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Performance of self-compacting concrete at room and after elevated temperature incorporating Silica fume

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Abstract. This paper evaluates the workability and hardened properties of self-compacting concrete (SCC) containing silica fume as the partial replacement of cement. SCC mixtures with 0, 2, 4, 6, 8 and 10% silica fume were tested for fresh and hardened properties. Slump flow with T_{500} time, L-box and V-funnel tests were performed for evaluating the workability properties of SCC mixtures. Compressive strength, splitting tensile strength and modulus of rupture were performed on hardened SCC mixtures. Experiments revealed that replacement of cement by silica fume equal to and more than 4% reduced the slump flow diameter and increased the T_{500} and V-funnel time linearly. Compressive strength, splitting tensile strength and modulus of rupture increased with increasing the replacement level of cement by silica fume and were found to be maximum for SCC mixture with 10% silica fume. Further, residual hardened properties of SCC mixture yielding maximum strengths (i.e., SCC with 10% silica fume) were determined experimentally after heating the concrete samples up to 200, 400, 600 and 800°C. Reductions in hardened properties up to 200°C were found to be very close to normal vibrated concrete (NVC). For 400 and 600°C reductions in hardened properties of SCC were found to be more than NVC of the same strength. Explosive spalling occurred in concrete specimens before reaching 800°C.

Keywords: self-compacting concrete; silica fume; mechanical properties; elevated temperature

1. Introduction

Self-compacting concrete does not need external vibration for its compaction, resulting in better durability, reduced time required for placing, environmental friendly and improved aesthetics (Okamura and Ouchi 2003, Salhi *et al*. 2017, Lenka and Panda 2017). Key properties of self-compacting concrete are filling ability, passing ability and segregation resistance which are achieved by reducing the coarse aggregate content, limiting the maximum aggregate size, reducing water-binder ratio and using superplasticizers. The increased flow-ability of SCC may cause segregation and bleeding during its transportation and placement which can be overcome by using viscosity modifying admixtures (VMA) (Okamura and Ouchi 1998, Ahmad and Umar 2018a, Khayat *et al*. 1999, Ahmad and Umar 2018b).

Silica fume is very fine noncrystalline silica obtained from electric arc furnaces as a by-product in the manufacturing of elemental silicon or alloys containing silicon. It is generally a grey coloured powder, slightly similar to some fly ashes or Portland cement. It exhibits both cementitious and pozzolanic properties (ACI 234 1995). Mazloom *et al*. (2004) studied the compressive strength of NVC by replacing 0, 6, 10, and 15%, of cement by silica fume with a water-powder ratio 0.35. They observed that 28 days compressive strength of concrete containing silica fume was 21% higher than that of control concrete. Sobolev (2004) found that NVC with 15% silica fume yielded highest compressive strength of 91 MPa at 28 day followed by 90 MPa at 10 and 20% of silica fume. Almusallam *et al*. (2004) concluded that NVC containing silica fume has more splitting tensile strength that of plain concrete. They also observed that highest splitting tensile strength was found in NVC specimens containing 15% silica fume followed by those prepared with 10% silica fume. Some researchers showed that use of silica fume in SCC as a partial replacement of cement enhances its mechanical properties. Bhanja and Sengupta (2005) observed that splitting tensile strength and modulus of rupture at 28 day of NVC mixtures increased significantly when 5, 10 and 15% of the cement was replaced by silica fume. This increase was found to be insignificant beyond 15% replacement. Yazici (2008) replaced 30, 40, 50 and 60% of cement in SCC by silica fume and fly ash. Compressive strength was found to be increased by 26% and 7% over control mix for 30% and 50% replacement. For 50 and 60% replacement, compressive strength was reduced by 4% and 16%, respectively over control mix. Splitting tensile strength was found to be increased by 20% when 30% of cement was replaced by silica fume and fly ash. When 40% of cement was replaced by silica fume and fly ash, splitting tensile strength was found to be reduced by 15%. Jalal *et al*. (2012) observed that incorporation of 10% silica fume in SCC reduced its workability properties. They also observed the improvement in compressive and splitting tensile strength after the addition of 10% silica fume in SCC. Sabet *et al*. (2013) found that replacement of cement by 10% of silica fume increased 28 day compressive strength of SCC by 25%. Further, 10% replacement of

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Table 1 Properties of cement used

Physical properties	
Normal consistency (%)	28
Initial setting time (min)	55
Final setting time (min)	175
Compressive strength (MPa)	
3 days	24.1
7 days	33.9
28 days	44.8
Soundness (mm)	2.5
Fineness (retained on 90μm sieve)	8
Specific gravity	3.15
Chemical properties (%)	
SiO_2	19.50
Al_2O_3	9.57
Fe_2O_3	3.36
CaO	60.00
MgO	1.63
SO_3	2.53
Na_2O	0.82
K_2O	1.21
Loss on ignition	1.23

Table 2 Properties of fly ash

Physical properties	
Colour	Grey (blackish)
Specific gravity	2.14
Chemical properties (%)	
Loss on ignition	4.15
Silica (SiO_2)	58.57
Iron oxide (Fe_2O_3)	3.46
Alumina (Al_2O_3)	28.18
Calcium oxide (CaO)	2.22
Magnesium oxide (MgO)	0.33
Alkalies	
Sodium oxide (Na_2O)	0.58
Potassium oxide (K_2O)	1.26

Table 3 Properties of silica fume

Physical properties		ASTM C1240-14 specifications
Specific gravity	2.22	-
Surface area	20000 m^2/kg	15000 m^2/kg (min)
Chemical properties		
SiO_2	94%	85% (min)
H_2O	0.8%	3% (max)
CaO	0.3%	1% (max)
Loss on ignition	4.9%	6% (max)

cement by silica fume in SCC had insignificant effect (only 3%) on its compressive strength. They also found that increasing the amount of silica fume in SCC increased the superplasticizer demand.

Sideris (2007) investigated mechanical characteristics of SCC subjected to elevated temperatures up to 700℃ He reported the residual compressive strength of SCC mixtures was higher than that of NVC for the same strength class. Fares *et al*. (2010) carried out an experimental study on the properties of SCC subjected to high temperature. They observed that the residual compressive strength and modulus of rupture decreased slightly between 20 and 150^{o}C. An increase in compressive strength between 150 and 300℃ was found but modulus of rupture continued to decrease. Beyond 300^{o}C significant loss in compressive strength and modulus of rupture was found. Pathak and Siddique (2012) studied the properties of SCC such as compressive strength, splitting tensile strength, rapid chloride permeability, porosity, and mass loss when exposed to elevated temperatures. Test results clearly showed that there was little improvement in compressive strength within temperature range of 200-300℃ as compared to 20-200℃ but there is little reduction in splitting tensile strength ranging from 20 to 300℃ with the increase in percentage of fly ash. Literature available on the effect of replacement of cement by silica fume in SCC is limited (Jalal *et al*. 2012, Sabet *et al*. 2013) and the replacement levels reported in all the studies are high (10 to 60%). There is a need of an experimental study that assesses the effect of low replacement levels (0 to 10%) of cement by silica fume on the fresh and mechanical properties of SCC. Therefore, a study was carried out to evaluate the effect of 2, 4, 6, 8 and 10% replacement of cement by silica fume on fresh and hardened properties of SCC. Further, SCC with 10% of silica fume was heated in an electric furnace up to 200, 400 and 600 and 800^{o}C and tested for compressive strength, splitting tensile strength and modulus of rupture.

2. Materials used

2.1 Cement

Grade 43 ordinary Portland cement complying with IS: 8112-1989 was used in the study. Physical and chemical properties of the cement used are given in Table 1.

2.2 Admixtures

2.2.1 Mineral admixture

Physical and chemical properties of the *class F* fly ash used in the study are given in Table 2. Elkem *silica fume* grade 920D was used in this study. Properties of silica fume used in the study are given in Table 3.

2.2.2 Chemical admixtures

Super-plasticizer and viscosity modifying admixture (VMA) were used in the study. Polycarboxylic ether based super-plasticizer, confirming to ASTM C 494 type F having pH approximately 5.0 and density approximately 1.10 was used. VMA meeting ASTM C 494 type S, specific performance admixtures was used.

2.3 Aggregates

Fine aggregate (sand) confirming to Indian Standard Specification IS: 383-1970 was used in the study after

Table 4 Physical properties of aggregates

Characteristic	Fine aggregate	Coarse aggregate
Specific gravity	2.46	2.66
Fineness modulus	2.65	6.88
Water absorption	0.85%	0.3%
Loose bulk density (kg/m^3)	1580	1470
Compacted bulk density (kg/m^3)	1760	1660

Table 5 Composition of different SCC mixtures

Material	SCC -M0	SCC -M2	SCC -M4	SCC -M6	SCC -M8	SCC -M10
Cement (kg/m^3)	530	519.4	508.8	498.2	487.6	477
Fly Ash (kg/m^3)	70	70	70	70	70	70
Fine Aggregate (kg/m^3)	725	725	725	725	725	725
Coarse Aggregate (kg/m^3)	775	775	775	775	775	775
Water (kg/m^3)	225	225	225	225	225	225
Superplasticizer (%)	1.2	1.2	1.2	1.2	1.2	1.2
VMA (%)	0.3	0.3	0.3	0.3	0.3	0.3
Silica Fume (kg/m^3)	0	10.6	21.2	31.8	42.4	53

sieving through 4.75 mm sieve. Maximum size of the used coarse aggregate was 12.5 mm. The results of different tests performed on fine and coarse aggregates are given in Table 4.

3. Mix proportions

Composition of different SCC mixtures is given in Table 5. Composition of all the mixtures was kept same except cement which was replaced by microsilica (silica fume) in the range 2-10%. SCC stands for self-compacting concrete. Number after letter '*M*' indicates the percentage of cement replaced by silica fume. Casting, curing and storage of concrete were done according on Indian Standards except compaction during casting.

4. Experimental program

4.1 Fresh properties of SCC

Following tests were performed on fresh SCC to measure the workability properties.

1. Slump flow and T_{500} time measurement as per BS EN 12350-Part 8:2010.
2. L-box test as per BS EN 12350-Part10:2010.
3. V-funnel tests; T_0 and T_5 as per BS EN 12350-Part 9: 2010.

4.2 Hardened properties of SCC

Compressive strength and modulus of rupture tests were done according to IS: 516-1959 while IS: 5816-1999 was used for splitting tensile strength. For compressive strength determination of each mix at different age three cylinders of 150 mm diameter and 300 height were tested in a compression testing machine. Three cylinders of the size mentioned above were tested for the determination of splitting tensile strength for each mix. For each mix three prisms of 100 mm×100 mm in cross section and 500 mm in length were tested under four point bending for the determination of modulus of rupture.

Table 6 Fresh properties of different mixes of SCC

Test		SCC -M0	SCC -M2	SCC -M4	SCC -M6	SCC -M8	SCC -M10
Slump flow (mm)		720	720	700	690	670	650
T_{500} (s)		3	3	3.5	3.9	4.25	4.5
L-Box Test (H_2/H_1)		0.95	0.94	0.90	0.85	0.84	0.84
V-funnel time (s)	T_0	4	4	6	6.5	7.5	8.5
	T_5	6.5	7	7.5	7.75	8.0	9.75

4.3 Heating of the specimens

Hardened concrete specimens were heated in an electric furnace at the rate of 3°C per minute. The electric furnace was 600 mm×600 mm in cross section and 700 mm in height. The temperature of the specimens was monitored using a *K*-type thermocouple embedded at the centre of the specimens during casting. After attaining the target temperature, the temperature is kept constant for 1 hr so that the steady state may be achieved. Specimens were allowed to cool up to room temperature within the furnace and tested for residual mechanical properties.

5. Results and discussions

In order to study the effect on SCC mixes having increasing amount of micro silica, VMA, glass fibres and polyvinyl alcohol fibres, slump flow with T_{500} , V-funnel (T_0 and T_5), L-box and J-ring tests were conducted. The results of fresh properties of all mixes are given in Table 6. All the properties are within the limits prescribed by EFNARC 2005.

5.1.1 Slump flow and T_{500} flow time

Measured slump flow was found to be in the range 650-720 mm. Slump flow diameters of SCC-M0 and SCC-M2 was found to be equal. The slump flow was found to be decreasing linearly for SCC-M4, SCC-M6, SCC-M8 and SCC-M10. T_{500} flow time was also found to be equal for SCC-M0 and SCC-M2. The maximum and minimum T_{500} flow time was found for SCC-M10 and SCC-M0 respectively. Fig. 1 shows the variation of slump flow and T_{500} flow time for SCC with various percentages of silica fumes. The decrease in slump flow and increase in T_{500} time may be attributed to the high surface area of silica fume which decreases the fluidity of concrete mixtures by adsorbing the superplasticizer (Park *et al*. 2005).

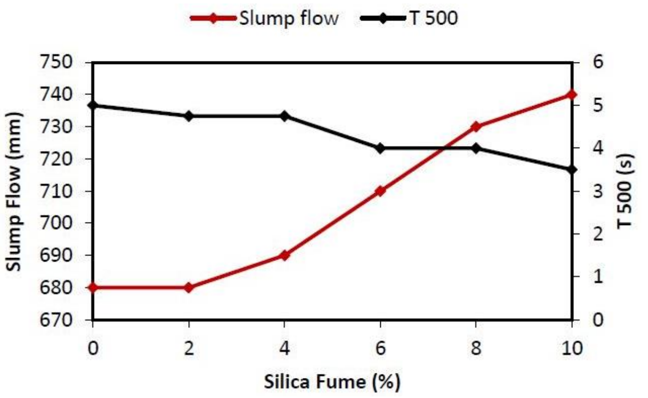

Fig. 1 Slump flow and T_{500} time variation with silica fume

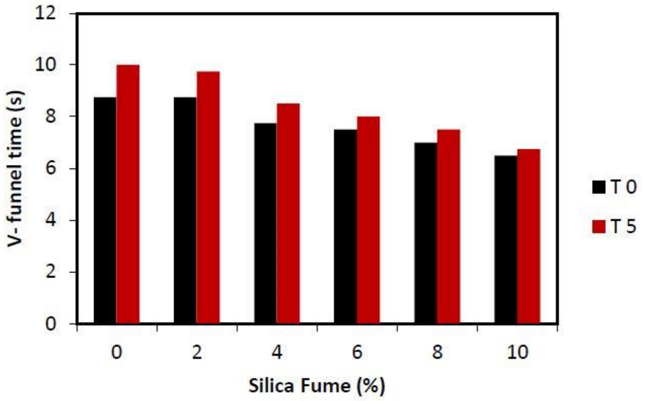

Fig. 2 V-funnel time variation with silica fume

5.1.2 L-box ratio

L-box ratio approximately remained unaffected up to 4 % replacement of cement by silica fume but was found to be decreased when replacement level of cement is increased beyond 4% and the lowest L-box ratio of 0.84 was found for SCC-M10.

5.1.3 V-funnel time

Table 6 and Fig. 2 shows that the replacement of cement by silica fume in SCC increased both T_0 (V-funnel time immediately after filling of funnel) and T_5 (V-funnel time after 5 minutes of filling of funnel) and the difference between both the times was found to be less than 3 s i.e., the segregation resistance of all the mixes were satisfactory. Minimum and maximum V-funnel times were found to be for SCC-M0 and SCC-M10 respectively.

5.2 Hardened properties

Hardened concretes were tested for compressive strength, splitting tensile strength and modulus of rupture and the influence of silica fume on self-compacting concrete was studied. The observations are given in Table 7.

5.2.1 Compressive strength

Table 7 Hardened properties of different mixes

Mix	Compressive strength (MPa)		Splitting tensile strength (MPa)	Modulus of rupture (MPa)
	7 day	28 day		
SCC-M0	28.15 (0.3)	38.85 (0.7)	4.06 (0.08)	5.11 (0.09)
SCC-M2	29.83 (0.4)	40.48 (1.0)	4.17 (0.09)	5.61 (0.07)
SCC-M4	32.73 (0.3)	45.41 (0.4)	4.51 (0.1)	6.06 (0.07)
SCC-M6	34.55 (0.4)	47.94 (0.4)	4.65 (0.07)	6.22 (0.04)
SCC-M8	36.35 (0.8)	50.03 (0.3)	4.80 (0.07)	6.55 (0.05)
SCC-M10	38.83 (0.4)	52.32 (0.2)	5.09 (.08)	6.74 (0.03)

*Numbers in the parentheses are the standard deviations

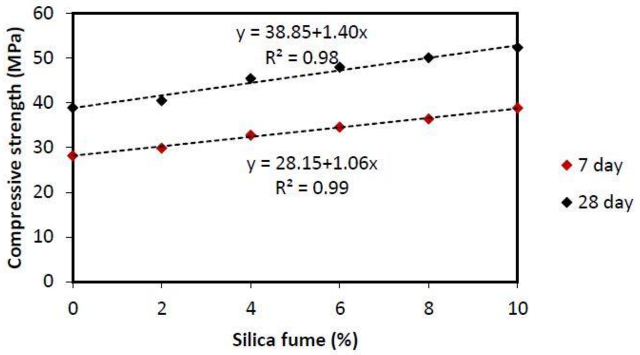

Fig. 3 Compressive strength variation with silica fume

It was found that compressive strength (f_c) increased with the increase in replacement level of cement by silica fume. Table 7 shows the results of compressive strengths of different mixes. Fig. 3 shows development of compressive strengths for different SCC mixtures with the addition of silica fume. Minimum and maximum compressive strengths were found for SCC-M0 and SCC-M10 respectively. After 10% replacement of cement by silica fume, 30% increase in compressive strength was found. Strong co-relations (0.99 for 7 day and 0.98 for 28 day compressive strength) are observed when the variations of compressive strengths with the replacement levels of cement by silica fume are joined by linear trend lines.

$$\text{For 7 day;}\quad f_{c,SF} = f_c + 1.06 \times \text{Silica fume content (\%)} \quad R^2=0.99 \qquad (1)$$

$$\text{For 28 day;}\quad f_{c,SF} = f_c + 1.40 \times \text{Silica fume content (\%)} \quad R^2=0.98 \qquad (2)$$

The effect of silica fume is more pronounced on 28 days compressive strength of SCC. This may be due to the fact that silica fume consumes crystalline $Ca(OH)_2$ which are formed during the hydration of Portland cement.

5.2.2 Splitting tensile strength and modulus of rupture

Minimum and maximum splitting tensile strengths were found for SCC-M0 and SCC-M10 respectively. The relationship between splitting tensile (f_{ct}) strength and compressive strength (Fig. 4) of SCC mixtures with silica fume was found to be

$$f_{ct} = 0.35 f_c^{2/3} \qquad (3)$$

Splitting tensile strength (f_{ct}) calculated from the above relation and the equations given by ACI-318 (2005), Eurocode 2 (2004), Felekoglu *et al.* (2007), Sukumar *et al.* (2008) are compared in Fig. 5. Splitting tensile strength

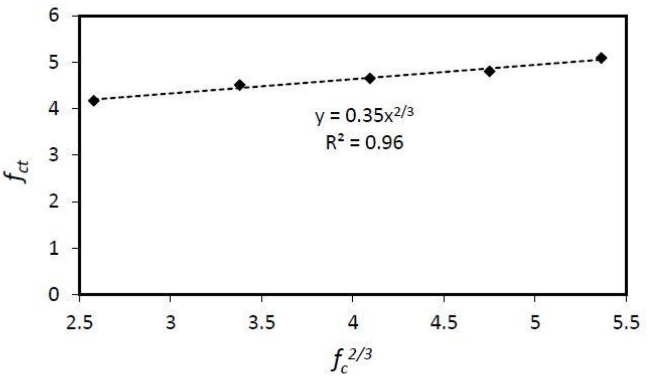

Fig. 4 Relation between splitting tensile strength and compressive strength

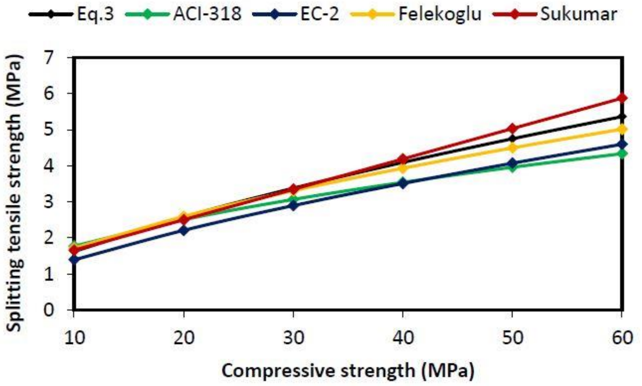

Fig. 5 Comparison between proposed splitting tensile strength equation and equations given by other researchers and committees

obtained by the proposed equation is higher than those obtained by ACI-318 and EC-2 because splitting tensile strength for SCC is higher than NC due to better homogeneity coming from vibration free production (Sonebi and Bartos 1999, Dinakar *et al*. 2008). Also, the splitting tensile strength obtained by the proposed equation is in good agreement with the values obtained by the equations given for SCC by Felekoglu *et al*. (2007), Sukumar *et al*. (2008) (Fig. 5).

Enhancement in mechanical properties of SCC is attributed to the pozzolanic action of silica fume and to the filler role of very fine particles of silica fume. Silica fume changes the structure of cement paste by reducing the weak and easily soluble calcium hydroxides and increases the strong calcium-silicate hydrates. This is the reason of markedly improved mechanical properties of concrete.

6. Effect of elevated temperature on SCC-M10:

6.1 Cracking of concrete specimens due to heating

The concrete specimens after exposure to high temperatures are shown in Fig. 6. Due to poor thermal conductivity of concrete its exposure to high temperature causes thermal gradient, resulting in its cracking. The thermal gradient is largely governed by heating rate, cooling rate, concrete thermal properties and intensity of heat. Pore pressure is also developed in the concrete during exposure to high temperature, which depends on the rate of heating, intensity of heat and size of the specimen (Bazant and Kaplan 1996). Cracks in concrete specimens were not observed when heated up to 200℃. The concrete started to crack when temperature is increased to 400℃ but the cracks were found to be significant when temperature was increased up to 600℃. Explosive spalling of concrete was also observed before reaching 800℃.

Fig. 6 Cracks in concrete specimens after heating

Table 8 Hardened properties of SCC-M10 after elevated temperature

Temperature	Compressive strength (MPa)	Splitting tensile strength (MPa)	Flexural strength (MPa)
28	52.32	5.09	6.74
200	44.67 (7.13)	3.83 (7.56)	5.12 (6.65)
400	26.16 (8.25)	2.49 (8.01)	2.9 (7.67)
600	17.13 (9.07)	1.42 (9.05)	1.82 (9.00)

*Numbers in the parentheses are the average mass loss of concrete specimens

6.2 Mass loss after exposure to elevated temperature

Average mass loss for SCC-M10 at 200, 400 and 600°C was found to be 7.13, 8.25 and 9.05% respectively. Mass loss between 20 and 300℃ is due to the loss of the evaporable and portion of the physically bound water (Bazant and Kaplan 1996, Ahmad *et al*. 2018). Beyond 300℃ mass loss is due to the elimination of chunks or spalling of concrete (Yuksel *et al*. 2011).

6.3 Effect of temperature on hardened properties of SCC with 10% silica fume

6.3.1 Compressive strength

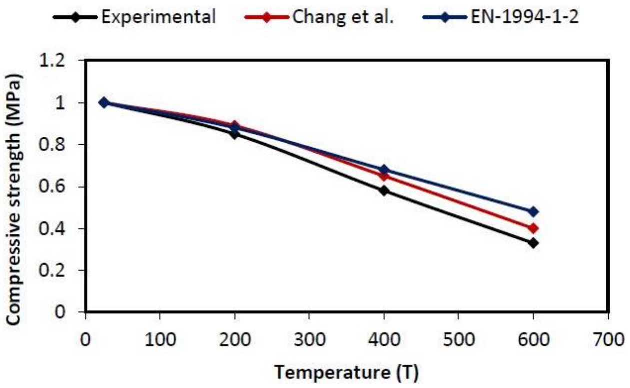

Fig. 7 Variation in compressive strength with temperature

Fig. 7 shows that the compressive strength of SCC-M10 reduced as the temperature was increased and the rate of reduction is lower (only 15%) for heating up to 200℃. However, for 400℃ and 600℃ the values of residual compressive strengths were reduced to 58% and 33% of the original strength. Higher reduction in compressive strength above 200℃ is due to the continuous dehydration of hydrated cement paste from 105 to 850℃, and crystalline modification from α-quartz to β-quartz take place between 500 and 650℃ (Bazant and Kaplan 1996).

Fig. 7 also compares the residual compressive strength of SCC-M10 with the residual compressive strength equations (Chang *et al*. 2006, Eurocode 4 1994) available in literature for NVC. All the results of residual compressive strength of SCC-M10 show similar trend as that for NVC but the reduction is found to be higher in temperatures above 200℃.

6.3.2 Splitting tensile strength

Reduction in splitting tensile strength (25%, 51% and 72%) was more than that in compressive strength (15%, 42% and 67%) for SCC-M10 at all temperatures (200, 400 and 600℃). The experimental results up to 200℃ are very close to the values obtained by equations proposed for NVC by Chang *et al*. (2006), Harada *et al*. (1972) (Fig. 8). Beyond 200℃ splitting tensile strength of SCC was found to be lower than that of NVC.

6.3.3 Modulus of rupture

Modulus of rupture of SCC-M10 after heating up to 200℃, 400℃ and 600℃ was found to be decreased by 24%, 57% and 73% respectively. When concrete is subjected to elevated temperatures, contraction of cement paste and expansion of aggregates occur. Therefore, transition zone and bond between paste and aggregates are weakened. This process and decomposition of hydration products causes deterioration and strength loss in concrete after subjected to elevated temperature. Comparing Fig. 7 and Fig. 8 it may be concluded that strength losses are more in SCC when compared to the strengths calculated by equations available for NVC. This observation is contradictory to the results obtained by other researchers. The reason for this contradiction may be attributed to the presence of silica fume that produces very dense transition zone between paste and aggregate due to extreme fine particles as filler.

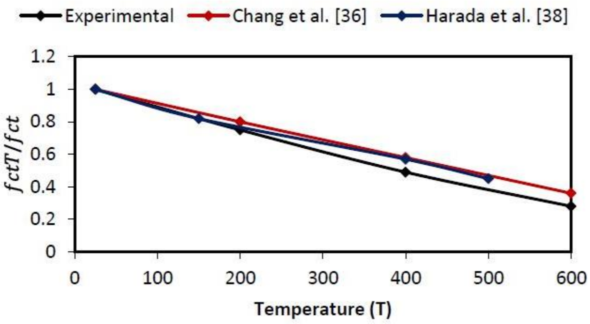

Fig. 8 Splitting tensile strength after heating at different temperatures

7. Conclusions

- Following conclusions can be drawn from the experimental study described in this paper:
- Increasing the replacement level of cement by silica fume in SCC reduced its workability properties. Filling ability of SCC was remained unaffected when 2% of cement was replaced by silica fume, since no change in slump flow diameter, T_{500} and V-funnel time was observed. Yield stress was found to be increased linearly when 4, 6, 8 and 10% of cement was replaced by silica fume because slump flow diameter reduced linearly for these replacements.
- Increase in T_{500} and V-funnel time after the replacement of cement by silica fume is an indication of the increased viscosity. This increase in viscosity was also found to be linear beyond 2% replacement levels.
- All the SCC mixtures had satisfactory segregation resistance since the difference between T_0 and T_5 for all the mixtures was less than 3 s.
- Increasing the silica fume content increased the compressive strength significantly, especially at older ages. Linear relations exists between compressive strength and percentage of silica fume added in SCC.
- For every 2% addition of silica fume the approximate increase in splitting tensile strength and modulus of rupture was found to be 4% and 5% respectively. The relation proposed between splitting tensile and compressive strength shows good agreement with the relations for SCC existing in literature.
- Explosive spalling occurred at 800^{o}C due to filling of the pores of SCC by silica fume, thereby increasing the pore water pressure above tensile strength of SCC-M10.
- Reduction in compressive strength, splitting tensile strength and modulus of rupture of SCC up to 200℃ was found to be comparable with that of NVC. Beyond 200℃ reduction in these properties of SCC-M10 was found to be more than that of NVC.

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