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Effects of silica fume addition and water to cement ratio on the properties of high-strength concrete after exposure to high temperatures

Ali Behnood *, Hasan Ziari

Department of Civil Engineering, Iran University of Science and Technology, Narmak, Tehran, Iran

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Abstract

This paper presents the results of an experimental investigation on the effect of different amounts of silica fume (SF) and water to cement ratios (w/c) on the residual compressive strength of high-strength concrete after exposure to high temperatures. Based on the results obtained the rates of strength loss for concrete specimens containing 6% and 10% SF at 600 °C were 6.7% and 14.1% lower than those of the ordinary concrete. The dosage of SF had no significant effect on the relative residual compressive strength at 100 and 200 °C, whereas the amount of SF had considerable influences on the residual compressive strength above 300 °C similar to the response at 600 °C. The optimum dosage of SF and w/c was found to be 6% and 0.35, respectively.

Keywords: High temperature; Mixture proportioning; Compressive strength; Silica fume; High-strength concrete

1. Introduction

Since the 1950s [1], high-strength concrete is widely produced as an appropriate substitute for normal-strength concrete (NSC). The lower water to cement ratio (w/c) and higher content of binder are needed to produce HSC. Consequently, high-range water-reducing admixtures (HRWRA) are used to achieve the required workability. Investigations of the performance of silica fume (SF) in concrete began since the 1950s [2]. During the previous decades, enormous researchers evaluated the effects of the partial replacement of cement by SF on the properties of concrete. Silica fume is a by-product resulting from the reduction of high-purity quartz with coal in electric arc furnaces in the manufacture of ferro-silicon alloys and silicon metal [3]. Nowadays, it has been well known that the use of SF can significantly improve the mechanical properties as well as durability of HSC. The very high content of amorphous silicon dioxide and very fine spherical particles are the main reasons for its high pozzolanic activity [2]. The advantages of SF caused SF being the most well-known additive material for HSC in recent years. Several research works have been done to investigate the behaviour of HSC containing SF after exposure to elevated temperatures [4–11]. The main aim of these works was evaluating the potential of HSC containing SF for explosive spalling. Hertz [4] suggested 10% of cement replacing by SF as an upper limit of SF content to avoid spalling. However, different researchers have reported inconsistently the relative residual compressive strength of concretes containing SF after subjecting to high temperatures [5–11]. Hertz [5] reported that the residual compressive strengths of the special 170-MPa concretes containing 14–20% SF increased after heating up to 350 °C and then decreased rapidly at higher temperatures. Phan and Carino [6] reported that concretes containing 10% SF showed better performance than OPC concretes at 100 and 200 °C, whereas higher relative strength losses were observed in the SF concretes in

* Corresponding author. Tel.: +98 218802 4784; fax: +98 217745 4053.
E-mail address: a_behnoud@iust.ac.ir (A. Behnood).

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comparison with the OPC concretes after subjecting to 300 and 450 °C. They showed that the relative residual strengths of concretes were increased approximately 13.6% and 6.1% by replacing of cement with 10% SF at *w/c* of 0.33 after heating to 100 and 200 °C, respectively, whereas the relative strengths of the SF concretes were 9.1% and 7.3% lower than those of the OPC concretes at 300 and 450 °C, respectively. Sarshar and Khoury [7] reported no significant advantages of the cement replacing by 10% SF at elevated temperatures. Poon et al. [8] observed the higher relative residual strengths of the SF concretes than those of the OPC concretes at 200 °C, whereas the relative residual strengths of all of the concretes at 400 °C were approximately the same. Above 400 °C, the SF concretes showed significant strength losses in comparison with the OPC concretes. Some investigators reported that the OPC concretes showed superior behaviour in comparison with the SF concretes under elevated temperatures [9,10]. In terms of *w/c*, Phan and Carino [6] reported that the relative residual strengths (the ratio of the strength at a desired temperature to initial strength at room temperature) of concretes with *w/c* of 0.22 and 0.33 at the same content of SF (10% of cement) were almost similar at 100 °C. The relative residual strengths of concretes with *w/c* of 0.22 were 22% and 30% higher than those of concretes with *w/c* of 0.33 at 200 and 300 °C, respectively, whereas concrete specimens with *w/c* of 0.22 were exploded at 450 °C and the relative residual strength of concrete with *w/c* of 0.33 was 25.6% of room-temperature value. Chan et al. [11] concluded that the moisture content has a dominant influence on spalling. In general, there is conflicting data on the effect and optimum amount of SF and *w/c* regarding the relative residual compressive strength of HSC after exposure to elevated temperatures and consequently, more researches are needed to identify the role of SF and *w/c*. Thus, this experimental study was carried out to evaluate the residual compressive strength of HSCs containing different dosages of SF with different levels of *w/c*.

2. Materials and mix proportions

The fine aggregate was river sand with a water absorption of 0.8% and a specific gravity of 2.70. Limestone coarse aggregate with a nominal maximum size of 12.5 mm was used in this study. The coarse aggregate met the grading requirements of ASTM C 33 for 12.5–4.75 mm size aggregates; its water absorption was 0.6% and its specific gravity was 2.65. Type I ordinary Portland cement (OPC) meeting the requirements of ASTM C 150 was used in the preparation of the concrete specimens. A commercial silica fume (SF) was used for preparing the SF concretes. The chemical compositions and physical properties of OPC and SF are presented in Table 1.

A commercially available modified polycarboxylate ether high-range water-reducing admixture (HRWRA) with 44% solid particles was used to prepare the concretes.

Table 1
Chemical composition and physical properties of ordinary Portland cement (OPC) and silica fume (SF)

Compound (%)	OPC	SF
SiO_2	21.46	91.7
CaO	63.95	1.68
Al_2O_3	5.55	1
Fe_2O_3	3.46	0.9
MgO	1.86	1.8
SO_3	1.42	0.87
K_2O	0.54	–
Na_2O	0.26	0.10
LOI	–	2
Specific gravity (gr/cm^3)	3.15	2.2
Specific surface (m^2/kg)	330	20,000

Table 2 shows the concrete mixture proportions and the fresh properties of concrete mixes.

Three different concrete mixtures were designed to evaluate the effect of silica fume (SF) on the compressive strength of the heated and unheated concrete specimens. To compare the test results, all three mixtures were made with constant value of water to cement ratio (*w/c*), which was 0.30. The dosages of replacing cement by SF were 0%, 6%, and 10%. Four mixtures were designed to evaluate the effects of *w/c* on the residual compressive strength of concrete mixtures after subjecting to high temperatures. Two mixtures were prepared with *w/c* of 0.30 and 0.40 without SF, whereas other concretes were produced with *w/c* of 0.30 and 0.35 containing 6% SF. Three different concrete mixes were prepared to evaluate the effect of increasing of SF from 0% to 10% and simultaneously decreasing of *w/c* from 0.4 to 0.3.

3. Specimen preparation and test method

The specimens were cast in the cylindrical molds of 102 mm diameter and a height of 204 mm in two layers; each layer being consolidated using a vibrating table. Mixing was according to ASTM C 192. Coarse aggregate was first added to the mixer, followed by approximately one-third of mixing water, and then the mixer was started. Fine aggregate, cement, SF, and the remaining water were added to the running mixer in a gradual manner. The mixing time for mixtures continued for 3-min. After 3-min as the rest time, the final mixing takes 2-min. Fresh mixes were tested for workability by slump according to ASTM C 143 and the unit weight and air content were measured in accordance with ASTM C 138. Following casting, concrete specimens were covered with wet burlap and polyethylene sheets and kept in the laboratory at room temperature for 24 h. After demolding, specimens were placed in a saturated limewater bath until the time of testing. Curing was done according to ASTM C 511. Special care was taken not to dry out the specimens prior to testing. Three concrete specimens from each mix were tested after exposure to the target temperatures and the compressive

Table 2
Concrete mix proportions and properties of fresh concretes (unit weight: kg/m^3)

Mixture	W40OPC	W35SF6	W30OPC	W30SF6	W30SF10
Cement	430	441	495	465	450
Silica fume	–	28	–	30	45
Water	172	164	149	149	149
Fine aggregate	687	653	615	615	615
Coarse aggregate	1030	1115	1168	1168	1168
w/c	0.40	0.35	0.30	0.3	0.30
HRWRA (L/m^3)	1.6	2.9	1.9	3.1	3.7
Slump (mm)	110	100	100	100	100
Unit weight	2310	2385	2421	2430	2412
Air content (%)	2.5	2.3	2.5	2.1	2.1

strengths were measured according to ASTM C 39. The specimens were placed in an oven and heated from room temperature (20 °C) to 100, 200, and 300 °C at an average rate of 3 °C/min. Heating the specimens to 600 °C was done by an electrically heated furnace with the same heating rate. The remaining time at the target temperature was approximately 3 h, then the furnace was turned off and specimens were cooled to room temperature. During the heating period, water vapor was allowed to escape freely.

4. Test results and discussion

The results of the compressive strength tests for all of the concretes before and after heating up to 600 °C are presented in Table 3 and Fig. 1. The relative residual compressive strengths of all five mixes after exposure to high temperatures are plotted in Fig. 2.

4.1. Effect of silica fume

The results of the residual compressive strength of concretes after heating to target temperatures versus the dosages of SF are plotted in Fig. 3. The relative residual compressive strengths of concretes are shown in Fig. 4.

As it would be expected, the replacement of cement by 6% and 10% SF increased the 28-day compressive strength

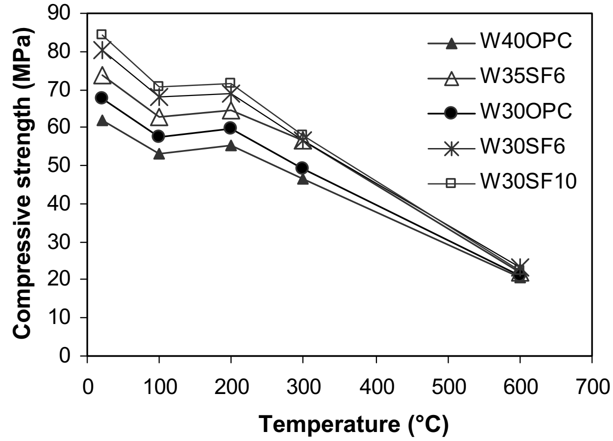

Fig. 1. Compressive strength of concretes after the different temperatures exposures.

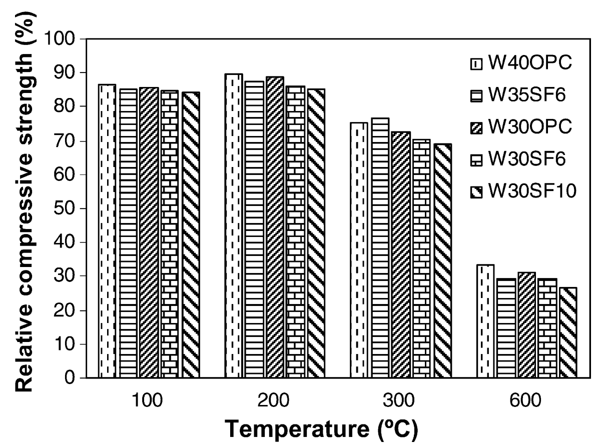

Fig. 2. Relative residual compressive strength of concretes after the different temperatures exposures.

approximately 19% and 25%, respectively. This is due to the reaction of the SF with calcium hydroxide formed during the hydration of cement that caused the formation of calcium silicate hydrate (C–S–H) as well as filler role of very fine particles of silica fume. The ratios of 7–28 days compressive strength for all of the concretes varied from 0.78 to 0.88, which were quiet compatible with 0.8 to 0.9 range reported by ACI 363 [1] based on the studies carried out by Parrott [12]. Furthermore, concretes containing

Table 3
Results of compressive strength test at different temperatures

Concrete	Compressive strength (MPa)					
	20 °C		100 °C	200 °C	300 °C	600 °C
	7-day	28-day				
W40OPC	48.3	61.8 (100%)	53.3 (86.3%)	55.5 (89.8%)	46.5 (75.3%)	20.6 (33.4%)
W35SF6	61.5	73.9 (100%)	62.8 (85.0%)	64.7 (87.5%)	56.5 (76.5%)	21.8 (29.5%)
W30OPC	55.3	67.4 (100%)	57.6 (85.4%)	59.7 (88.6%)	49.0 (72.7%)	21.0 (31.2%)
W30SF6	69.1	80.3 (100%)	68.0 (84.7%)	69.0 (85.9%)	56.5 (70.4%)	23.4 (29.1%)
W30SF10	74.1	84.2 (100%)	70.8 (84.1%)	71.7 (85.2%)	57.9 (68.7%)	22.6 (26.8%)

The value in each parenthesis is the ratio of the strength at a desired temperature to initial strength.

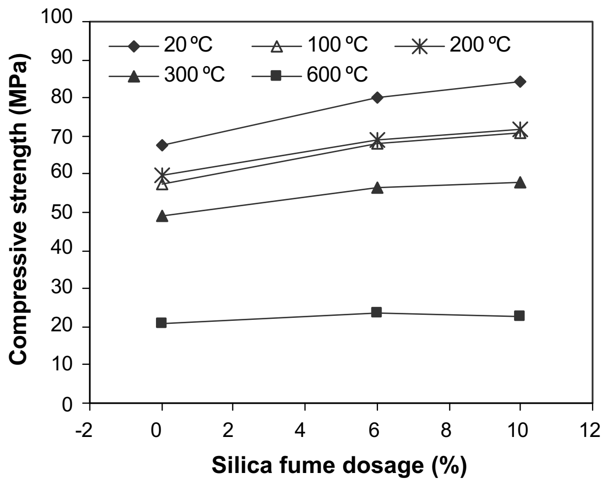

Fig. 3. Compressive strength of concretes versus silica fume dosage after the different temperatures exposures.

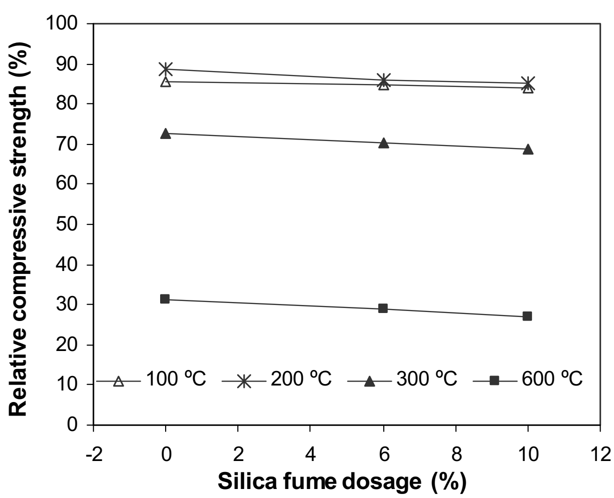

Fig. 4. Relative residual compressive strength of concretes versus silica fume dosage after the different temperatures exposures.

different levels of SF showed lower rates of compressive strength gain in early ages. This is attributed to the low content of calcium hydroxide to develop the pozzolanic reactions at early ages. In general, it can be concluded that concretes containing SF had significantly higher strength than that of OPC concretes at room temperature. After exposure to 100 °C, significant reductions occurred in the compressive strength of concretes with and without SF. As it can be seen from Fig. 4, no considerable differences were observed in the relative residual compressive strengths at 100 °C. The relative compressive strengths of concrete specimens containing 6% and 10% SF were 84.7% and 84.1% of room-temperature strengths, respectively, whereas, this value was 85.4% for W30OPC concrete. Test results showed the strength recovery between 1.3% and 3.7% for all of the concretes after heating to 200 °C when compared to 100 °C. This observation is consistent with what has been reported by other researchers [13–15]. Some researchers have reported that the compressive strength of a concrete specimen is increased if its moisture content is uniformly decreased [16]. The compressive strength gains at 200 °C are attributed to the increase in the forces between gel particles (Van der Walls forces) due to the removal of water content [17]. The W30OPC concretes showed higher residual compressive strength than the W30SF6 concretes, which, in turn, showed higher residual compressive strength than the W30SF10 concretes. With regard to the same amount of *w*/*c* in all three concretes, these differences in strength improvements are attributed to the presence of the ultra-fine particles of SF that serve as excellent fillers as well as their pozzolanic reactions that lead to formation a very dense microstructure in the SF concretes. Thus, moisture content of concretes containing SF cannot escape freely when compared to the OPC concretes. As a result, the recoveries of strength in the W30SF6 and W30SF10 concretes were lower than those of the W30OPC concretes after exposure to 200 °C. As seen, the compressive strength of all three concretes at 300 °C retained on average 81.6 % of the values at 200 °C. After exposure to 300 °C, the relative residual compressive strength of the W30OPC, W30SF6, and W30SF10 concretes decreased approximately 27.3%, 29.6%, and 31.3% in comparison with the room-temperature values, respectively. The compressive strength reductions of concretes containing 6% and 10% SF were 8.4% and 14.7% higher than those of the OPC concretes, respectively. The quick losses in compressive strength for SF concretes are attributed to the dense microstructure in this type of concretes, which caused the build up of higher internal pressure due to the water vapor transition of the interlayer water. In the range of 300–600 °C, severe strength losses occurred in all three concretes, which were 68.8%, 70.9%, and 73.2% of the initial values for W30OPC, W30SF6, and W30SF10 concretes, respectively. As seen, the residual compressive strengths of concretes containing 6% and 10% SF and the OPC concretes at 600 °C were 41.4%, 39%, and 42.9% when compared to 300 °C, respectively. During exposure to high temperatures, cement paste contracts, whereas aggregates expand. Thus, the transition zone and bonding between aggregates and paste are weakened. As a result, this process as well as chemical decomposition of hydration products causes severe deteriorations and strength loses in concrete after subjecting to high temperatures. After heating to 600 °C, the residual compressive strengths of all three concretes were approximately the same, whereas the relative residual compressive strengths of concretes containing 6% and 10% SF were 6.7% and 14.1% lower than those of the OPC concretes, respectively, after exposure to 600 °C. Thus, it can be concluded that the rates of strength loss were significantly higher in SF concretes, especially for the W30SF10 concretes, than those of the OPC concretes. This is attributed to the presence and amount of SF in concretes that produced very denser transition zone between aggregates and paste due to its ultra-fine particles as filler and its pozzolanic reactions.

During expansion of aggregate and contraction of paste, higher stress concentrations are produced in the transition zone. This causes more sensitivity of the bonding between aggregate and paste containing SF than that of the OPC concrete. Thus, greater strength losses are occurred in SF concretes. As seen in Fig. 3, the residual compressive strengths of the W30SF6 concretes were marginally higher than those of the W30SF10 concretes. It can be concluded that SF concretes were more sensitive to high temperatures and showed worse performance than OPC concretes after heating to elevated temperatures. It seems that the dosage of SF has no significant effect on the relative residual compressive strength at 100 and 200 °C, where the relative residual compressive strengths of 10% SF concretes were only 0.7% and 0.8% lower than those of the 6% SF concretes, respectively. Above 300 °C, the amount of SF has significant effects on the residual compressive strength; so that, the relative residual compressive strength of concrete containing 10% SF was approximately 8% lower than that of the 6% SF concrete. In general, it can be concluded that the optimum dosage of cement replacing by SF is 6%, which showed lower deterioration and strength loss than other amounts. The greatest relative residual strength losses of concretes containing 6% and 10% SF were observed at 300 °C, which were 8.4% and 14.7% higher than those of the OPC concretes, respectively. Thus, it seems that 300 °C can be considered as a critical temperature particularly for concretes containing SF regarding compressive strength loss. It is consistent with the results of other works which have been reported the occurrence of spalling at the range of temperatures close to 300 °C [2,6].

4.2. Effect of *w/c*

The effects of *w/c* on the residual and relative residual compressive strengths of concretes without silica fume after exposure to elevated temperatures are plotted in Figs. 5 and 6.

The residual and relative residual compressive strengths of concretes containing the constant dosage of silica fume (6%) after subjecting to high temperatures versus *w/c* are plotted in Figs. 7 and 8.

As indicated in Figs. 5 and 6, the strength improvements occurred at 200 °C when compared to 100 °C, which were 3.7% and 4.13% for W30OPC and W40OPC concretes, respectively. After heating to 300 °C, the relative strength losses of concretes with *w/c* of 0.40 and 0.30 were 24.7% and 27.3%, respectively. The relative residual compressive strengths of the W30OPC and W40OPC concretes at 600 °C were 31.2% and 33.4% of room-temperature values, respectively. It can be seen from Fig. 8 that no significant differences occurred in the relative residual compressive strengths of the W35SF6 and W30SF6 concretes after heating to 100 and 600 °C, whereas the relative residual compressive strength of concrete with *w/c* of 0.30 was 8% lower than that of concrete with *w/c* of 0.35 at 300 °C. It

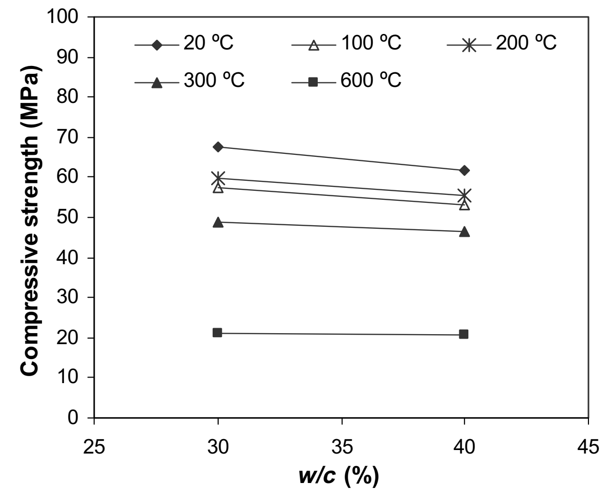

Fig. 5. Compressive strength of concretes (without silica fume) versus *w/c* ratio after the different temperatures exposures.

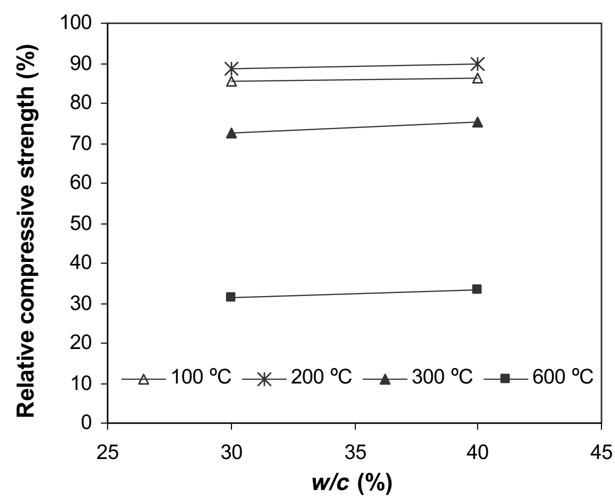

Fig. 6. Relative residual compressive strength of concretes (without silica fume) versus *w/c* ratio.

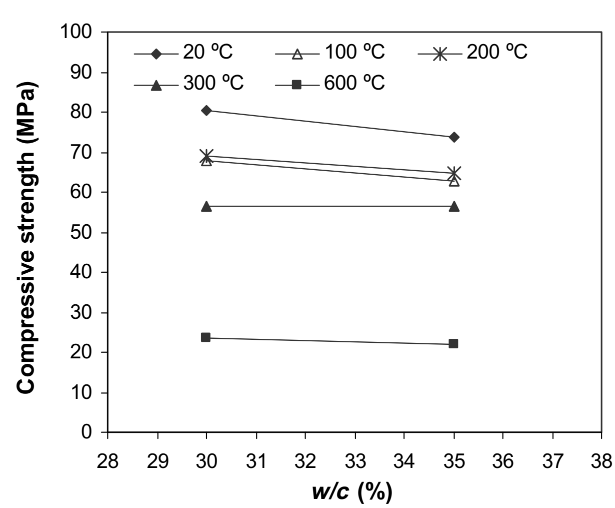

Fig. 7. Compressive strength of concretes containing 6 wt.% silica fume versus *w/c* ratio after the different temperatures exposures.

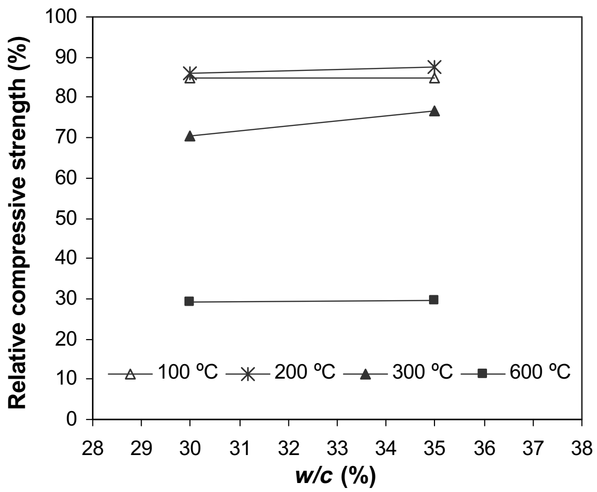

Fig. 8. Relative residual compressive strength of concretes with 6 wt.% silica fume versus *w/c* ratio after the different temperatures exposures.

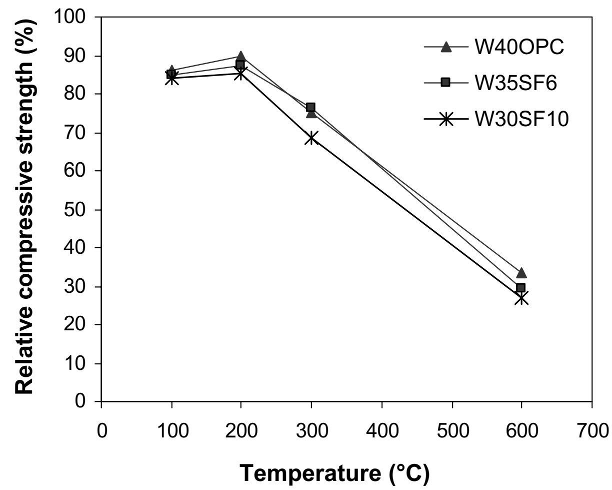

Fig. 9. Relative residual compressive strength of concretes after the different temperatures exposures.

has been well known that the increase of *w/c* will both increase the moisture content and the permeability of the hardened concrete. The increased moisture content will have a negative influence on the behaviour of concrete under high temperatures, whereas the increased permeability will have a positive influence. In terms of the moisture content, when the moisture content increases, the amount of evaporable water increases. The increased moisture content will lead to both increased pore pressure and increased temperature gradient during heating. Several researchers have reported that reduced moisture content reduces the spalling [11,18]. With regard to the test results of the present work, it can be concluded that the positive effect of the increased permeability is more than negative effect of the increased moisture content in concretes with higher *w/c*.

4.3. Combined effect of w/c and SF

The relative residual compressive strengths of the intended concretes after heating to elevated temperatures are plotted in Fig. 9.

When the *w/c* was decreased from 0.40 to 0.35 and 6% of cement was replaced with SF, the relative residual compressive strength was 11.7% lower than that of the W40OPC concrete at 600 °C. Furthermore, the relative strength loss was 9.5% higher than that of OPC concrete with *w/c* of 0.4 after heating to 100 °C. The strength recovery of W40OPC concrete was approximately 36% higher than that of the W35SF6 concrete. With 10% replacing of cement by SF and reduction of *w/c* from 0.4 to 0.3, the relative residual compressive strengths were decreased 9% and 20% higher than those of W40OPC concretes after heating to 300 and 600 °C, respectively. At 200 °C, the strength improvements of the OPC and W30SF10 concretes were 4% and 3% when compared to 100 °C, respectively. The average of relative residual compressive strengths of the W40OPC, W35SF6, and W30SF10 concretes were 71%, 70%, and 66% of room-temperature values, respectively. Based on the tests carried out in this research, it can be deduced that the presence of SF has more negative effects on the compressive strength than changing in *w/c*. In spite of the significant strength reductions of concretes containing SF and lower *w/c* under high temperatures, the optimum values of SF and *w/c* are 6% and 0.35, respectively, to reach lower strength loss and deterioration when SF concretes are required to use in the construction projects.

5. Conclusions

Based on the results of this experimental investigation, the following conclusions are drawn:

1. The rates of strength loss were significantly higher in SF concretes, especially for the W30SF10 concretes, than those of the OPC concretes. As indicated, the residual compressive strengths of all three concretes were approximately the same at 600 °C, whereas the relative compressive strengths of concretes containing 6% and 10% SF were 6.7% and 14.1% lower than those of the OPC concretes, respectively, after exposure to 600 °C.
2. The dosage of SF has no significant effect on the relative compressive strength at 100 and 200 °C, where the relative residual compressive strengths of 10% SF concretes were only 0.7% and 0.8% lower than those of the 6% SF concretes, respectively. Above 300 °C, the amount of SF has significant effects on the residual compressive strength; so that, the relative residual compressive strength of concrete containing 10% SF was approximately 8% lower than that of the 6% SF concrete.
3. With regard to the results of the present work, it can be concluded that the positive effect of the increased permeability is more than negative effect of the increased moisture content in concretes with higher *w/c*.
4. In general, the presence of SF has more negative effects on the compressive strength than changes of *w/c*. However, despite the significant strength reductions of

concretes containing SF and lower w/c at high temperatures in comparison with the OPC concretes, it can be suggested that the optimum values of SF and w/c are 6% and 0.35, respectively, when high-strength concretes containing SF are required to use in the construction projects.

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