | Content, % |
|---|---|
| CaO | 62.1 |
| $SiO_2$ | 22.1 |
| $Al_2O_3$ | 4.2 |
| $Fe_2O_3$ | 3.9 |
| MgO | 3.3 |
| $SO_3$ | 1.9 |
| Free lime | 0.7 |
| L.O.I. | 3.1 |
| L.S.F. | 0.86 |
| Insoluble residue | 1.1 |

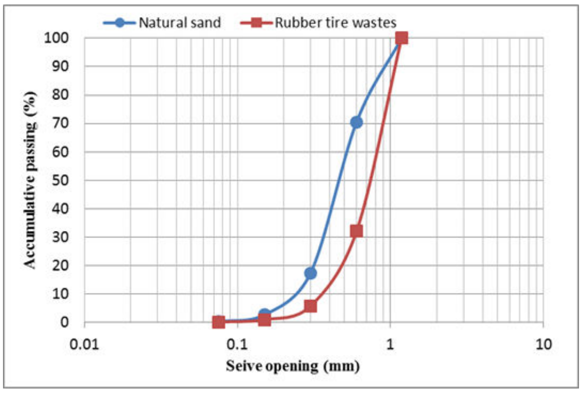


**Figure-1.** Grading of the natural aggregate (sand) and rubber tire wastes.


**Figure-2.** (a) Rubber tire wastes, (b) steel and polypropylene fibres.

The flow of the fresh RPC was measured according to ASTM C1437 [14]. After mixing ending, a number of 12 (50×50×50 mm) cubes were cast in metal standard moulds for each mix. So, a total of 120 cubes were made for this study. The fresh RPC mixes were compacted using a vibrated table. After 20-24 hours of curing in the moulds, the specimens were left and placed in water tanks for 27 days. At 28 days, the specimens were taken out and dried indoors for at least 7 days before exposure to elevated temperature. Four temperature rates were considered: 25, 200, 300 and 400 ºC. Three cubes were cast for each target temperature. The specimens want to burn were fed into a controlled oven and allowed to soak at the target temperature for two hours. The temperature increasing rate of the oven was 30 ºC/min. The degradation behaviour under elevated temperature for the different mixes was monitored through the compressive strength loss, weight loss, ultrasonic pulse velocity and visual inspection tests.

**Table-2.** Properties of steel and polypropylene fibres.

| Property | Value | |
|---|---|---|
| | **Steel fibres** | **Polypropylene fibres** |
| Tensile strength (MPa) | 2600 | 320-400 |
| Density (kg/m$^3$) | 7800 | 910 |
| Length (mm) | 15 | 12 |
| Diameter (mm) | 0.2 | 0.18 |
| Aspect ratio | 75 | 67 |
| Melting point (ºC) | --- | 160 |

**Table-3.** Mix proportion details for 1 kg/m$^3$ of reactive powder concrete.

| Mix designation | Cement | Silica fume* | Sand | Rubber tire wastes* | Steel fibres* | Polypropylene fibres ** | Water/ binder | Super-plasticizer* |
|---|---|---|---|---|---|---|---|---|
| Con | 920 | 230 (20%) | 1150 | 0 | 0 | 0 | 0.18 | 28.75 (2.5%) |
| 15RW+0.5StF | 920 | 230 (20%) | 978 | 49 (15%) | 5.75 (0.5%) | 0 | 0.18 | 28.75 (2.5%) |
| 15RW+1StF | 920 | 230 (20%) | 978 | 49 (15%) | 11.5 (1%) | 0 | 0.18 | 28.75 (2.5%) |
| 15RW+2StF | 920 | 230 (20%) | 978 | 49 (15%) | 23 (2%) | 0 | 0.18 | 28.75 (2.5%) |
| 15RW | 920 | 230 (20%) | 978 | 49 (15%) | 0 | 0 | 0.18 | 28.75 (2.5%) |
| 25RW | 920 | 230 (20%) | 863 | 82 (25%) | 0 | 0 | 0.18 | 28.75 (2.5%) |
| 50RW | 920 | 230 (20%) | 575 | 164 (50%) | 0 | 0 | 0.18 | 28.75 (2.5%) |
| 15RW+0.5PP | 920 | 230 (20%) | 978 | 49 (15%) | 0 | 0.455 (0.5%) | 0.18 | 28.75 (2.5%) |
| 15RW+0.75PP | 920 | 230 (20%) | 978 | 49 (15%) | 0 | 0.68 (0.75%) | 0.18 | 28.75 (2.5%) |
| 15RW+1PP | 920 | 230 (20%) | 978 | 49 (15%) | 0 | 0.91 (1%) | 0.18 | 28.75 (2.5%) |

* The per cent (%) is by weight of the binder.
**Polypropylene fibres per cent (%) are by volume of the concrete.

## 3. RESULTS AND DISCUSSIONS

### 3.1 Visual inspection

The colour change, the presence of cracks and spalling state of the RPC specimens were observed. It can be noticed for the burned samples that at 200 °C there was no significant change in colour and no visible cracks on the surface of the cubic specimens. At 300 °C, the colour of the cubes was found to be light grey and some samples showed brown colour. In addition, the 15RW+0.5StF and 25RW mixes were completely broken. At 400 °C, all samples were broken except for 50RW specimens where they preserved their shape with some hair cracks found as shown in Figure-3.

### 3.2 Weight loss results

The weight loss results of RPC mixes after exposure to the elevated temperature are shown in Figure-4. It can be seen from the figure that the weight loss increases with the temperature increase which is considered as a logical behaviour. However, at 200 ºC, the 50RW mix recorded 6.3% loss in weight compared to only 1.6% for control mix (about 4 times). At 300 ºC, the maximum weight loss was also found in the 50RW mix, about 8.9%, in comparison to the control specimen (3.3%). The evaporation of capillary, adsorbed and interlayer water could be the reason for the initial weight loss in concrete [15]. For steel fibre mixes, at 200 ºC, the weight loss values were more than the control mix for 0.5% StF

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addition while the situation was reversed for 1% and 2% StF (the weight loss was 1.4% for both). The same trend was noticed at 300 ºC for 15RW+1StF and 15RW+2StF mixes. The weight loss values in the presence of polypropylene fibres were less than that for control sample at 200 ºC and 300 ºC except for 1%PP which yielded higher loss at 400 ºC (6.3%). This behaviour for 1%PP can be attributed to the increase of the water evaporating as a result of the channels that left after melting of the PP fibres, where, these channels increased with the increase of the polypropylene fibres content [2].


**Figure-3.** (a) Spalling of specimens in the oven at 400 °C, (b) cube with hair cracks at 400 °C (for 50RW mix).

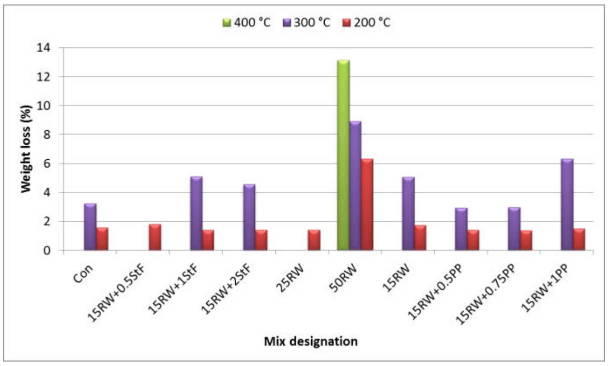


**Figure-4.** Weight loss results for reactive powder concrete mixes at elevated temperature.

### 3.3 Compressive strength results

Results of compressive strength test are illustrated in Figures 5 and 6. At ambient temperature, results indicated that the presence of rubber tire wastes reduced considerably the compressive strength compared to the plain specimens. The higher the replacement of aggregate with the rubber wastes the higher the reduction in compressive strength. The decreasing in strength were 9%, 23% and 45% for 15%, 25% and 50% substitutions of natural sand with rubber tire wastes. In the presence of polypropylene and steel fibres, the compressive strength values remained less than for the control sample except for 15RW+0.5StF mix which awarded 6% enhancement.

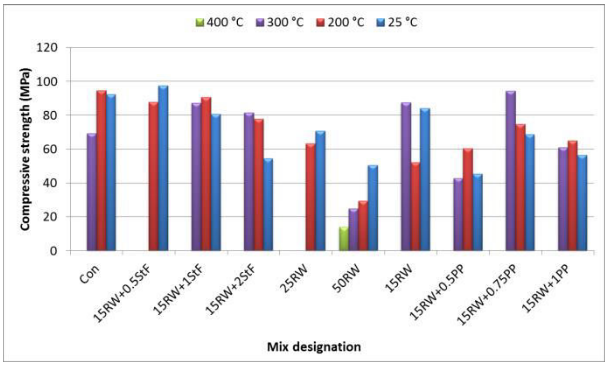


**Figure-5.** Compressive strength results at different temperature rates.

For elevated temperature, the compressive strength results were compared with that at 25 ºC for each mix. In general behaviour, the 15RW+0.5StF and 25RW mixes were fragmented at 300 ºC. On the other hand, all mixes except for 50RW, lost completely (spalling) their strength at 400 ºC. At 200 ºC temperature, the control specimens showed 3% increase in compressive strength, while the residual strength was 75% at 300 ºC.

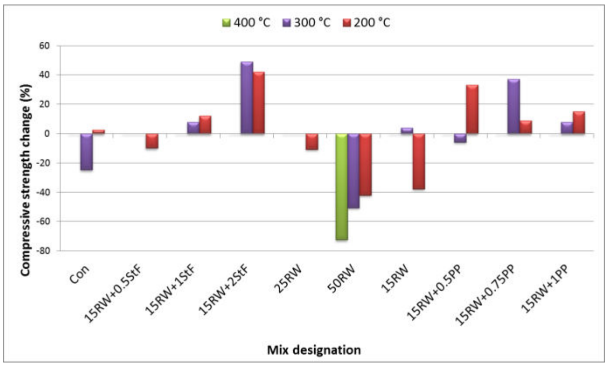


**Figure-6.** Compressive strength change percentages after exposing to elevated temperature.

The results also revealed that the residual strength of 15%, 25% and 50% rubber replacements at 200 ºC were 62%, 89% and 58% respectively. While 25RW specimens were fragmented at 300 ºC, the 15RW mix exhibited an increase in compressive strength related to those at 25 ºC. The 50RW mix was the only one that showed residual strength at 400 ºC, about 28%, which indicated the role of rubber tire wastes to create channels into the concrete that absorbed the vapour pressure inside the pores and prevented the spalling to be taken place.

The polypropylene fibres mixes showed an improvement in compressive strength at 200 ºC. The improvement was continued at 300 ºC for 15RW+0.75PP and 15RW+1PP mixes (by about 37% and 8% respectively), however, the 15RW+0.5PP mix appeared 94% residual strength. For steel fibres mixes, the adding of 0.5% steel fibres showed 90% residual strength at 200 ºC and chipped at 300 ºC. On the other hand, the presence of 1% and 2% of steel fibres enhanced the compressive strength by (12% and 42%) and (8% and 49%) at 200 and

300 ºC respectively compared to their values at ambient temperature.

The strength increasing after exposure to 200 ºC or 300 ºC can be attributed to the water removal that led to increasing the Van der Walls forces between gel particles [16, 17]. This behaviour can be supported by the role of steel and polypropylene fibres. Steel fibres can prevent the cracking from passing inside the concrete in addition to its role in dominating the vapour pressure under elevated temperature [18]. Otherwise, polypropylene fibres can melt beyond 165 ºC and left channels for thermal energy and water vapour to be escaped [2]. However, this behaviour was noticed up to 300 ºC, were after that (at 400 ºC), as mentioned above, all fibres contained specimens were fragmented.

### 3.4 UPV results

The ultrasonic velocity results of RPC mixes are illuminated in Figure-7. The UPV values were obtained by dividing the pulse time required to move within the concrete by the cube side (50 mm). The UPV is affected by the medium in which pulse is transformed [19]. The denser the structure (less porous) of the medium the higher the velocity and vice versa. In addition to the porosity, the UPV values are influenced by aggregate type, moisture content and the interfacial transition zone properties [20]. It can be seen from results that, at ambient temperature, the UPV values of all mixes contained rubber tire wastes were less than control mix (without RW). The reduction rates were within the range 8% to 11%, except for 50RW mix where the reduction in the velocity was 19%.

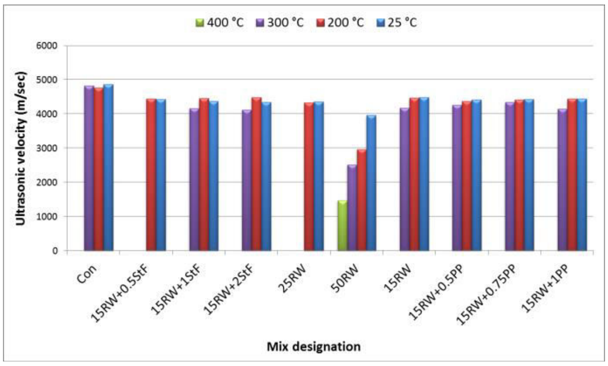


**Figure-7.** Ultrasonic pulse velocity results at different temperature rates.

At elevated temperature, the results indicated that the change in UPV values for all mixes was not exceeded (-1% to +3%) at 200 ºC and (-1% to -7%) at 300 ºC in comparison with their corresponding values at ambient temperature, except for 50RW mix. The 50RW mix showed a reduction in the UPV in the rates 25%, 37% and 63% at 200 ºC, 300 ºC and 400 ºC respectively. This behaviour of 50RW mix at the elevated temperature indicated that the high content of rubber wastes (50% of aggregate) created a porous structure that led to reducing the UPV values. Similar results were found in previous work [11]. However, this porous structure had an important role in absorbing the vapour pressure inside the RPC and prevented the spalling to be happened at 400 ºC.

## 4. CONCLUSIONS

Based on the findings obtained in this study, the following conclusions can be derived:

a) At ambient temperature, replacing of natural sand with rubber tire wastes leads to reduce the compressive strength significantly. The reduction rates in comparison to the control sample are 9%, 23% and 45% for 15RW, 25RW and 50RW mixes.

b) At elevated temperature, replacing of natural aggregate with 50% rubber tire wastes (50RW mix) can prevent the reactive powder concrete from broken at 400 ºC compared with plain and all other mixes that considered in this study. The residual strength values of the 50RW mix are 25%, 37% and 63% at 200, 300 and 400 ºC, respectively.

c) The presence of polypropylene fibres in the volume percentages of 0.75% and 1% can improve the compressive strength at 200 and 300 ºC related to those at 25 ºC. Similar behaviour is recorded for 1% and 2% (by cement weight) adding of steel fibres.

d) For UPV results, at elevated temperature, the change in the velocity is not exceeded 7% for 15% and 25% substitutions of rubber tire wastes. However, for 50% substitution, the UPV values are reduced by 25%, 37% and 63% at 200 ºC, 300 ºC and 400 ºC respectively which indicate a highly porous structure are created.

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