Fire flame effect on the compressive strength of reactive powder concrete using different methods of cooling

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Abstract. This research focused on the effect of fire flame of different burning temperatures (300, 400 and 500°C) on the compressive strength of reactive powder concrete (RPC). The steady state duration of the burning test was (60) min. Local consuming material were used to mixed a RPC of compressive strength around (100) MPa. The tested specimens were reinforced by (3.0) cm hooked end steel fiber of (1100) MPa yield strength. Three steel fiber volume fraction were adopted in this study (0, 1.0 and 1.5)% and two cooling process were included, gradual and sudden. It was concluding that increasing burning temperature decreases the residual compressive strength for RPC specimens of (0%) steel fiber volume fraction by (12.16, 19.46 & 24.49) and (18.20, 27.77 & 36.07) for gradual and sudden cooling respectively. This reduction was modified by adding steel fiber, the percentage of (1%) characterized the optimum response. Burning RPC that has non-zero steel fiber content up to 400 °C caused an increase in the residual compressive strength for a case of gradual cooling to be (4.37 & 6.25)% for steel fiber volume fraction of (1 & 1.5) % respectively. Sudden cooling method was improved to be the critical cooling method, the negative influence of this method was directly proportion with both burning temperature and steel fiber volume fraction.

1. Introduction

Reactive powder concrete can be consider as one of the most important and advanced concrete technology. Its modified properties increased the probability of using this concrete type in fortified structures that exposed to fire flame effect by highly percentage during their service life. It is also highly suitable for different types of complex structures such as bridges, large-span arch roof, prestressed concrete structures, nuclear power stations, and more [1,2]. Fire and elevated temperatures still consider as potential risks since the exposure to such effect represents the most severe exposure conditions for buildings and structures. Although concrete does not burn however, the elevated temperature produced areduction in elastic modulus and strength for both concrete and steel reinforcement. This reduction depends on the rate of fire temperature increasing, the type of concrete and its thickness. For this reason, concrete structures should be design for fire effects to avoid these problems. In this research an experimental study was presented about the effect of adding different percentage of hooked steel fiber on the compressive strength of RPC after being exposed to different burning temperatures and two cooling process. Gai-Fei Peng et all, investigated heat effect on RPC after being subjected to fire temperatures ranged from 200 to 600°C. Both steel and polypropylene fibers were adopting with W/B ratio from 0.16 to 0.20. It was detected that the exposure to temperatures ranged between 200-400 °C, maintained or smoothly advanced the original mechanical properties, while for a range from 400–600 °C the original strength started to decrease and the RPC loses its strength. RPC fractural energy after being exposed to 600 °C was high. This may be belong to the high bonding force of hardened cement paste in RPC so that extrapull-out process can occur during fracture of RPC after burning [3]. Samir Al-Mashhadi and Farah Alwash, studied the mechanical
properties such as compressive strength, modulus of rupture, splitting tensile strength and modulus of elasticity of reactive powder concrete (RPC) and normal strength concrete (NSC) slabs subjected to fire flame of different burning temperatures and burning durations. The out comes confirmed that elevating burning temperature up to (400°C) reduced all the mechanical properties. This decrease proportioned directly with the razing in the temperature to (600°C), RPC specimens spalled and lost their mechanical and physical properties under burning temperature level of 600°C and for (60 min.) burning duration. Partial or full spalling perceived to be occurred. It was concluded from this study that the load- deflection patterns of slab specimens that affected by a fire flame temperatures around 600°C are flat, representing softer load deflection response than that of the control slab specimens [4].

Rungrawee Wattanapornprom et al., explored the fire resistance of RPC columns of different steel and polypropylene fiber ratio. Four columns of different fiber ratio were examined in fire burning duration of 30 and 60 minutes. Then after, the behaviour of RPC columns in elevated temperature was detect, concerning spalling depth, failure mechanism of fiber and residual strength. The out comes exhibited that increasing the volume fraction of steel fiber or the presence of polypropylene fiber improves the fire resistance of the columns [5].

2. Constitutive materials

Ordinary Portland cement conforms the Iraqi specification No.5/1984 [6] was used. The chemical composition and physical properties were present in Table 1. Fine aggregate of grain size distribution ranging from (150 to 600)µm as used. Physical and chemical properties of fine aggregate was conformed to the Iraqi specification No.45/1984 [8] as illustrated in Table 2.

Table 3 shows the physical properties and chemical composition of the silica fume, which conforms the requirements of ASTM C1240-03[9].The chemical admixture that used in this study as super plasticizer was (Sika ViscoCrete -5930). It meets the requirements of super plasticizer according to ASTM C494-05[10], types G and F and its properties had shown in Table 4. In the current study, hooked end steel fiber was used. Table 5 listed the properties of the hooked end steel fiber. The mix proportions of the used RPC were presented in Table 6. After mixing the concrete, it was casted in (100x100x100) mm cubic moulds in an average of three cubes for each test.

| Abbreviation | Results | Limit of Iraqi Specification No. 5 [6] | Limit of ASTM C150 [7] |
|--------------|---------|----------------------------------------|------------------------|
| Chemical properties (%) | CaO | 63.7 | - |
| | SiO₂ | 22.5 | - |
| | Al₂O₃ | 4.01 | - |
| | Fe₂O₃ | 3.56 | - |
| | SO₃ | 2.53 | ≤ 2.8 if C₃A ≥ 5% |
| | MgO | 2.37 | ≤ 5.0% |
| | L.O.I. | 2.77 | ≤ 4.0% |
| | L.R. | 0.66 | ≤ 1.5% |
| | L.S.F | 0.69 | 0.66-1.02 |
| Bogue's equations | C₃S | 57.11 | - |
| | C₂S | 17.79 | - |
| | C₃A | 3.96 | - |
| | C₄AF | 10.83 | - |
| Setting time (Vicat's method) Initial setting Final setting | 1:45(hrs.:min.) | ≥ 45 min. | ≥ 45 min. |
| | 5:49(hrs.:min.) | ≤ 10 hrs. | ≤375min. |
| Compressive strength (MPa) | 3 days | 17.2 | ≥ 15 |
| | 7 days | 26.3 | ≥ 23 |
| | Blaine surface area(m²/ kg) | 319 | ≥ 230 |
| | Soundness (Autoclave method) (%) | 0.47 | ≤ 0.8 |
Table 2. Physical and chemical properties of fine aggregate.

| Properties                           | Test results | Limit IQS No.45/1984(8) |
|--------------------------------------|--------------|-------------------------|
| Apparent specific gravity            | 2.65         |                         |
| Saturated and surface dry specific gravity | 2.59        |                         |
| Absorption, %                        | 0.98         |                         |
| Sulfate content (SO$_3$), %          | 0.18         | ≤ 0.5                   |
| Soluble salts, %                     | 0.07         | ≤ 0.1                   |

Table 3. Physical properties and chemical composition of silica fume.

| Oxide composition | Oxide content % | ASTM C1240-03 (9) |
|-------------------|-----------------|-------------------|
| SiO$_2$           | 93.45           | Min. 85%          |
| Al$_2$O$_3$       | 0.17            |                   |
| Fe$_2$O$_3$       | 0.04            |                   |
| MgO               | 0.03            |                   |
| CaO               | 0.69            |                   |
| SO$_3$            | 0.39            |                   |
| K$_2$O            | 0.08            |                   |
| L.O.I             | 3.2             | Max. 6%           |

Physical properties
- Fineness (Blaine): 14950 m$^2$/kg
- Specific gravity: 2.13
- Physical form: Powder

Table 4. The properties of superplasticizer (Sika ViscoCrete -5930).

| Form                 | Viscous liquid                      |
|----------------------|-------------------------------------|
| Basis                | Aqueous solution of modified polycarboxlate |
| Appearance           | Turbid liquid                       |
| Relative density     | 1.08 g/l±0.005                      |

Table 5. Properties of hooked steel fiber.

| Parameters          | Measured Unites | Standard Unites | Deviation Limits |
|---------------------|-----------------|-----------------|------------------|
| Diameter, D (D)     | mm              | 1.05            | +0.04            |
| Length, L (L)       | mm              | 30              | +0.5             |
| Aspect ratio L/D    | unitless        | 28.57           | + 7.1            |
| Tensile strength    | N/mm$^2$        | Min. 1100       | +15%             |
| Bend trials         | -               | Min. 3 bending  | -                |

Table 6. The mix proportions used in preparing the test specimens.

| Concrete Mix | W/b | Cement kg/m$^3$ | Fine aggregate kg/ m$^3$ | Silica fume kg/ m$^3$ | $V_f$% |
|--------------|-----|-----------------|--------------------------|-----------------------|-------|
| Hf$_1$       | 0.2 | 850             | 1030                     | 200                   | 0     |
| Hf$_2$       | 0.2 | 850             | 1030                     | 200                   | 1     |
| Hf$_3$       | 0.2 | 850             | 1030                     | 200                   | 1.5   |
3. Burning and Cooling
A direct fire flame burners has been used to burn the RPC specimens. The fire flame aimed to simulate heating status in actual fire. The burning process and the measurement devices are shown in figure 1 and figure 2. After burning at steady state temperatures from 300°C to 500°C for a duration of (60 min.), concrete specimens were cooled to laboratory temperature using two methods of cooling sudden and gradual.

4. Compressive Strength Test
The compressive strength test was done according to B.S.1881: part 116 [11] using the average of three cubes with dimensions (100x100x100) mm for each test as illustrated in Table 7.

Table 7. Results of the compressive strength.

| Temp. °C | Sudden  | Gradual |
|----------|---------|---------|
|          | Hf₁     | Hf₂     | Hf₁     | Hf₂     | Hf₁     |
| 25       | 90.30   | 109.09  | 127.27  | 90.30   | 109.09  |
| 300      | 73.86   | 95.45   | 110.23  | 79.32   | 113.36  |
| 400      | 65.23   | 92.05   | 105.45  | 72.73   | 113.86  |
| 500      | 57.73   | 79.32   | 82.95   | 68.18   | 104.32  |

5. Results and discussions
Highlight on the results of the examinations for specimens of(0%) steel fiber volume fraction (V₁%) indicated that there was a reduction in the compressive strength for all the adopted burning temperatures (300, 400 and 500)°C. This reduction was varied in its magnitude according to the burning temperature and method of cooling (sudden or gradual) as shown in figure 3. It had been detected that the presence of steel fiber in the RPC mix caused a change in the behavior regarding the residual compressive strength after burning in case of gradual cooling as compared with (0%) steel fiber volume fraction. A positive effect was achieved in both burning temperature (300 and 400) °C on the values of the residual compressive strength by (2.08 and 4.37) % in case of (1%) steel fiber volume fraction and (4.1 and 6.25) % in the other case (1.5%) as shown in figure 4, figure 5 and Table 8. Studying the effect of burning temperature on the compressive strength signposted that at degree of (500°C), the compressive strength drops with different levels depending on the percentage of steel fiber volume fraction, figure 9. This reduction reached to (24.49, 4.38 and 10.89) % in case of gradual cooling for steel fiber volume fraction (0.1, 0.0 and 1.5%) respectively as illustrated in Table 8. The optimum behavior concerning the reduction in the compressive strength had represented by the percentage of (1%) while the worse one was of (0%). Using (1.5%) of steel fiber produced a percentage reduction in the compressive strength greater than that of (1%) due to the influence of the expansion damage for steel fiber which was greater in amount than that’s in specimen of (1%).
The overall results for all the adopted burning temperatures had showed that although the percentage reduction in the compressive strength for specimens of (1.5)% is greater than that of (1)%, but the residual compressive strength concerning (1.5)% is greater than of (1)% as shown in figure 6, figure 7 and figure 8.

Navigating through the outcomes of the sudden cooling specimens improved that this method is more critical. The amount of percentage reduction in the compressive strength concerning sudden cooling canceled the improvement of the compressive strength that's gained in burning temperatures (300 and 400) °C in case of gradual cooling for both (1.0 and 1.5) % as shown in figure 9, figure 10, Table 8 and Table 9. This behavior can be demonstrated by the different in the thermal expansion for concrete (10 x 10^-6/°C) and steel (7.2 x 10^-6/°C) that causes a different in the contraction volume for both concrete and hooked steel fiber which brakes the bond force between them. The results of the sudden cooling burning specimens indicated that there are two parameters affected upon the residual compressive strength, these are burning temperature and steel fiber volume fraction. The influence relation was directly proportion for both burning temperature and steel fiber volume fraction, figure 10. A comparison study between the adopted methods of cooling according to the residual compressive strength indicated that the minimum reduction had obtained in case of (0%)steel fiber content. Adding hooked steel fiber caused a jump in the percentage difference of the residual compressive strength due to the difference in the thermal expansion of concrete and hooked steel fiber. It had also noticed that the rate of increasing was directly proportioned with the burning temperature as shown in figure 11 and Table 10.

**Figure 3.** Compressive strength for specimens of $V_f$ equal to 0% .  

**Figure 4.** Compressive strength for specimens of $V_f$ equal to 1% .  

**Figure 5.** Compressive strength for specimens  

**Figure 6.** Compressive strength for specimens
of $V_f$ equal to 1.5%.

b) burning at (300 °C)

Figure 7. Compressive strength for specimens burning at (400 °C)

Figure 8. Compressive strength for specimens burning at (500 °C).

Figure 9 Effect of gradual cooling method on the compressive strength.

Figure 10 Effect of sudden cooling method on the compressive strength.

Figure 11. Percentage difference in compressive strength between gradual and sudden cooling.
Table 8. Percentage of compressive strength reduction in case of gradual cooling.

| Temp. | Steel fiber V_f % |
|-------|-------------------|
|       | 0                 | 1     | 1.5   |
| 300   | 12.16             | -2.08 | -4.11 |
| 400   | 19.46             | -4.37 | -6.25 |
| 500   | 24.49             | 4.38  | 10.89 |

Table 9. Percentage of compressive strength reduction in case of sudden cooling.

| Temp. | Steel fiber V_f % |
|-------|-------------------|
|       | 0                 | 1     | 1.5   |
| 300   | 18.20             | 12.50 | 13.39 |
| 400   | 27.77             | 15.63 | 17.14 |
| 500   | 36.07             | 27.29 | 34.82 |

Table 10. Percentage difference in compressive strength between gradual and sudden cooling.

| Temp. | Steel fiber V_f % |
|-------|-------------------|
|       | 0                 | 1     | 1.5   |
| 300   | 6.88              | 14.29 | 16.81 |
| 400   | 10.31             | 19.16 | 22.02 |
| 500   | 15.33             | 23.97 | 26.85 |

6. Conclusions

- Increasing steady state burning temperature decreased the residual compressive strength for RPC specimens of (0%) steel fiber volume fraction.
- Adding steel fiber to RPC mix modified the behavior of the burning specimens regarding the residual compressive strength. Steel fiber of (1%) volume fraction characterized the optimum response.
- Burning RPC specimens of non-zero steel fiber volume fraction with temperature not more than 400°C increased the compressive strength in case of gradual cooling.
- Cooling methods (sudden or gradual) had a significant effect upon the residual compressive strength of the burning RPC specimens. Sudden cooling method reduced the compressive strength more significantly than that of gradual method.
- The negative influence of sudden cooling method was directly proportioned with both burning temperature and steel fiber volume fraction.

References

[1] Shatha D, Wasan Z, Nesreen B and Nada M 2017 concrete Nuclear Science and Techniques doi: 10.1007/s 41365-017-0305-9.
[2] Hala A and Shatha D 2018 Civil Engineering Journal doi: 10.28991/cej-0309166.
[3] Gai-Fei P, Yi-Rong K, Yan-Zhu H, Xiao-Ping L, and Qiang C 2012 Advances in Materials Science and Engineering 1-6.
[4] Samir A and Farah A 2015 International Journal of Civil Engineering and Technology (IJCIET) 6 126-138.
[5] Rungrawee W, Daniel N, Withit P, Thuc N and Phoonsak P 2018 Engineering Journal 22 67-82.
[6] IQS 5-84 Iraq standard specification for Portland Cement.
[7] ASTM C150-07 Standard Specification for Portland Cement American Society for Testing and Materials.
[8] IQS 45-84 Aggregate from natural sources for concrete and building construction.
[9] ASTM C1240-03 Standard Specification for Use of Silica Fume as a Mineral Admixture in Hydraulic Cement Concrete Mortar, and Grout. American Society for Testing and Materials.
[10] ASTM C494/C494M – 05 Standard specification for chemical ad-mixtures for concrete American Society for Testing and Materials.
[11] B.S.1881 part 116 1983Methods for determination of compressive strength of concrete cubes, British Standard Institution.