Behavior of SCC Incorporating Granulated Blast Furnace Slag and Ground Clay Brick Powders at High Temperatures

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Abstract. Behavior of self-compacting concrete (SCC) produced from local waste powder materials was experimentally investigated at high temperatures. Two types of wastes powder, granulated blast furnace slag (GBFS) and ground clay bricks (GCB) were used as a partial replacement of cement by weight. Five concrete mixes were prepared with 0% wastes powder, 30% GBFS, 20% GBFS +10% GCB, 10% GBFS+20% GCB and 30% GCB. The total cementitious materials content and water/cementitious materials ratios were 450 kg/m^3 and 0.39 respectively for all mixes. After water curing for 28 days, the test specimens were dried at 105 °C for 24 h before exposure to the desired high temperatures of 200, 400, 600 and 800 °C for 2 h. After exposure to the desired target temperature, the test specimens were allowed to cool at room temperature (RT) before testing. Fresh properties of all SCC mixes were measured and evaluated. Weight loss, residual compressive and splitting tensile strengths were measured after exposure to high temperatures. Properties at RT were also measured for comparison. Changes in physicochemical properties were explained based on the results of mass loss and X-ray diffraction analysis. Test results indicated that most of the original strength was lost on exposure to temperature between 600 and 800 °C. The performance of SCC mixes incorporating high content of GCB was better than that with GBFS at high temperatures. Utilization of GBFS, GCB or a combination of them as 30% partial replacement of cement content can produce economically and environmentally friendly concrete mixes.

1 Introduction

Portland cement concrete is a major construction material worldwide. Unfortunately, the production of portland cement releases large amounts of CO_2 into the atmosphere (Bilodeau and Malhotra 2000). The increase in the cement production is expected to be in the developing countries. Therefore, increasing the use of supplementary cementitious materials (SCMs) in concrete is an obvious and necessary step to reduce carbon emissions and produce environmentally friendly concrete (Malhotra 2006). SCMs, such as silica fume, fly ash and slag are often waste materials from industrial processes. These wastes possess hydraulic and/or pozzolanic properties and, when used at optimal levels, enhance fresh state properties, mechanical performance and durability (Kuder et al. 2012).

L. Struble and G. Tebaldi (eds.), *Materials for Sustainable Infrastructure*,
Sustainable Civil Infrastructures, DOI 10.1007/978-3-319-61633-9_13

Self-compacting concrete (SCC) is a new generation of concrete that can be compacted under its own weight without the need of external vibration. It is characterized by its ability to flow and fill narrow and deep members and produces uniform concrete mixes without any sign of segregation or bleeding. The development of SCC is considered to be one of the most significant developments in the building material domain. This is due to its advantages over the conventional concrete. One of the disadvantages of SCC is its cost, associated with the use of high volumes of Portland cement and use of chemical admixtures. Some researchers tried to reduce the cost of SCC by the use of mineral admixtures as a partial replacement of cement (Uysal and Sumer 2011; Uysal and Yilmaz 2011; Seleem et al. 2006; Ahmed et al. 2007). They found that, besides the decrease in the cost of cement, the use of mineral admixture may eliminate the need for viscosity-enhancing admixtures. Also, the use of mineral admixtures may improve the rheological properties of SCC and reduce thermally-induced cracking of concrete due to the reduction in the overall heat of hydration and increase in the workability and long-term properties of concrete (Dinker et al. 2008). Granulated blast furnace slags (GBFS) and ground clay bricks (GCB) are local industrial by-products mineral admixtures that can be used to reduce the cost of SCC.

In case of fire, concrete is exposed to high temperature that induces a material degradation: strength decrease, cracking and in some conditions spalling. Up to now, the effect of elevated temperatures has been studied mainly on vibrated ordinary and high performance concretes. The few studies on SCC subjected to high temperatures showed either a decrease in strength or an increase in the risk of spalling, or a behavior similar to that of vibrated concrete (Badawy et al. 2011a; Uysal 2012; Uysal et al. 2012). Using mineral admixture powders in the production of SCC mixes led to dense microstructure of mixes compared with those of normal concrete. The dense microstructure of SCC introduces a high strength and a very low permeability. However, the dense microstructure of SCC seems to be a disadvantage when exposed to fire (Fares et al. 2009). Therefore, the strength and durability characteristics after exposure to high temperatures of SCC containing mineral admixtures as partial replacements of cement should be investigated.

The objective of this study is to investigate the effect of high temperatures up to 800 °C on the properties of SCC incorporating two types of local wastes powder; GBFS, GCB or combinations of them as a partial replacement of cement weight. Fresh properties of the investigated SCC mixes were measured. Compressive and tensile strengths of the studied SCC mixes were also estimated at room and high temperatures. Moreover, weight loss and X-ray diffraction were used to explain the changes in physicochemical properties.

2 Experimentation

2.1 Materials

Ordinary Portland cement, conforming to Egyptian Standard Specifications (ESS 373/1991) and labeled as CEM I 42.5N was used. A natural well-graded river sand and dolomite with a maximum nominal size of 14 mm were used as fine and coarse aggregates respectively. The specific gravity and water absorption of the used sand and dolomite were 2.63, 0.65%, and 2.61, 0.8%, respectively. Two different types of by-products namely; GBFS and GCB ground to pass 170 µm sieve were used as mineral admixtures. Table 1 shows the chemical composition and specific gravities of cement, GBFS and GCB. A third generation super plasticizer, Sika Viscocrete-5930, based on modified polycarboxylate, was used as a viscosity enhancing admixtures (VEA). It has a dual action. It gives excellent flowability and in the same time enhances the stability (viscosity) of concrete. It meets the requirements for superplasticizers according to EN 934-2 and ASTM-C-494 type G and F.

Table 1. Chemical composition and specific gravity of cement and by-products

Component (%)	Cement	GBFS	GCB
SiO_2	21.0	35.78	57.7
Al_2O_3	6.1	10.94	15.6
Fe_2O_3	3.0	0.43	8.16
CaO	61.5	34.22	4.65
MgO	3.8	6.52	1.38
SO_3	2.5	3.01	7.02
Na_2O	0.4	1.06	1.26
K_2O	0.3	1.02	1.67
TiO_2	–	0.02	0.19
Specific gravity	3.15	2.89	2.5

2.2 Experimental Program and Mix Proportions

One control SCC mix without waste powders and four SCC mixes incorporating waste powders were prepared with 0% wastes powder (CM), 30% GBFS (S-30), 20% GBFS +10% GCB, (SH20-10), 10% GBFS+20% GCB (SH10-20) and 30% GCB (H-30) as a partial replacement of cement, see Table 2. After trial mixes the total content of cementitious materials and water/cementitious materials ratio (w/cm) were kept at 450 kg/m^3 and 0.39 respectively. The VEA was added in the amount of 2% from the total cementitious materials.

Table 2. Concrete mix proportions of SCC mixes

Mix code	Materials, kg/m^3							
	Cement	GBFS	GCB	W/CM	Water	Sand	Dolomite	VEA
CM	450	–	–	0.39	175	883	883	9
S-30	315	135	–			877	877	
SH20-10	315	90	45			874	874	
SH10-20	315	45	90			871	871	
H-30	315	–	135			868	868	

2.3 Fresh and Hardened Concrete Tests

The slump-flow, V-funnel and L-box tests were conducted to assess the workability, filling and passing abilities of SCC mixes in the fresh state according to the European guidelines (EFNARC 2002). Cube specimens having dimensions of 100 × 100 100 mm were used to determine the compressive strength and cylindrical specimens having dimensions of 75 × 150 mm were used to determine the splitting tensile strength. All specimens were cast after carrying out the fresh properties tests. The cast specimens were removed from moulds after 24 h and were cured in water for 28 days. After removing from water, the test specimens were air dried for the next day in the laboratory environment (30 °C temperature and 80% relative humidity). After that, the specimens were oven dried at approximately 105 °C for 24 h. For the high temperature tests, the specimens were heated until reaching to the desired target temperatures of 200, 400, 600 or 800 °C and held at that temperature for 2 h. The heated specimens were taken out from the furnace and left to cool at room temperature (RT). Fresh and hard properties were measured at room temperature (RT). Residual strength properties, weight loss due to high temperature exposure were also measures. XRD analysis and specimen surface examination due to exposure to high temperatures were conducted.

3 Results and Discussions

3.1 Properties of Fresh Concrete

The fresh properties of SCC mixes were measured in terms of slump flow diameter, slump flow time (T50), efflux time, flow time at T5 min, average flow velocity (V_{av}) and blocking ratio (H2/H1). These properties were used to assess the workability, filling and passing ability of SCC mixes. The fresh properties of all investigated concrete mixes are given in Table 3. The properties of all investigated SCC mixes satisfy the requirements of the European guidelines for SCC (EFNARC 2002) as illustrated in Table 3. Based on the results of fresh properties of SCC mixes, it can be concluded that the inclusion of GBFS in SCC mixes led to a significant improvement in their fresh properties. In contrast there was worsening in the fresh properties of SCC mixes containing GCB compared to control mix.

Table 3. Fresh properties of SCC mixes

Mix code	Slump-flow test		V-funnel test		L - box test	
	Flow diameter (mm)	T50 (Sec)	Efflux time (Sec)	T5 Min (Sec)	Velocity (cm/sec)	H2/H1
CM	730	2.85	7.28	8.73	24.29	0.94
S-30	765	1.90	6.00	7.12	29.82	0.97
SH20-10	740	2.45	6.46	7.7	24.90	0.94
SH10-20	720	2.71	6.82	7.64	23.80	0.87
H-30	695	3.15	7.8	8.40	21.94	0.85
EFNARC Req.	**650–800**	**2–5**	**6–12**	Efflux time increase **0–3**	–	**0.80–1**

3.2 Properties of Hardened Concrete

3.2.1 Mass Loss

Figure 1 shows the effect of high temperatures on the mass loss for the investigated SCC mixes. The figure shows a gradual increase in the mass loss with the increase in temperature. The increase in the mass loss for all mixes is more significant after 600 ° C. Also, there was a marginal increase in the weight loss of specimens prepared from SCC mixes with GBFS and/or GCB compared to specimens of the control mix. The highest mass loss was observed for specimens containing 30% GBFS, (S-30). Causes of mass loss due to water evaporation from concrete specimens were discussed and illustrated based on XRD analysis in several previous works (El-Shihy et al. 2009; Piasta et al. 1984; Phan 2002; Peng and Huang 2008; Fares et al. 2010).

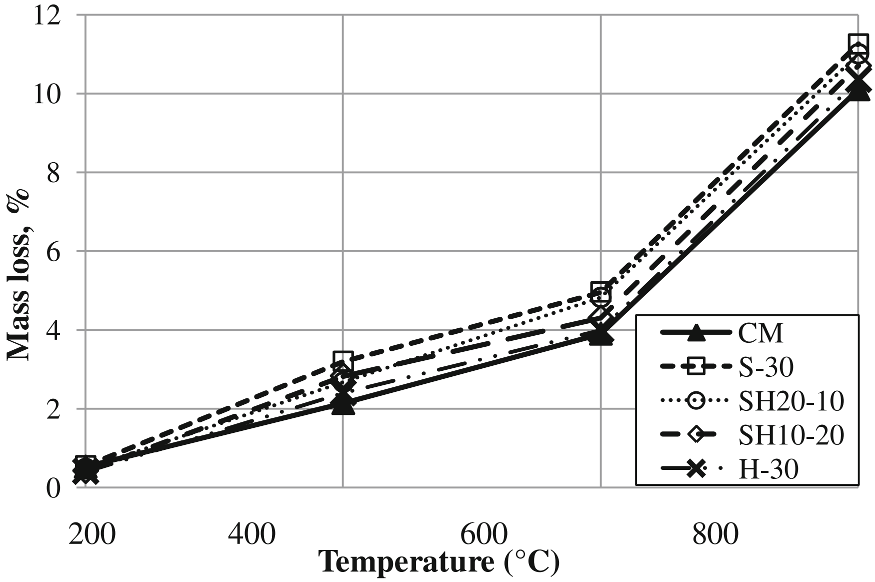

Fig. 1. Mass loss for SCC specimens after exposure to high temperatures

3.2.2 Compressive Strength

Results of compression strength test for the five investigated SCC mixes are given in Table 4. The results in Table 4 were represented in Figs. 2 and 3 in two forms; as values in MPa, Fig. 2, and as relative to the corresponding strength of the same mix at RT (without heating), Fig. 3. It is clear from Fig. 2 that, the control mix recorded the highest compressive strength among all SCC mixtures for different exposure temperatures. Comparing the results of compressive strength at 200 °C to those at RT indicates an increase in the strength for all specimens except mix containing 30% GCB, H-30, which showed a decrease in the compressive strength, see Fig. 3 at that temperature. With the increase in temperature above 200 °C, there was a gradual decrease in compressive strength. The percentage loss or gain in compressive strength for all

Table 4. Compressive strength results for SCC mixes at different exposure temperatures

Mix code	Temperatures								
	RT	200°**C**		400°**C**		600°**C**		800°**C**	
	MPa	MPa	%	MPa	%	MPa	%	MPa	%
CM	52.0	53.5	102.9	50.0	96.2	38.0	73.1	22.6	43.5
S-30	46.0	48.2	104.8	44.6	97.0	31.5	68.5	17.9	38.9
SH20-10	46.8	47.7	101.9	45.8	97.9	33.4	71.4	18.6	39.7
SH10-20	47.8	48.2	100.8	46.0	96.2	34.3	71.8	19.5	40.8
H-30	50.0	47.0	94.0	46.8	93.6	33.0	66.0	20.8	41.6

SCC mixes due to exposure to high temperatures from 200 °C to 800 °C is given in Table 4. Specimens of the control mix exhibited the best performance when exposed to high temperatures, followed by mixes containing large amount of GCB, while the lowest strength was recorded for specimens containing 30% GBFS as shown in Fig. 2.

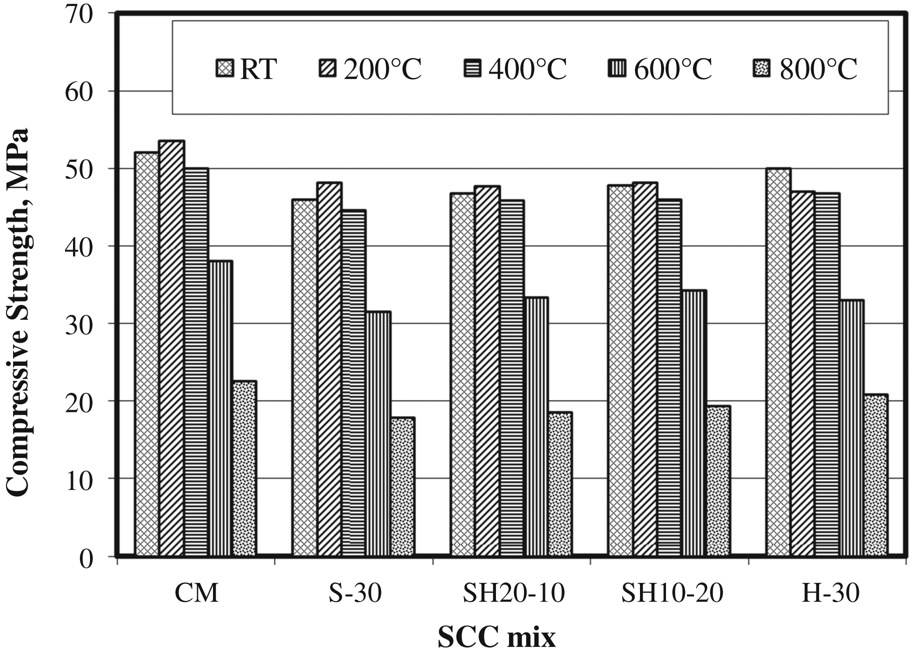

Fig. 2. Compressive strength of SCC specimens after exposure to high temperatures

The enhancement in the compressive strength of SCC specimens exposed to temperature from RT to 200 °C may be attributed to the formation of C-S-H from the reaction between the unhydrated cement particles and lime at these temperatures (Tanyildizi and Coskun 2008). Several hypotheses have been proposed to explain this

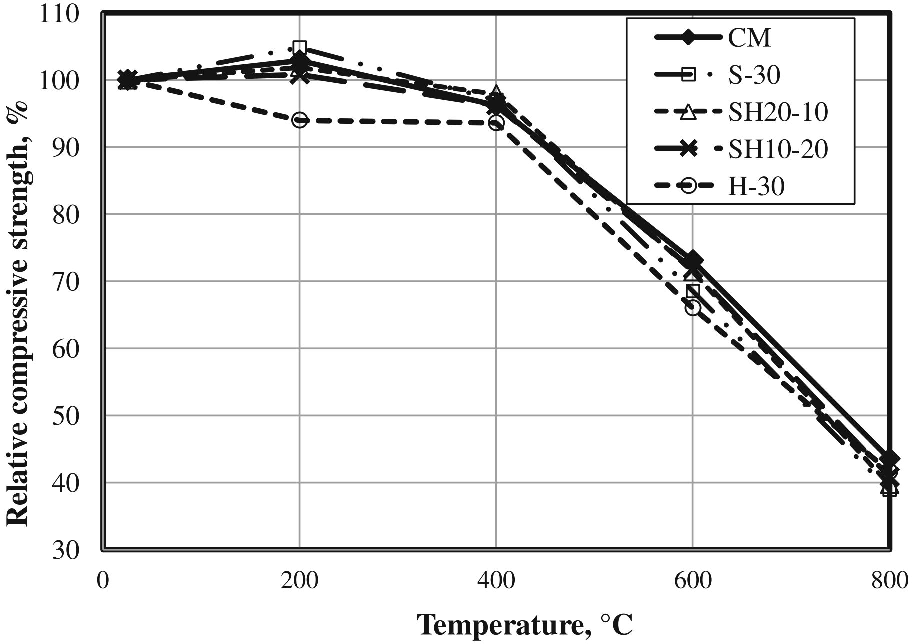

Fig. 3. Relative compressive strength of SCC specimens after exposure to high temperatures

increase in strength. Dias et al. (1990) attributed the increase in compressive strength at that temperature to a rehydration of the paste due to migration of the water in the pores. Also, it can be attributed to the increase in forces between the gel particles (Van der Waal's forces) due to the water removal (Behnood and Ziari 2008; Castillo and Durrani 1990).

From 200 to 400 °C, there was only a marginal decrease in the compressive strength of SCC mixes of about 2–7%. This may be due to the water loss from pores of the hydrates as well as the first stage of dehydration (Ye et al. 2007). Also, it may be due to the increase in the amounts of C-S-H and CH with the heating to 400 °C. It is postulated that the pore-structure coarsening can be regarded as the formation of equivalent cracks which should be responsible for the reduction in mechanical properties of concrete, especially as no chemical decomposition of hardener cement paste occurs below 400 °C (Peng and Huang 2008).

A severe loss in strength of about 27–34% was observed when the temperature increased to 600 °C. This great loss in compressive strength can be attributed to the dense microstructures of this type of concrete, that lead to the building up of high internal pressure during heating. Moreover, some researchers reported this strength loss is largely attributed to the decomposition of calcium hydroxide, which is known to occur between 450 and 500 °C (Zhang and Bicanic 2002). According to Peng and Huang (2008), the decomposition of CH and $CaCO_3$ was initiated at 430 °C and 530 °C, respectively. Also, the main hydration product in hardened cement paste started to decompose to C_2S and C_3S at 560 °C. In addition, at 573 °C, the allotropic transformation of α-quartz into β-quartz occurs with an expansion in the volume (Fares et al. 2010).

Above 600 °C, the decomposition became significant and the C-S-H decomposition rate increased dramatically with temperature (Peng and Huang 2008). All SCC mixes showed severe deterioration in compressive strength at 800 °C, about 57–61%. This may be due to breaking down of bond between aggregate and cement paste as a result of expansion of aggregates and contraction of cement paste, that produce higher stress concentrations at the transition zone. In addition, the decomposition of the C-S-H gel may be another cause of this severe deterioration (Demirel and Kelestemur 2010)

3.2.3 Tensile Strength

Results of indirect tensile strength of the five SCC mixes are given in Table 5. The results in Table 5 were represented in Figs. 4 and 5 in two forms; as values in MPa and as relative to the corresponding strength of the same mix at RT (without heating). The results in Table 5 and Fig. 4 show that the control mix recorded the highest tensile strength among all mixtures. The control mix recorded the highest relative tensile strength up to 400 °C. Above 400 °C, the SCC mix contained 10% GBFS and 20% GCB showed the highest relative tensile strength, Fig. 5. In general there is a pronounced decrease in the tensile strength for the five SCC mixes with increasing exposure temperatures from RT to 800 °C. It is clear also that SCC mix incorporating 30% GBFS indicate the lowest tensile strength among other mixes at exposure temperature of 400 °C or more. The reduction in splitting tensile strength with the increase in heating temperature can be attributed to the thermal stresses induced in dense microstructure and thermal incompatibility between aggregates and cement paste that resulted in micro and macro cracks (Heikal 2008).

Table 5. Tensile strength results for SCC mixes at different exposure temperatures

Mix code	Temperature								
	RT	200 °C		400 °C		600 °C		800 °C	
	MPa	MPa	%	MPa	%	MPa	%	MPa	%
CM	5.6	5.40	96.4	4.39	78.4	2.5	44.6	1.25	22.3
S-30	4.8	4.60	95.8	3.30	68.8	2.0	41.7	0.97	20.2
SH20-10	5.0	4.58	91.6	3.50	70.0	2.6	52.0	1.05	21.0
SH10-20	5.0	4.80	96.0	3.79	75.8	2.7	54.0	1.20	24.0
H-30	5.2	4.40	84.6	4.00	76.9	2.4	46.2	1.10	21.2

Comparing the results of the relative tensile and compressive strengths, Figs. 3 and 5, for different SCC mixes clearly indicate excessive deterioration in the tensile strength compared to that of compressive strength after exposure to high temperatures. This behaviour can be explained as follows: On heating, a thermal stresses at the interface are occurred as a result of different coefficient of thermal expansion between mortar and coarse aggregate. These stresses break the bond at the interface between the mortar and aggregate and thus creating cracks. These cracks are more effective in the mode of failure under tension compared to those under compression.

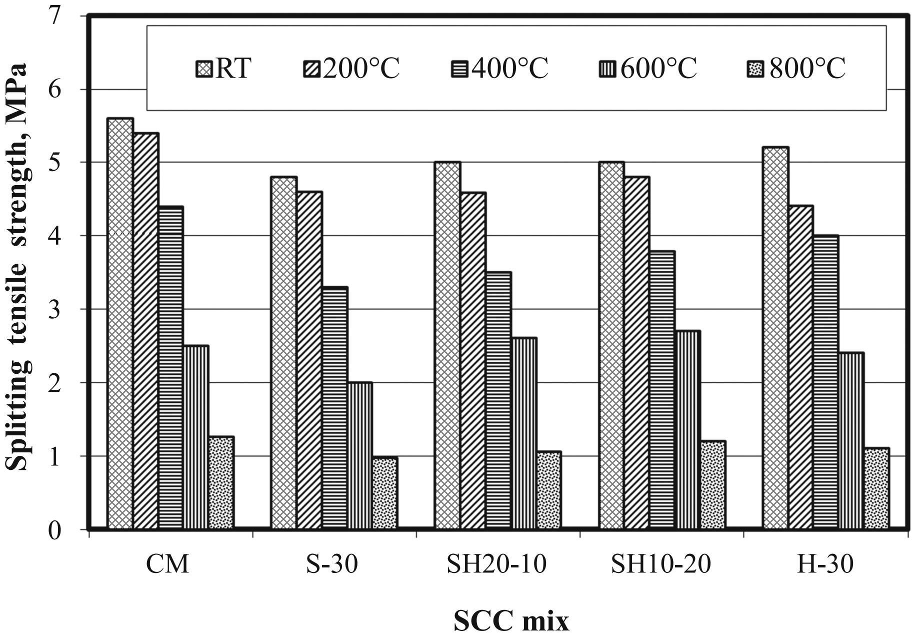

Fig. 4. Tensile strength of SCC specimens after exposure to high temperatures

3.3 XRD Analysis

X-ray diffraction technique was used to find changes in the mineralogy of hydration products of cement paste. Results from XRD of concrete samples were also used to verify the decomposition of C-S-H, CH and aggregates after exposure to high temperatures. Concrete samples were taken from specimens fractured during compression and splitting tension tests to carry out these tests.

The XRD diagrams of the control mix at RT and those after exposure to temperatures of 200, 600 and 800 °C for 2 h are shown in Fig. 6. The main phases in samples are C-S-H gel, portlandite $Ca(OH)_2$, calcite $CaCO_3$, dolomite, quartz and microcline. Microcline is considered impurity in sand. It is observed that C-S-H and CH are still found at 200 °C. The intensity of the peaks characteristic of C-S-H increased while those of CH decreased with the increase in temperature up to 200 °C. This is because further hydration of cement residues occurred and C-S-H may simply have become more crystalline with heating. This may be the reasons of increasing the compressive strength at 200 °C.

Intensity of the peaks characteristic of C-S-H and CH phases disappeared in SCC samples subjected to 600 °C. This is due to a dehydration of $Ca(OH)_2$ into $CaO+H_2O$, where H_2O evaporated at this temperature. However, intensity of the peak characteristic for calcite increased. This may be due to the reaction of the free lime, CaO, with CO_2 from the surrounding atmosphere during cooling. These results can explain the sharp drop in the values of compressive strength for specimens subjected to 600 °C temperature.

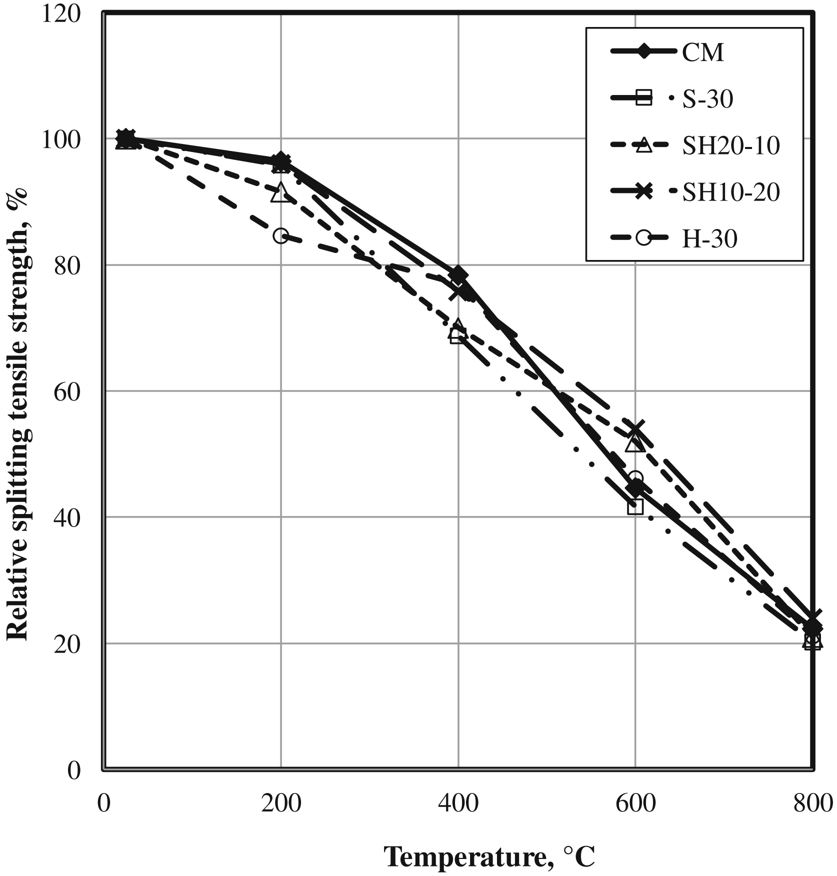

Fig. 5. Relative tensile strength of SCC specimens after exposure to high temperatures

The XRD diagram of the control specimen subjected to 800 °C, Fig. 6d, shows the presence of quartz and calcite in contrast to C-S-H and CH. The dolomite peaks intensity disappeared, which means the occurrence of the dolomite decomposition. The main components of dolomite are calcium and magnesium carbonate $CaCO_3$ and $MgCO_3$. At high temperatures, there is partial transformation of CaCO3 and $MgCO_3$ into oxides. Firstly $MgCO_3$ in dolomite decomposes at 800 °C, and then the decomposition of $CaCO_3$ occurs at 900 °C (Mitchell 1962). Therefore, the reduction in strength at 800 °C was due to the decomposition of the hydration products in cement paste in additional to the decomposition of dolomite.

Figure 7 shows the XRD diagrams of mix which contained 30% slag (S-30) at RT and after exposure to temperatures of 200, 600 and 800 °C for 2 h. Referring to Fig. 7a, it is clear that at RT, the intensities of C-S-H and CH are less than those for control mix at the same temperature, Fig. 6a. This may explain the increase in the strength of control mix compared to that of 30% slag (S-30) at RT. At temperatures of

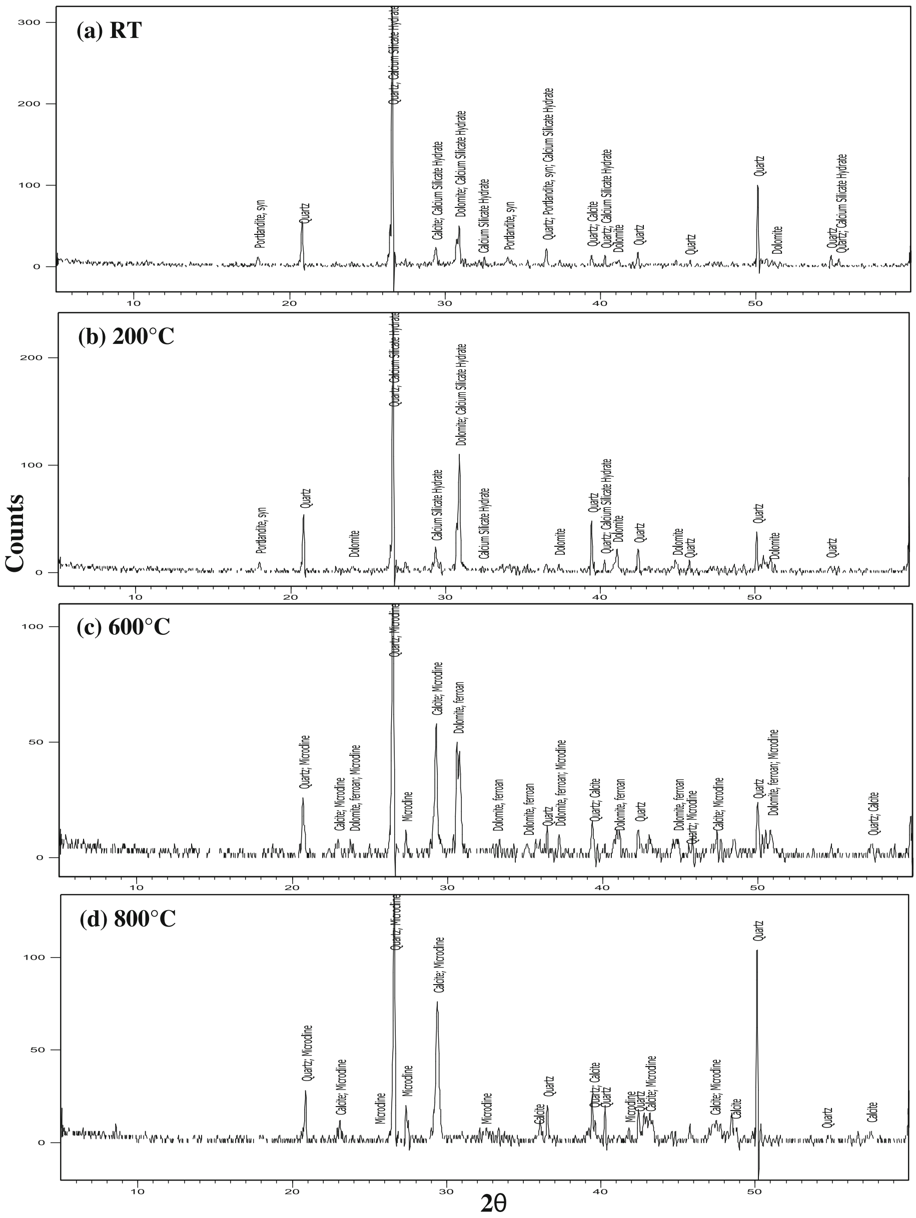

Fig. 6. XRD pattern of control mix at RT, 200, 600 and 800 °C

200, 600 and 800 °C, similar tends is observed between the XRD of the control mix and the mix containing 30% slag (S-30).

The XRD diagrams for mix containing 30% GCB (H-30) at RT and after exposure to temperatures of 200, 600 and 800 °C for 2 h are shown in Fig. 8. It is obvious that

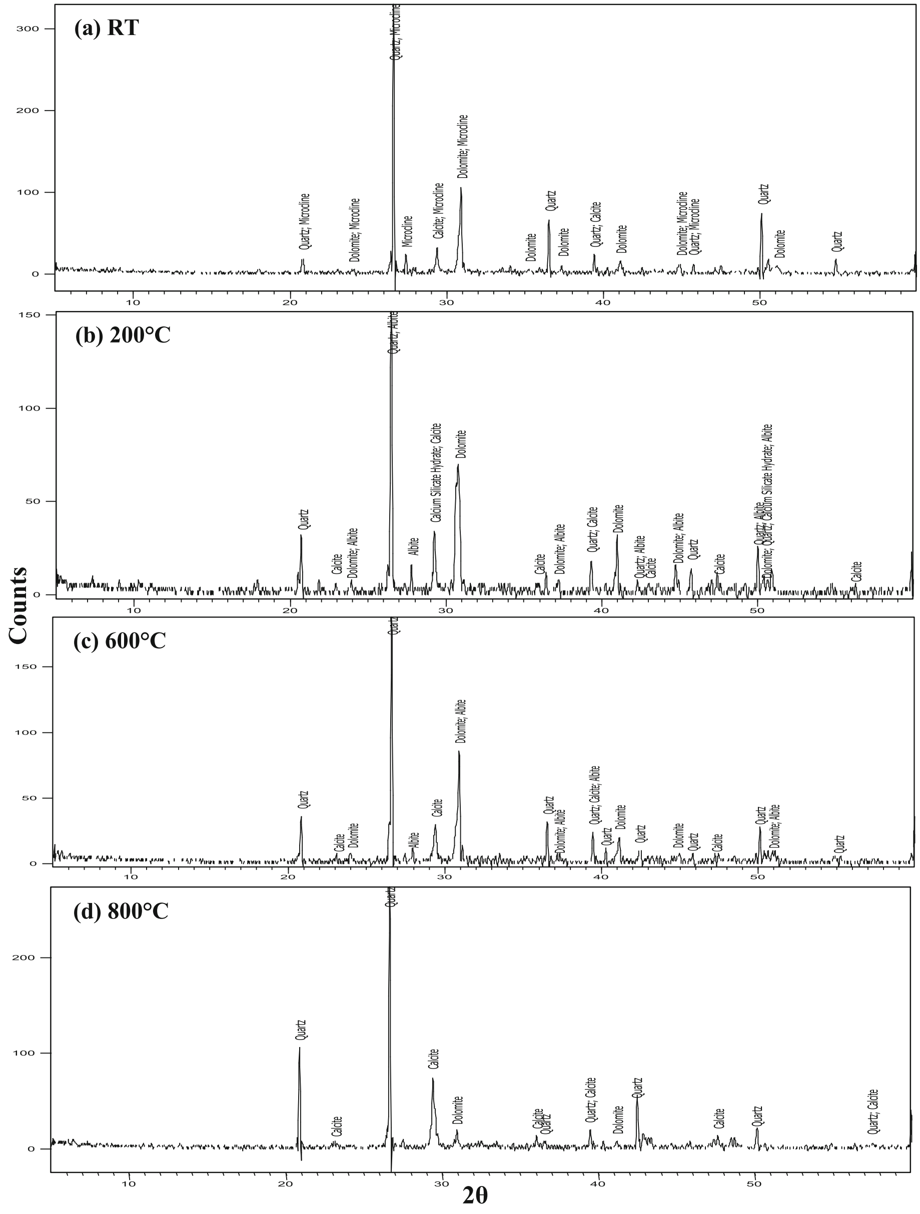

Fig. 7. XRD pattern of S-30 mix at RT, 200, 600 and 800 °C

there is difference between the XRD analysis of the control mix and the corresponding mix containing 30% GCB, (H-30) at 200 °C, Fig. 8b. The intensities of peaks characteristic of CSH and CH phases decreased with increasing temperature up to 200 °C, in contrast to the control mix and mix containing 30% GBFS. This may explain the

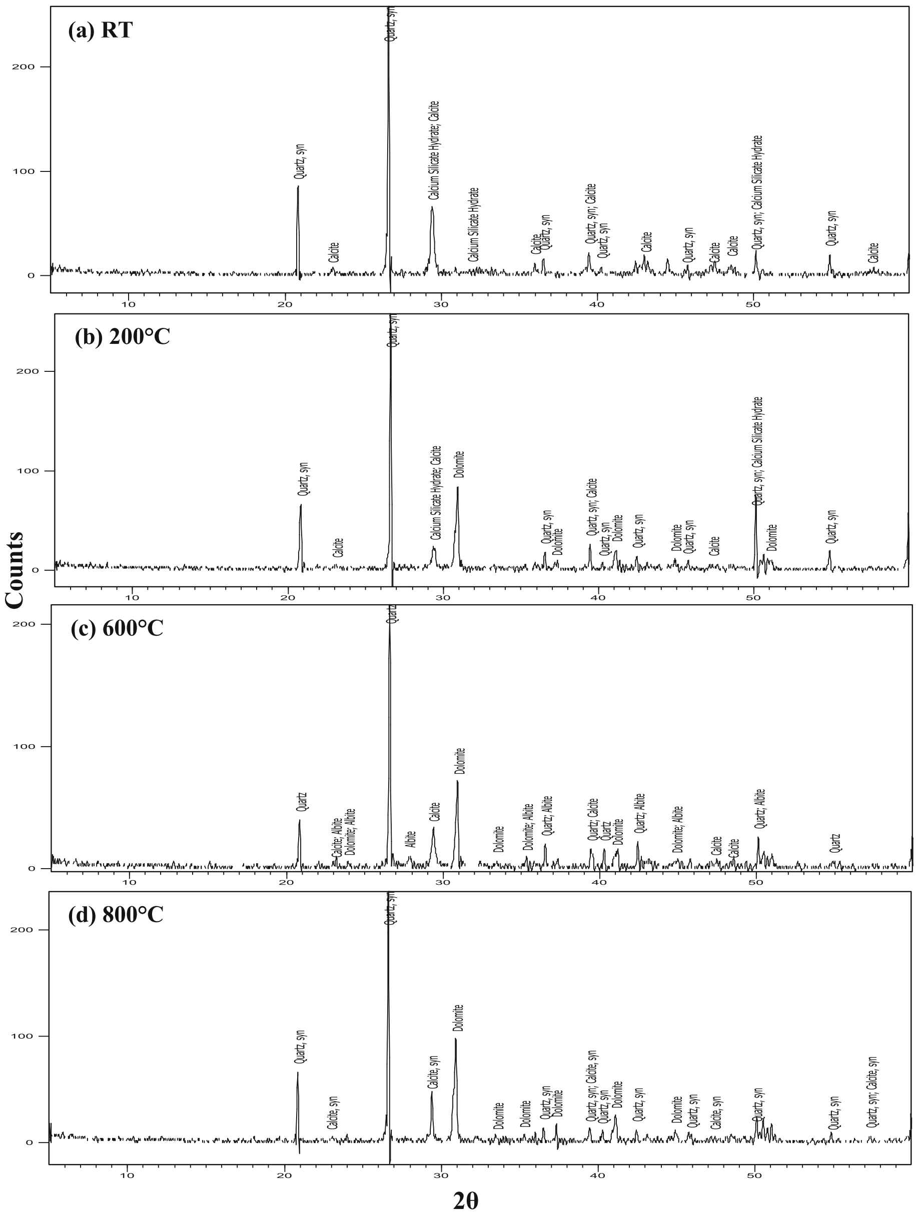

Fig. 8. XRD pattern of H-30 mix at RT, 200, 600 and 800 °C

reduction in the compressive strength at this temperature for mix containing 30% GCB. Also dolomite peak intensity still presented up to exposure to 800 °C. This is an indication to the good performance of this mix at 800 °C.

3.4 Surface Characteristics of SCC Samples

Visual inspection of the surfaces of SCC test specimens after exposure to high temperatures was performed to detect the signs of cracking and occurrence of spalling. No visible cracking or spalling was observed in SCC samples subjected to temperatures of 200 or 400 °C, as shown in Fig. 9. Hairline cracks appeared extensively at approximately 600 °C as shown in Fig. 10. In Fig. 11, the crack intensity increases as the temperature increases up to 800 °C. However, no spalling occurred for all SCC specimens heated to temperatures range from 200–800 °C. These result confirmed those found by Chan et al. (1999). They mentioned that the explosive spalling of HPC is governed by a vapour pressure mechanism. Spalling depends on both the strength

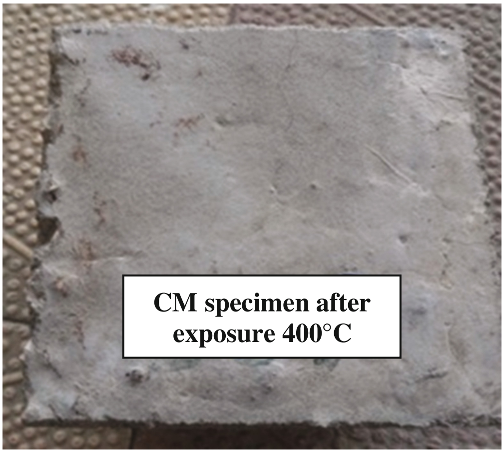

Fig. 9. Surface characteristic of SCC samples after exposure to 400 °C

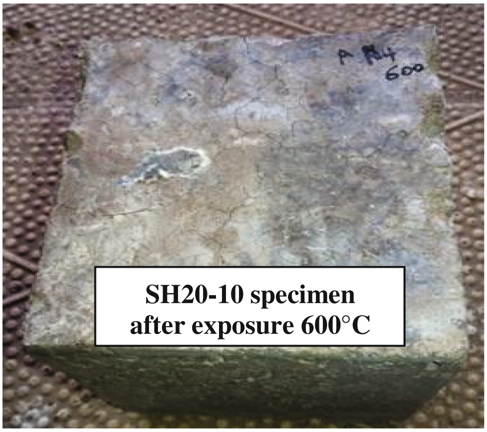

Fig. 10. Surface characteristic of SCC samples after exposure to 600 °C

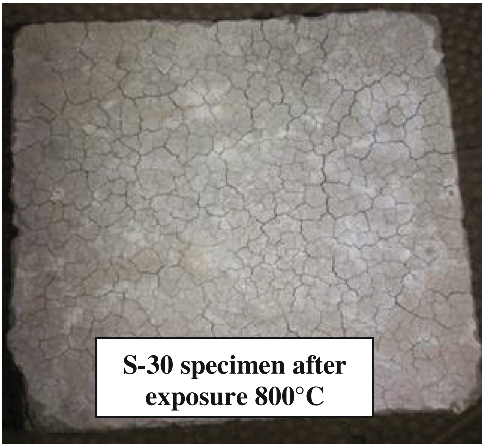

Fig. 11. Surface characteristic of SCC samples after exposure to 800°C

and moisture content of concrete. For concrete strength less than 60 MPa, there was no spalling even with the concrete fully saturated.

4 Conclusion

Based on the results of fresh and hardened tests of SCC mixes at room and high temperatures, it can be concluded that:

1. All the mixtures had satisfactory self-compacting properties in the fresh state according to EFNARC requirements.
2. An improvement in the fresh properties was observed in SCC mixes incorporating higher contents of GBFS, in contrast to those containing high contents of GCB that showed worsening in the fresh properties compared to the control mix.
3. The use of GBFS and GCB as partial replacement of cement in SCC mixes produced slight decrease in the compressive strength ranging from 3.8–11.5%. For the tensile strength this reduction was in the range of 8.8–14% relative to the control mix.
4. The reduction in both compressive and tensile strengths due to high temperatures exposure was less with GCB than with GBFS as a result of its chemical composition.
5. After exposure to high temperatures, specimens of the control mix exhibited the best strength, followed by mixes containing large amounts of GCB, while the worst strength was recorded for specimens containing large amounts of GBFS, especially at 800 °C.
6. Utilization of GBFS, GCB or a combination of them as 30% partial replacement of cement content can produce environmentally friendly concrete mixes.

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