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Compressive strength of concrete made with silica fume at elevated temperatures

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ABSTRACT

This paper deals with the effect of silica fume (SF) replacement on the compressive strength of Portland cement concrete made with siliceous aggregates at elevated temperatures (up to 800°C). To achieve this objective the compressive strength was measured at different SF contents (0% to 25%), temperatures, as well as curing ages (up to 90 days). The samples were cured under 95% RH at room temperatures (20–22°C), heated in the oven to the desired temperatures, allowed to cool to ambient temperatures, and then tested for their residual compressive strength.

The results of this study showed that: The compressive strength of silica fume concrete (SFC) decreases with increasing temperatures down to 20% of its original value around 800°C. Curing age (up to 90 curing days) hardly affects SFC behavior. The compressive strength of SFC increases with the content of SF up to 250°C, remains constant at 500–600°C, and tends to decrease around 800°C.

Validation with trends in earlier work compares favorably with the results of this study.

INTRODUCTION

Silica fume concrete (SFC) is widely used in modern structures under normal temperature conditions. Used as an admixture, microsilica can improve the properties of both fresh and hardened concrete and as a partial replacement for cement it can substitute for energy-consuming cement without sacrifice of quality (Anon 1985). Recent uses of SF concrete include bridge deck overlays, repair of concrete structures, stabilization of rock faces etc. Properties of SFC, under ambient temperature conditions, has received considerable research attention lately (Anon 1985, Carlsson *et al.* 1991, Neville 1981, Sandvik & Gjorv 1991, Tazawa & Yonekura 1991). However, the behavior of SFC at elevated temperatures has hardly been discussed in the literature despite the possibility of concrete structures being exposed to such circumstances during their service life. Examples of concrete structures involving exposure to elevated temperatures include nuclear reactors, industrial furnace walls, hazardous fires, etc. It has been shown that normal Portland cement concrete maintains its residual compressive strength almost completely up to nearly 200°C (Schneider 1985). With increasing temperatures up to 600°C, the compressive strength of normal concrete drops to 50% of its original value. Sullivan (Sullivan &

Sharshar 1992) tested cement paste samples with 10% SF content under temperatures up to 600°C. He noticed that at 600°C the residual compressive strength dropped to 40% of its initial value at ambient temperatures. However, the effect of SF content on the behavior of concrete at elevated temperatures has not been covered in the literature, to the knowledge of the authors.

The current research is mainly concerned with the study of the effect of elevated temperatures on the compressive strength of condensed SFC. Factors including temperatures up to 800°C, SF contents up to 25% by weight as partial replacement to the cement and curing ages up to 90 curing days were particularly considered. Although in practice SF replacement up to 10% is only recommended, percentages as high as 40% have been reported (Anon 1985).

EXPERIMENTAL SET-UP

To achieve the objectives of the research work, siliceous aggregate concrete was mixed according to ASTM C305 and compacted as described in ASTM C192. The specifications of the cubes and concrete proportions are shown below:

Dimension of specimen 100 × 100 × 100 mm^3
Typical mix proportions without SF:

		kg/m^3
Cement type	Ordinary Portland Cement	445
Coarse aggregate	Local crushed stone (Siliceous Gravel)	1289
Fine aggregate	Local sand	800
Water		245
W/C		0.55

Testing conditions:

Temperatures tested	20, 150, 250, 500, 600, 800°C
SF content as replacement of cement by mass	0, 5, 15, 20, 25%
Curing Ages	7, 28, 90 days

The grading of the aggregates and the mix proportions are shown in Appendix II. The silica fume (ferrosilicon dust) used in the test was sprinkled evenly by hand in several layers with the cement and aggregates to ensure a reasonably uniform distribution prior to the addition of the water. Three specimens were used for each testing condition. The average of the 3 readings obtained is used to represent the condition of the experimental test. The total number of cube specimens tested was 270. The raw data of the experimental program are included in Appendix III to give an idea of the statistical variations in the strength data.

APPARATUS

The workability of the designed concrete mixes ranged from 13 mm to 3 mm for SF contents of 0% to 25% respectively. The samples were cured at 95% RH (in water tanks) and at 20–22°C for the desired ages prior to heating. Next, they were taken out of the curing tanks after ages of 7, 28 and 90 days were reached respectively, and placed in the heating furnace. Heating of the samples was performed using a muffle furnace that can reach temperatures up to 1000°C. A constant rate of heating of 12 to 16°C per minute was maintained in the furnace. The rate of heating was automatically regulated by a thermostat built into the furnace. This adopted range for the rate of heating conforms to other tests made on the compressive strength of concrete at elevated temperatures (Schneider 1985). The samples were left in the furnace, after reaching the desired temperatures, for 7 to 10 hours to achieve a uniform temperature distribution across the specimens and, therefore, eliminate any differential thermal stresses. They were then allowed to cool in the oven for 15 hours and a further 7 hours in the air before testing for their residual compressive strength. Therefore, a typical specimen cured for 7 days in the water tank, was subjected to heating for 10 hours and cooling for 22 hours, i.e. a total of 32 hours of heating and cooling past the curing age. A loading rate of 3 kN/s was used for the residual compressive strength testing.

RESULTS AND DISCUSSION

The variation with temperature of the ratio of the residual compressive strength of concrete at high temperatures to that at ambient was obtained for the various curing ages considered in this work. As a typical example, Fig. 1 shows these results for 28-day specimens. The measured values of the residual compressive strengths for the tested SF contents at elevated temperatures for curing ages of 7, 28, and 90 days are given in Tables 1 and 2 and 3, respectively.

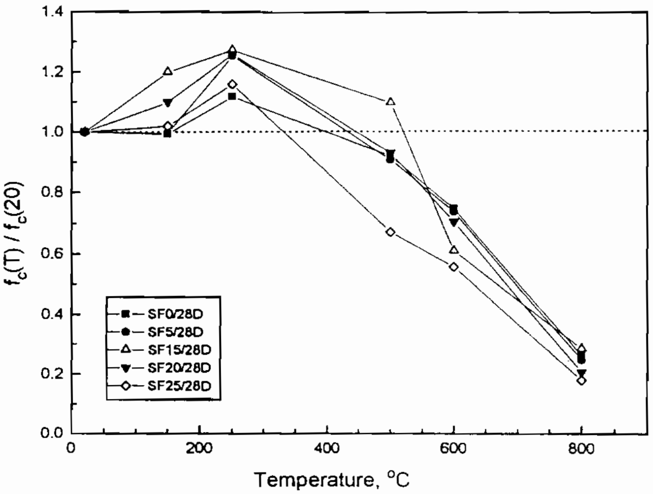

Fig. 1. The effect of temperature on the compressive strength of concrete made with different silica fume contents after 28 days.

Table 1. The effect of silica fume content on the compressive strength of concrete at elevated temperatures after 7 days.

7 Days	f'_c (T)				
T (°C)	0% SF	5% SF	15% SF	20% SF	25% SF
20	31.87	27.40	21.63	30.73	25.87
150	31.67	28.20	27.77	32.43	29.37
250	34.57	36.60	38.73	35.63	31.67
500	21.77	24.57	25.07	22.33	20.67
600	17.43	17.43	19.43	21.70	13.80
800	10.57	8.50	5.40	5.07	4.13

In general, the compressive strength of SFC decreases at elevated temperatures. Around 250°C, however, a noticeable increase in the compressive strength is observed. This is due to the evaporation of the free water content, which starts at around 100°C. This evaporation causes a reduction in the size of existing pores in the concrete specimen and hence increases its compressive strength. This increase in the compressive strength is higher for SFC samples made with 15% SF contents. At temperatures higher than 250°C, the strength of SFC starts to decrease. This is attributed to the fact that chemically-bound water starts to disintegrate and evapo-

Table 2. The effect of silica fume content on the compressive strength of concrete at elevated temperatures after 28 days.

28 Days	f'_c (T)				
T (°C)	0% SF	5% SF	15% SF	20% SF	25% SF
20	29.10	29.47	31.43	31.70	34.33
150	28.93	29.40	37.70	34.87	35.03
250	32.57	36.97	40.03	39.93	39.87
500	26.83	26.83	34.60	29.57	23.13
600	21.83	21.83	19.27	22.43	19.20
800	7.70	7.50	9.03	6.63	6.23

Table 3. The effect of silica fume content on the compressive strength of concrete at elevated temperatures after 90 days.

90 days	f'_c (T)				
T (°C)	0% SF	5% SF	15% SF	20% SF	25% SF
20	29.97	33.03	33.93	36.37	39.27
150	30.17	34.23	35.27	36.23	39.57
250	33.50	35.70	36.43	40.23	41.07
500	24.67	26.53	26.83	23.27	22.07
600	21.97	22.53	21.83	19.43	23.60
800	10.17	9.63	7.70	6.23	5.90

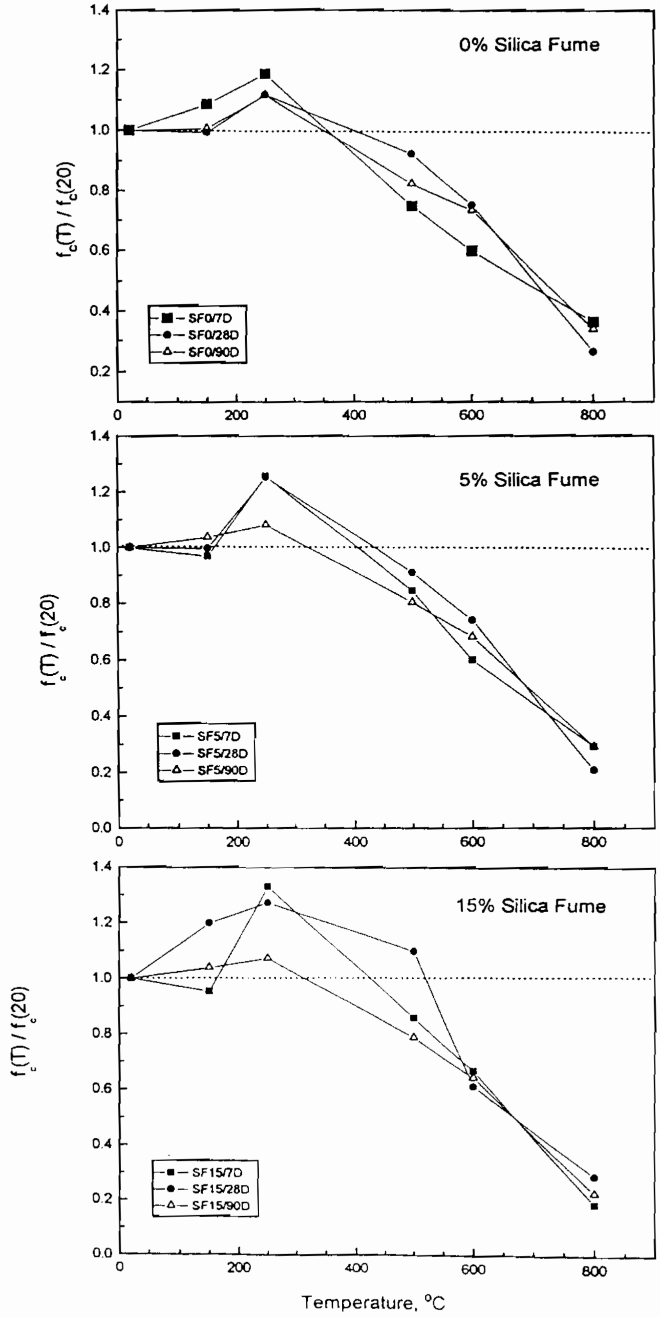

Fig. 2A. Effect of age on the compressive strength of silica fume concrete after 7, 28 and 90 days.

rate at this stage (Khoury 1983). At 800°C and above the SFC specimen starts to lose its integrity. The compressive strength of an SFC specimen is reduced on average to around 20% of its original value at 800°C. It should be noted, however, that the presence of free water in larger specimens exposed to high rates of heating and loaded while hot, could cause a build-up of pore pressure which would eventually cause explosive spalling instead of strengthening the specimen, as described above for specimens at 250°C.

Figures 2(A & B) shows the variation with temperature of the ratio of the compressive strength of SEC made with different SF contents at high temperatures to that at ambient for curing ages of 7, 28 and 90 days. In these figures, it is consistently observed that the peak value of the ratio of the compressive strength at high temperatures to that at ambient is reached at around 250°C. This peak value is highest for SFC samples tested after 7 days of curing. This is due to the fact that 7-day SFC samples have more free water content prior to testing in the oven. Therefore, they have more water to evaporate around 250°C, which causes this observed additional increase in the strength of the specimen due to the increase in its com-

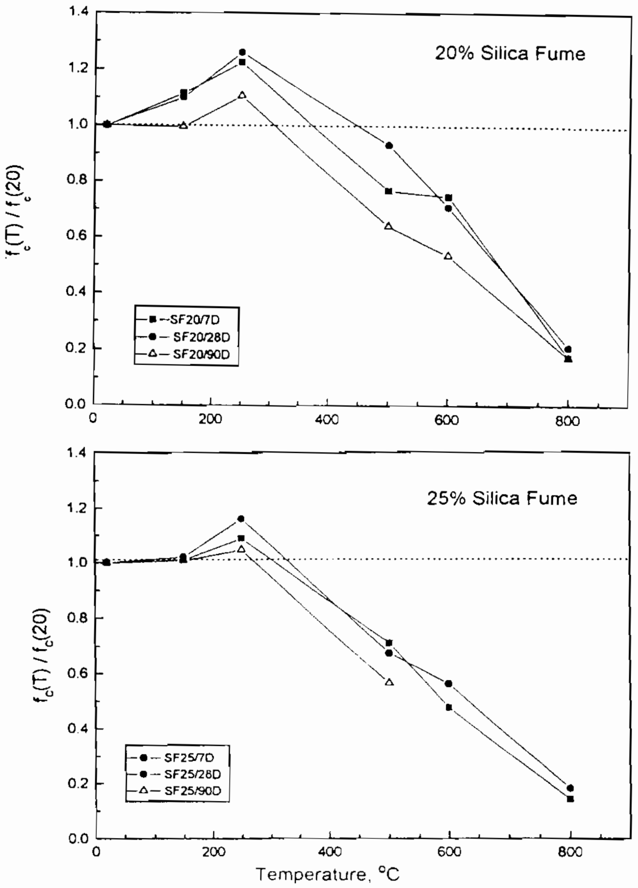

Fig. 2B. Effect of age on the compressive strength of silica fume concrete after 7, 28 and 90 days.

pactness after evaporation. As SF is introduced to the mix, however, the added fine particles of microsilica absorb some of the free water in the pores and retain it for a longer period. The 7-day and 28-day SFC samples, therefore, consistently show higher peak values of the strength than the 90-day ones since the former have more water prior to testing. At temperatures above 500°C, no obvious trend in the effect of curing age, up to 90 days, is observed. The effect of the curing age, within the tested age range, on the compressive strength ratio appears to be hardly dominant at temperatures of higher or equal to 500°C (Figs. 1, 2(A) and 2(B)).

In Fig. 3, the effect of SF content on the compressive strength of SFC samples is shown for samples cured for 90 days. Curing ages of 7 and 28 days have shown the same trend. Temperature curve families of 20, 150 and 250°C exhibit an increase in the compressive strength of up to 15% and 25% over that of plain concrete with the increase of SF content. Also in Fig. 3, curve families of 500°C and 600°C show stability, in general, in the value of the compressive strength of SFC samples with different SF contents. SFC samples at 800°C exhibit a decrease of up to 20 to 38% in the compressive strength over that of plain concrete with the increase in SF content.

A comparison is shown in Fig. 4 between the strength ratio at elevated temperatures of plain concrete specimens at 7, 28 and 90 curing days and similar results from Anderberg (Anderberg 1976, Anderberg & Thelandersson 1976) on quartzite aggregate concrete who used the following mix proportions:

Mix proportions	weight units
Cement	1
Water	0.6
Sand (<8 mm)	2.88
Aggregate (8–12 mm)	1.92

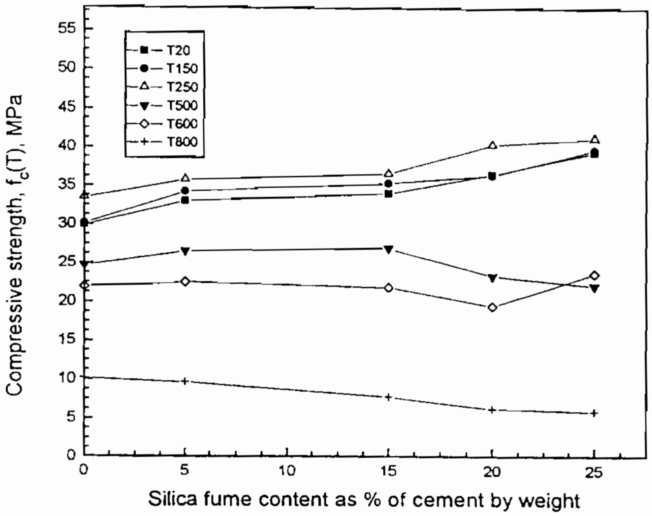

Fig. 3. The effect of silica fume content on the compressive strength of concrete at elevated temperatures after 90 days.

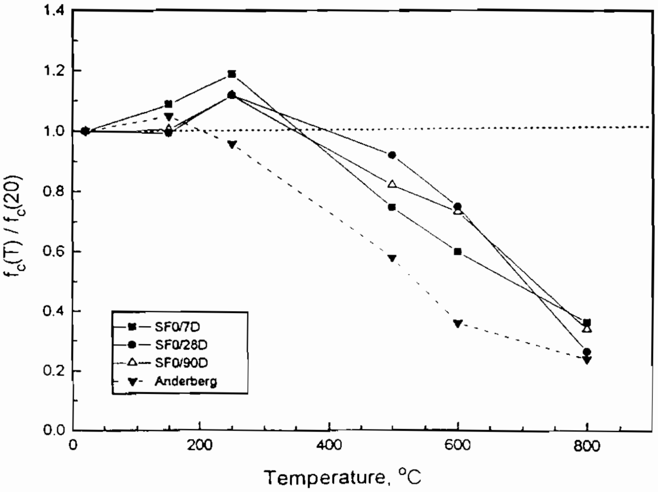

Fig. 4. The effect of temperature on the compressive strength of plain concrete as compared with data obtained from reference (Anderberg 1976).

The results of the present investigation are somewhat higher than those reported by Anderberg (1976). This can be attributed to the difference in concrete mixture. However, the trend of decreasing residual strength with higher temperatures and the peak strength value due to the free water evaporation phenomenon are similar to those reported by Anderberg (1976).

Figure 5 shows the strength ratio of SFC samples made with 5% and 15% SF content at high temperatures compared with similar results on cement paste made with silica fume from Sullivan & Sharshar (1992) for 28-day specimens. The results

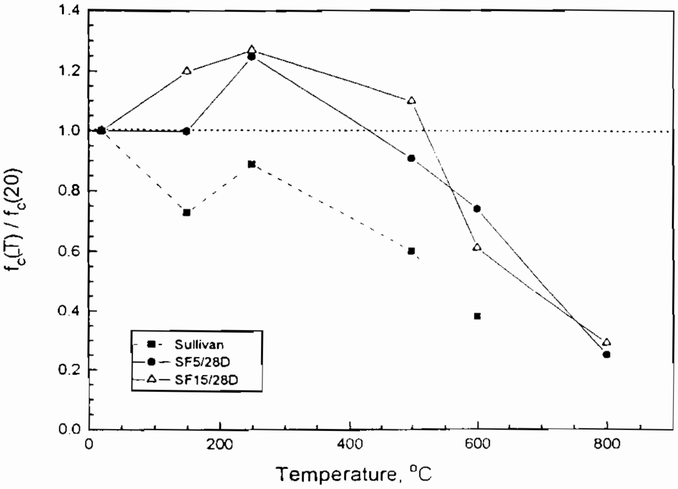

Fig. 5. The effect of temperature on the compressive strength of concrete made with 5% and 15% silica fume content as compared with data obtained from reference (Sullivan and Sharshar 1992).

from Sullivan and Sharshar are obtained from specimens made with the following mix proportions:

Constituents	weight units
Cement	0.90
Silica fume (SF)	0.10
Water	0.43
Strength (N/mm^2)	66.3

The curves indicate similar trends of decreasing strength with high temperatures of SFC. The peak value of the strength ratio for results from Sullivan and Sharshar (1992) also occurs around 250°C. The fact that the peak value reported by Sullivan & Sharshar at 250°C is well below 1.0 could be due to the faster disintegration of cement pastes than that of concrete at high temperatures, as observed in the literature (Schneider 1985). It should also be pointed out that differences in experimental details such as heating rate, time of exposure etc., within the ranges normally adopted in the literature (Schneider 1985), should not have considerable effects on the results of the compressive strength of concrete.

CONCLUSIONS

The following conclusions are drawn from the study presented in this paper:

1. In general, the compressive strength of silica fume concrete (SFC), like that of normal concrete, decreases with increasing temperatures (Fig. 1). At 250°C a peak value in the ratio of the compressive strength at high temperatures to that at ambient is observed (Figs. 2(A) & 2(B)). This peak value could be attributed to the evaporation of the free water content. At 800°C the compressive strength of SFC is reduced to around 20% of its original value at ambient temperature.
2. The effect of curing ages, up to 90 days, on the compressive strength behavior of silica fume concrete (SFC) is negligible (Figs. 2(A) & 2(B)). This is particularly observed at temperatures above 250°C after the free water content evaporates.
3. Based on typical results from 90-day samples, it was observed that the compressive strength of SFC increases with the increase in SF content at temperatures up to 250°C. At temperatures of 500°C to 600°C, the compressive strength of SFC remains reasonably constant with increasing SF content, whereas higher contents of SF tend to decrease the compressive strength of SFC around 800°C (see Fig. 3).
4. In general, silica fume concrete (SFC) made with 15% SF content showed higher compressive strength ratio values up to 600°C. Results also indicated that siliceous concrete with 15% SF content has the slowest rate of decrease in strength, and therefore the relatively most stable behavior, at high temperatures (Figs. 1 & 2(A)).
5. The trend of the results of the present investigation compare reasonably well with those reported by Sullivan & Sharshar (1992) for 10% silica fume cement paste.

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APPENDIX I. GLOSSARY

SF = Silica Fume
SFC = Silica Fume Concrete
SF0/7D = Concrete with 0% Silica Fume at 7 curing days
SF5/7D = Concrete with 5% Silica Fume at 7 curing days
SF15/7D = Concrete with 15% Silica Fume at 7 curing days
SF20/7D = Concrete with 20% Silica Fume at 7 curing days
SF25/7D = Concrete with 25% Silica Fume at 7 curing days
SF0/28D = Concrete with 0% Silica Fume at 28 curing days
SF5/28D = Concrete with 5% Silica Fume at 28 curing days
SF15/28D = Concrete with 15% Silica Fume at 28 curing days
SF20/28D = Concrete with 20% Silica Fume at 28 curing days
SF25/28D = Concrete with 25% Silica Fume at 28 curing days
SF0/90D = Concrete with 0% Silica Fume at 90 curing days
SF5/90D = Concrete with 5% Silica Fume at 90 curing days
SF15/90D = Concrete with 15% Silica Fume at 90 curing days
SF20/90D = Concrete with 20% Silica Fume at 90 curing days
SF25/90D = Concrete with 25% Silica Fume at 90 curing days

APPENDIX II. GRADING OF FINE AND COARSE AGGREGATES

Grading of coarse aggregates
(local crushed stone-gravel):

Sieve Size ASTM	Weight Retained (grams)
1″	0.00
$\frac{3}{4}''$	470.40
$\frac{1}{2}''$	158.70
3/8″	328.20
3/10″	39.90
Pan	2.60
Total	999.80

Grading of fine aggregates
(local sand):

Sieve Size ASTM	Weight Retained (grams)
#4	0.00
#8	20.90
#16	56.50
#30	128.60
#50	210.30
#100	70.60
#200	9.8
Pan	3.30
Total	500.00

Mix proportions (in kg/m^3)

% SF	0%	5%	15%	20%	25%
Cement	445.00	422.41	378.00	355.70	333.50
Silica Fume	0.00	22.20	66.70	89.00	111.20
Sand	800.80	800.00	800.00	800.00	800.00
Gravel	1289.30	1289.30	1289.30	1289.30	1289.30
Water	245.00	245.00	245.00	245.00	245.00

APPENDIX III. COMPRESSIVE STRENGTH DATA

Strength at 7 days

SF0/7 T(C)		Fc(T)		Fc(T) average	Fc(T)/Fc(20)
20	32.5	33.0	30.1	31.87	1.00
150	33.50	31.30	30.20	31.67	1.09
250	33.60	35.00	35.10	34.57	1.19
500	21.20	21.00	23.10	21.77	0.75
600	16.00	18.10	18.20	17.43	0.60
800	11.10	10.70	9.90	10.57	0.36
SF5/7 T(C)		Fc(T)		Fc(T) average	Fc(T)/Fc(20)
20	27.9	27.0	27.3	27.40	1.00
150	28.00	29.40	27.20	28.20	0.97
250	36.70	37.00	36.10	36.60	1.26
500	24.60	25.00	24.10	24.57	0.84
600	17.60	18.00	16.70	17.43	0.60
800	9.20	8.40	7.90	8.50	0.29

Appendix III — *continued*

SF15/7 T(C)	Fc(T)			Fc(T) average	Fc(T)/Fc(20)
20	21.9	21.3	21.7	21.63	1.00
150	28.00	26.60	28.70	27.77	0.95
250	37.10	40.00	39.10	38.73	1.33
500	24.00	25.20	26.00	25.07	0.86
600	19.10	20.10	19.10	19.43	0.67
800	5.90	5.10	5.20	5.40	0.19

SF20/7 T(C)	Fc(T)			Fc(T) average	Fc(T)/Fc(20)
20	30.1	31.0	31.1	30.73	1.00
150	32.40	32.70	32.20	32.43	1.11
250	33.30	37.50	36.10	35.63	1.22
500	22.00	22.10	22.90	22.33	0.77
600	20.70	21.50	22.90	21.70	0.75
800	5.30	4.70	5.20	5.07	0.17

SF25/7 T(C)	Fc(T)			Fc(T) average	Fc(T)/Fc(20)
20	25.7	26.0	25.9	25.87	1.00
150	28.90	29.10	30.10	29.37	1.01
250	30.40	32.20	32.40	31.67	1.09
500	20.70	21.00	20.30	20.67	0.71
600	12.10	15.10	14.20	13.80	0.47
800	5.10	3.50	3.80	4.13	0.14

Strength at 28 days

SF0/28 T(C)	Fc(T)			Fc(T) average	Fc(T)/Fc(20)
20	30.2	29.1	28.0	29.10	1.00
150	30.00	27.90	28.90	28.93	0.99
250	31.90	33.70	32.10	32.57	1.12
500	27.20	26.30	27.00	26.83	0.92
600	21.20	21.70	22.60	21.83	0.75
800	6.70	7.80	8.60	7.70	0.26

SF5/28 T(C)	Fc(T)			Fc(T) average	Fc(T)/Fc(20)
20	29.5	29.8	29.1	29.47	1.00
150	30.10	29.00	29.10	29.40	1.00
250	36.40	37.20	37.30	36.97	1.25
500	27.20	26.30	27.00	26.83	0.91
600	21.20	21.70	22.60	21.83	0.74
800	24.10	22.00	21.20	22.43	0.76

Appendix III – *continued*

SF15/28 T(C)	Fc(T)			Fc(T) average	Fc(T)/Fc(20)
20	32.0	32.2	30.1	31.43	1.00
150	36.5	37.6	39.0	37.70	1.20
250	39.1	40.1	40.9	40.03	1.27
500	36.2	34.1	33.5	34.60	1.10
600	20.1	19.1	18.6	19.27	0.61
800	10.1	9.2	7.8	9.03	0.29

SF20/28 T(C)	Fc(T)			Fc(T) average	Fc(T)/Fc(20)
20	31.2	32.0	31.9	31.70	1.00
150	33.4	35.2	36.0	34.87	1.10
250	40.1	40.2	39.5	39.93	1.26
500	30.0	29.6	29.1	29.57	0.93
600	20.7	23.7	22.9	22.43	0.71
800	6.3	6.5	7.1	6.63	0.21

SF25/28 T(C)	Fc(T)			Fc(T) average	Fc(T)/Fc(20)
20	34.1	33.9	35.0	34.33	1.00
150	35.1	34.0	36.0	35.03	1.02
250	39.7	39.2	40.7	39.87	1.16
500	22.6	23.7	23.1	23.13	0.67
600	19.8	19.1	18.7	19.20	0.56
800	7.8	5.2	5.7	6.23	0.18

Strength at 90 days

SF0/90 T(C)	Fc(T)			Fc(T) average	Fc(T)/Fc(20)
20	30.0	31.0	28.9	29.97	1.00
150	31.00	30.00	29.50	30.17	1.01
250	33.10	34.20	33.20	33.50	1.12
500	25.00	24.30	24.70	24.67	0.82
600	22.00	22.20	21.70	21.97	0.73
800	11.10	9.30	10.10	10.17	0.34

SF5/90 T(C)	Fc(T)			Fc(T) average	Fc(T)/Fc(20)
20	33.0	33.2	32.9	33.03	1.00
150	34.30	35.20	33.20	34.23	1.04
250	34.60	35.20	37.30	35.70	1.08
500	27.10	26.30	26.20	26.53	0.80
600	22.20	23.10	22.30	22.53	0.68
800	9.50	9.30	10.10	9.63	0.29

Appendix III — *continued*

SF15/90 T(C)		Fc(T)		Fc(T) average	Fc(T)/Fc(20)
20	33.5	34.1	34.2	33.93	1.00
150	34.30	35.40	36.10	35.27	1.04
250	34.90	37.10	37.30	36.43	1.07
500	27.20	26.30	27.00	26.83	0.79
600	21.20	21.70	22.60	21.83	0.64
800	6.70	7.80	8.60	7.70	0.23

SF20/90 T(C)		Fc(T)		Fc(T) average	Fc(T)/Fc(20)
20	36.1	37.0	36.0	36.37	1.00
150	37.90	36.20	34.60	36.23	1.00
250	39.10	42.60	39.00	40.23	1.11
500	22.50	23.00	24.30	23.27	0.64
600	19.60	18.60	20.10	19.43	0.53
800	5.50	6.30	6.90	6.23	0.17

SF25/90 T(C)		Fc(T)		Fc(T) average	Fc(T)/Fc(20)
20	40.0	39.1	38.7	39.27	1.00
150	38.60	38.30	41.80	39.57	1.01
250	39.40	41.00	42.80	41.07	1.05
500	23.10	22.00	21.10	22.07	0.56
600	24.00	23.10	23.70	23.60	0.60
800	20.10	16.00	17.10	17.73	0.45

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مقاومة الضغط في الخرسانة المكونة من بودرة السيليكا تحت تأثير الحرارة المرتفعة

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خلاصة

يعالج هذا البحث تأثير بودرة السيليكا على تصرف خرسانة اسمنت البورتلند المصنوعة من ركام السيليكا وذلك تحت تأثير الحرارة المرتفعة. لإنجاز هذه الأهداف ، تم تحضير عينات وفحص مقاومتها للضغط عند محتويات مختلفة من بودرة السيليكا (00% حتى 25%) وبدرجات حرارة مختلفة ، وأعمار معالجة مختلفة(حتى 90 يوما) . لقد تم معالجة العينات تحت 95% رطوبة نسبية وبحرارة من 20 الى 22 درجة مئوية ، ومن ثم تم تسخينها بالفرن حتى بلغت درجة الحرارة المرجوة . بعد ذلك تركت حتى تبرد الى درجة الحرارة الخارجية. وأخيرا تم فحصها للحصول على مقاومتها للضغط المتبقية.

وقد أثبتت نتائج هذا البحث أن المقاومة للضغط في الخرسانة المكونة من بودرة السيليكا تنخفض مع ارتفاع الحرارة حتى تبلغ هذه المقاومة 20% من قيمتها الأصلية عندما تبلغ درجة الحرارة نحو 800 درجة مئوية ، كما أثبتت أن أعمار المعالجة (حتى90 يوما) تؤثر بالكاد على مقاومة هذا النوع من الخرسانة عند درجات الحرارة المرتفعة ، وأن المقاومة للضغط في الخرسانة المكونة من بودرة السيليكا تتزايد مع ارتفاع نسبة بودرة السيليكا عند درجات الحرارة دون 250 درجة مئوية ، وتبقى ثابتة عند الدرجة 500 الى 600 مئوية ، وأخيرا تميل الى التناقص عندما تقارب درجة الحراة 800 درجة مئوية.

نتائج هذا البحث إيجابية بالمقارنة مع اعمال علمية سابقة.