Construction and Building Materials 26 (2012) 701–706

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Self-compacting concrete incorporating filler additives: Performance at high temperatures

Mucteba Uysal *

Sakarya University, Civil Engineering Department, Sakarya 54187, Turkey

ARTICLE INFO

Article history:
Received 3 March 2011
Received in revised form 20 June 2011
Accepted 23 June 2011
Available online 20 July 2011

Keywords:
Self-compacting concrete
Elevated temperature
Filler additives
Polypropylene fibers

ABSTRACT

An experimental investigation was conducted to evaluate the performance of self-compacting concrete (SCC) subjected to elevated temperatures. For this purpose, Portland cement (PC) was replaced with limestone powder (LP), basalt powder (BP) and marble powder (MP) in various proportioning rates. Half of the total specimens for each mix type were studied by adding polypropylene (PP) fibers to improve the understanding of the effect of PP fibers on the behavior of SCCs subjected to high temperatures. SCC mixtures were prepared with water to cement ratio of 0.33 and polypropylene fibers content was 2 kg/m^3 for the mixtures containing polypropylene fibers. Specimens were heated up to elevated temperatures (200, 400, 600 and 800 °C) at the age of 56 days. Then, tests were conducted to determine loss in weight and compressive strength. Moreover, the change of ultrasonic pulse velocity (UPV) was determined and surface crack observations were made after being exposed to elevated temperatures. Experimental results indicate that a severe strength loss was observed for all of the SCC mixtures after exposure to 600 °C, particularly the concretes containing polypropylene fibers though they reduce and eliminate the risk of the explosive spalling. At higher replacement levels of LP, BP and BP further lower resudial strength was observed. In terms of percent residual properties, control mixture specimens performed better than filler additive specimens for all heating cycles.

1. Introduction

Self-compacting concrete (SCC) is a special high performance concrete type that is a highly flowable concrete that can fill formwork without any mechanical vibration. SCC's unique property gives it significant constructability, economic and engineering advantages [1,2]. Due to its specific properties, which are achieved by the excellent coordination of deformability and segregation resistance, SCC may contribute to a significant improvement in the quality of concrete structures and open up new fields for the application of concrete [3]. SCC mixes often use a large quantity of powder materials as mineral additives and/or viscosity-modifying admixtures. The powder materials or viscosity agents are required to maintain sufficient cohesion/stability of the mix. The requirement for increased powder content in SCC is usually met by the use of pozzolanic or less reactive filler materials. A number of studies [4–7] have been reported in the literature concerning the use of mineral admixtures to enhance the self-compactibility characteristics and to reduce the material cost of the SCCs. These may include silica fume and fly ash as pozzolanic materials and/or limestone powder (LP), marble powder (MP), basalt powder (BP) as filler materials. When used in SCC, filler additives can reduce the amount of superplasticizer necessary to provide a given fluidity [8]. The successful utilization of LP, BP and MP in SCC mixtures would not only provide a solution regarding the disposal and environmental problems connected with these fillers but might also reduce the cost of SCC. These fillers can significantly increase the workability of SCC. Moreover, the incorporation of filler additives also eliminates the need for viscosity-enhancing chemical admixtures. The lower water content of the concrete leads to higher durability, in addition to better mechanical integrity of the structure [9]. The characteristics of this concrete such as high content of filler additives, large paste volume linked to its placing conditions could modify its mechanical behavior, comparatively to traditional vibrated concrete. The behavior of SCC subjected to high temperature has in particular to be evaluated. The few studies on SCC subjected to high temperature show both a decrease in strength and an increase in the risk of spalling [10] or a behavior similar to that of vibrated concrete [11].

High temperature causes dramatic physical and chemical changes resulting in the deterioration of the concrete [12]. Although concrete is recognized as an excellent thermal-resistant material among various construction materials, critical deterioration of concrete is observed when it is exposed to high temperature like as in the case of fire. A number of physical and chemical

* Tel.: +90 264 295 57 45; fax: +90 264 346 01 51.
E-mail address: mucteba@sakarya.edu.tr

0950-0618/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.conbuildmat.2011.06.077

nonreversible changes occur in concrete when subjected to high temperature. Concrete damage due to high temperature includes weight loss, reductions in strength and modulus of elasticity, and formation of cracks and large pores [13]. The fire resistance capacity of concrete is complicated because not only is concrete a composite material with components having different thermal characteristics, it also has properties that depend on porosity and moisture. As the cement paste is exposed to increasing temperatures the following process takes place: (1) the expulsion of evaporable water at a temperature of 100 °C, (2) the beginning of the dehydratation of the hydrates of calcium silicate at 180 °C, (3) the decomposition of calcium hydroxide at a temperature of 500 °C and (4) the decomposition of which hydrate calcium silicate begins around 700 °C. The alterations produced by high temperatures are more evident when the temperature exceeds 500 °C. At this temperature level, most changes experienced by concrete can be considered to be irreversible [14]. Industrial by-products and solid wastes such as LP, BP or MP could be used in concrete as a replacement material to reduce harmful effects of concrete industry on the environment. It is clear that the concrete containing such by-products or wastes should have equal or slightly lower properties than normal concrete. Therefore, strength and durability characteristics of concrete containing LP, BP and MP as partial replacement of cement should be investigated.

The advantages of SCCs result from the improvement of internal structure of the material as compared to that of the normal concrete. The dense microstructure of SCC ensures a high strength and a very low permeability. The low permeability is probably essential to obtain good durability in severe exposure conditions where there are aggressive agents such as sulfate, and chloride. However, the dense microstructure of SCC seems to be a disadvantage in the situation where the SCC is exposed to fire. Recent fire test results show that there is a great difference between the properties of SCC and normal vibrated concrete after being subjected to high temperature [15]. Some authors [10,16,17] have already observed that the risk of spalling is more pronounced for SCC than for vibrated concrete when subject to rapid temperature rise such as in the case of a fire.

Fibers have extensively been used to improve the ductility of concrete. Recently, it has been found that a number of fibers can also improve the residual properties of concrete after exposure to elevated temperatures. Several studies carried out by different authors [18,19] show that concrete thermal stability is improved by incorporating PP fibers to the mix. PP fibers have been used to considerably reduce the amount of spalling and cracking and to enhance the residual strength [20,21]. Since the fibers melt at approximately 160–170 °C, they produce expansion channels. The additional porosity and small channels created by PP fibers melting may lower internal vapor pressure in the concrete and reduce the likelihood of spalling, according to Noumowé [22]. But minimal or even negative effects of PP fibers on the residual performance of the heated concrete were also observed. The additional porosity due to the melting of PP fibers can lead to a decrease of the residual mechanical performances of concretes. Results of literature on this subject are contradictory. Several studies carried out by different authors as [22,23] show a decrease of residual strength in agreement with the additional porosity while others authors as [18,24] obtain the improvement of the residual strength. The difference between the results can be related to the experimental conditions, the cure condition of the specimen (dry or saturated state) and the heating rate.

The main objective of this investigation was to study the effects of elevated temperatures on the properties of SCC was produced with filler additives. The study also improves the understanding of the influence PP fibers on the behavior of SCCs subjected to elevated temperatures up to 800 °C. It was assessed in terms of changes in compressive strength, ultrasonic pulse velocity, weight and survey of crack patterns on the concrete surface which exposed to elevated temperatures.

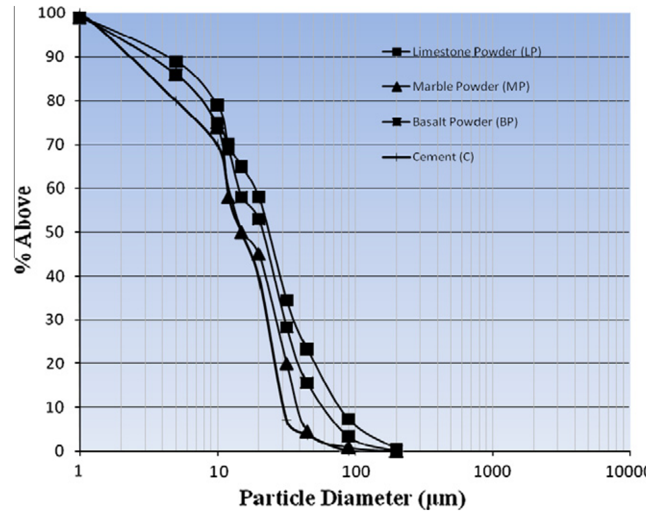

Fig. 1. The particle size distributions of fillers and Portland cement.

2. Experimental procedures

2.1. Materials and mixtures

The Portland cement used in this study complied with EN 197-1 and labeled as CEM I 42.5N. Specific surface area by Blaine and 28th day compressive strength of cement were 399.6 m^2/kg, and 48.3 MPa, respectively. A natural river sand and crushed limestone with a maximum size of 16 mm was used as fine and coarse aggregates, respectively. The specific gravity and water absorption properties of river sand and crushed limestone are 2.59%, 1.44%, and 2.73%, 0.22%, respectively. Marble powder (MP) was obtained from a marble managing plant in Bilecik directly used in SCC without any processes. Basalt powder and limestone powder were by-product of quarry crushers and collected from the filtration system of a quarry crushers. The particle size distributions of these materials were obtained by a laser scattering technique and are presented in Fig. 1. The physical, chemical and mechanical characteristics of Portland cement and mineral admixtures used in this study are given in Table 1.

2.2. Mix proportions

A total of 20 concrete mixtures with filler additives were prepared in two series with different combinations. Specimens of the first series were made without PP fibers while specimens of the second series were made with PP fibers. The second

Table 1
Properties of Portland cement and fillers.

Component (%)	Cement	MP	BP	LP
SiO_2	19.10	0.70	54.62	4.93
Fe_2O_3	3.24	0.12	4.14	0.58
Al_2O_3	4.85	0.29	9.60	0.82
CaO	61.86	55.49	12.80	51.97
MgO	2.02	0.23	4.66	0.58
SO_3	2.63	–	0.66	–
Cl^-	–	–	–	–
Loss ignition	2.90	42.83	9.94	40.40
K_2O	–	1.80	1.62	–
Na_2O	–	2.44	0.84	–
Physical properties				
Specific gravity	3.08	2.71	2.76	2.79
Blaine (cm^2/g)	3996	8889	6284	2500
Mechanical properties				
Compressive strength (MPa)				
2 days	28.3			
7 days	41.9			
28 days	51.6			

Table 2
Mix proportions of SCC for 1 m^3.

Materials (kg/m^3)	Control	LP10	LP20	LP30	BP10	BP20	BP30	MP10	MP20	MP30
Cement	550	495	440	385	495	440	385	495	440	385
LP	–	55	110	165	–	–	–	–	–	–
BP	–	–	–	–	55	110	165	–	–	–
MP	–	–	–	–	–	–	–	55	110	165
Water	182	182	182	182	182	182	182	182	182	182
w/c	0.33	0.37	0.41	0.47	0.37	0.41	0.47	0.35	0.37	0.39
w/p	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33
Sand	869	866	863	860	866	863	861	867	865	863
CSI	467	464	463	461	465	463	462	466	465	463
CSII	311	311	308	307	310	309	307	311	309	312

series were designed to evaluate the effects of PP fibers after subjecting to high temperatures contained 2% PP fibers. Details of mixture proportions were shown in Table 2 for only first series without PP fibers. As seen in that table, the mixtures were coded such that the ingredients were identifiable from their IDs. As filler materials, MP, LP and BP were replaced at same proportions (10%, 20% and 30%) with cement. After the preliminary investigations, the total powder content was fixed to 550 kg/m^3 and the water–powder ratio (w/p) was selected as 0.33. A 50 dm^3 batch has been prepared for each mixture. Tap water used was obtained from the city waterworks of Sakarya for the production of concrete mixtures during the experimental procedure. A new generation polycarboxylate based superplasticizer having 20.5% solid content, 1.04 specific gravity and 8 pH was employed. It was used in the mixtures at the ratio of 1.6% of binder materials by weight for reducing the water/binder ratio of SCC. PP fibers were supplied from a local producer and its some physical and mechanical properties were shown in Table 3.

2.3. Casting, curing and testing

Each concrete mixture was cast in cubic molds with dimensions of 10 × 10 × 10 cm to determine the variation of compressive strength, ultrasonic pulse velocity, weight of SCC specimens and survey of crack patterns on the concrete surface after being exposed to elevated temperatures. Before casting, slump-flow test, T_{50} test, V-funnel test were attempted as workability tests on fresh concrete for determining the properties of SCC such as filling ability and passing ability according to the EFNARC Committee's suggestions [25]. Specimens were then cast in steel molds and were not subjected to any compaction other than their own self-weights. The specimens were kept covered in a controlled chamber at 20 ± 2 °C for 24 h until demoulding. Thereafter, specimens were placed in water at 20 °C and 60% RH until the 28th days. Later, they were kept in air until 56th day in laboratory where the relative humidity and the temperature were about 60% and 20 °C respectively.

At the 56th day after the specimens placed in an electric furnace in which temperature is increased to the desired temperatures at a rate of 1 °C/min, and they were kept at maximum temperature for 3 h. At the end of 3 h exposure to the maximum temperature the power was turn off and the specimens were remained until the furnace cooled down to room temperature to prevent the thermal shock to the specimens. During the heating period moisture in the test specimens was allowed to escape freely. The applied heating curve was not the standard fire time–temperature curve but a heating–cooling cycle close to RILEM recommendations [26]. The test specimens were subjected to 200, 400, 600, 800 °C, and the variation of compressive strength, ultrasonic pulse velocity and weight of SCC specimens were compared to that observed at 20 °C. After the specimens cooled to room temperature they were taken out of the furnace and their residual compressive strength and ultrasonic pulse velocity, along with the weight values were determined. Thereafter, for each type of concrete the residual properties were compared to the properties of unheated control specimens. Six specimens of each mix type and heating cycle, three of them with PP fibers and the rest without PP fibers, were tested for loss in weight, the reduction of ultrasonic pulse velocity and loss in compressive strength. Immediately after cooling of the heated specimens, crack pattern on the SCC surfaces were inspected. Weight losses were determined by weighing specimens with a precision balance. The velocity of the propagation of ultrasound pulses was measured according to ASTM C 597 [27] by direct transmission using a Controls E48 ultrasound device. This measures the time of propagation of ultrasound pulses in a sample in the range (0.1–9999.9) μs with a precision of 0.1 μs. The transducers used were 50 mm in diameter, and had maximum resonant frequencies, as measured in our laboratory, of 54 kHz.

Table 3
Some physical and mechanical properties of PP fiber.

Technical specification	PP fiber
Purity (%)	100
Strain (%)	24
Minimum elongation at break (%)	100
Thickness (μ)	0.04
Density (kg/m^3)	910
X-section	Circular
Young modulus (MPa)	7051
Length (mm)	20
Color	White, transparent
Tensile strength (MPa)	389
Melting point (°C)	162

3. Results and discussion

3.1. Weight loss after exposure to high temperatures

The weight losses (in percent) of the SCC mixtures with increasing temperatures are given in Fig. 2a and b, respectively. It was observed that the evolution of weight loss versus temperature is very close for the three studied concretes. At higher replacement levels of LP, BP and BP further higher weight losses were observed. Higher weight losses were observed in LP series than BP and MP series. On the other hand, the comparison of Fig. 2a and b reveal that the weight losses for SCC mixtures in which containing filler additives with PP fibers were lower than without PP fibers in all replacement ratios. Moreover, the performance of control mixture with and without PP fibers was better than other mixtures when weight loss is considered.

There could be many causes of weight loss after high temperature exposure in concrete. However, expulsions of chunks or spalling of concrete from the surface layers are main reasons of weight loss [28]. In this experiment, small explosive spalling or expulsion of chunks was observed. So, the observation of negligible weight loss can be accepted as normal. In low temperatures, the weight loss may be due to the departure of free water contained in the capillary pores. According to Kanema [29], the weight loss between 150 °C and 300 °C corresponds to the evaporation of bound water. It was mentioned earlier that the series containing PP fibers in addition to the same mixture properties showed fewer losses in weight. The main reason for this was that as the concrete was subjected to heat, the melted PP fibers created micro pathways within the concrete to exhaust of water vapor and any other gaseous products, which was reduced the internal pressure [28].

3.2. Change in UPV after exposure to high temperatures

Fig. 3a and b shows the results obtained from the UPV measurements of all the SCC specimens subjected to different high temperatures. Each data point represents the average of three measurements. It is shown in the Fig. 3a that the UPV of heated SCC specimens decrease with an increasing temperature, and there is a notable reduction in UPV shortly after the specimens are subjected to elevated temperature over 400 °C. It is obvious that the transmission of pulse waves through a concrete mass is highly

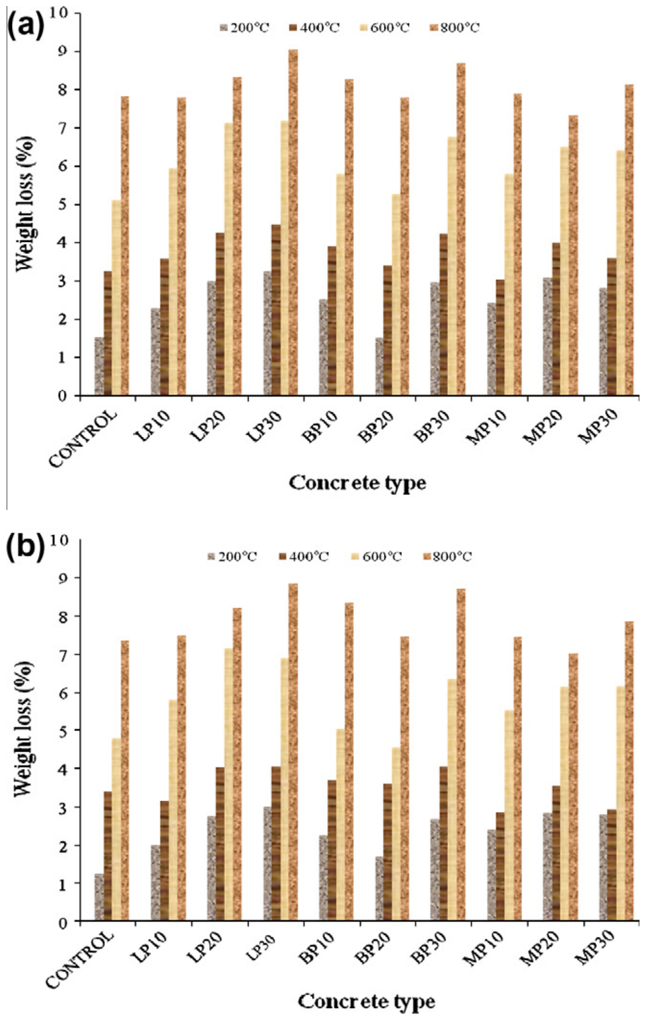

Fig. 2. Weight losses of (a) SCC mixtures without PP fibers and (b) SCC mixtures with PP fibers after exposure to various high temperatures.

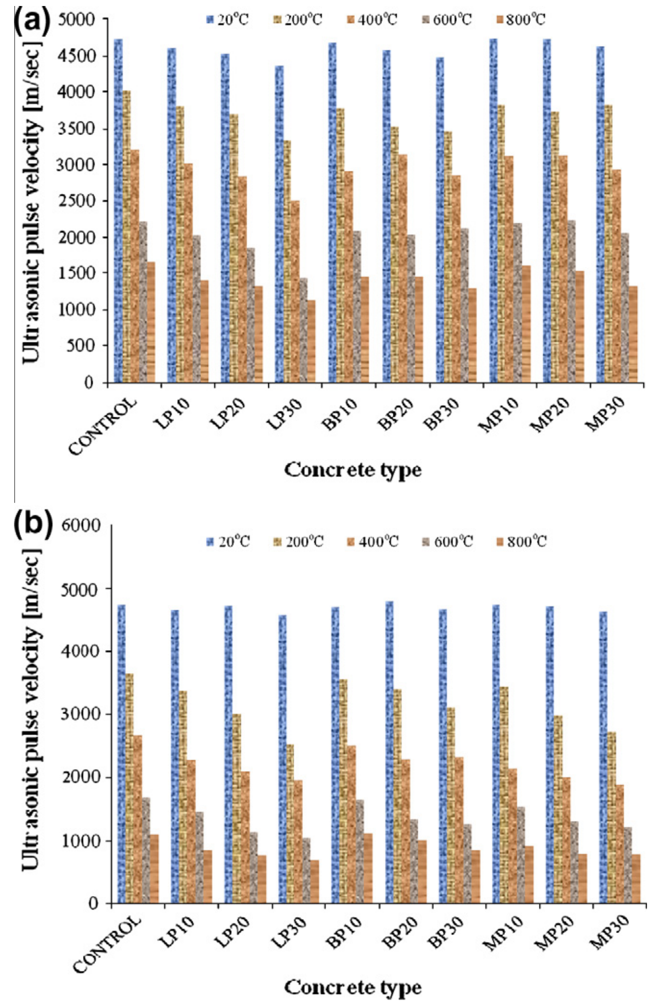

Fig. 3. UPV of (a) SCC mixtures without PP fibers and (b) SCC mixtures with PP fibers after exposure to various high temperatures.

influenced by the microcracking of concrete. Thus, the decrease in pulse velocity with increasing temperature is a sensitive measure of the progress of cracking in the material. Yang et al. also found similar results in their experiments [30].

Test results indicated that SCC mixtures were exposed to high temperatures, LP series showed higher reduction of pulse velocity when compared to BP and MP series. Furthermore, it was noticed that the reduction of pulse velocity of SCC mixtures in which containing PP fibers were significantly higher than without PP fibers in all replacement ratios. As it can be seen from Fig. 3b pulse velocity had a continuous drop as the temperature was increased. It can be concluded that the addition of PP fibers had negative effect on the UPV of SCC mixtures was exposed to high temperatures. When the temperature was raised to above the melting point (162 °C) of PP fibers more randomly distributed pathways or voids in SCC were generated [16]. In addition, thermal expansion and dehydration of the concrete due to high temperature might lead to the formation of fissures in the concrete. Because of more fissures, cracks or micro pathways in concrete pulse velocity delays to reach from transmitter to receiver [28]. Therefore, micro cracks cause the reduction of pulse velocity and results in low UPV values.

3.3. Change in strength after exposure to high temperatures

Fig. 4a and b present the changes of the compressive strength of SCC mixtures as a function of temperature. From 20 °C to 200 °C, BP10, BP30 and control mixtures without PP fibers showed small increases in strength (Fig. 4a) with the highest increase in strength of about 4% in control mixture. The strength gain was probably due to the formation of tobermorite from the reaction between unhydrated cement particles and lime at high temperatures [31]. On the other hand, 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 [32]. This finding is also consistent with the work of other researchers [33]. Several hypotheses have been proposed in the literature to explain this increase in strength. Dias et al. [34] attributed the increase in the compressive strength between 150 °C and 300 °C to a rehydration of the paste due to the migration of water in the pores. In another study, Khoury [35] assumes that the silanols groups lose a part of their bonds with water, which induces the creation of shorter and stronger siloxane elements (Si–O–Si) with probably larger surface energies that contribute to the increase in strength. From 200 °C to 400 °C, a decrease was observed in SCCs, which was 16–23% of the original strength and this reduction can be due to the pore structure coarsening. In addition, this reduction is due mainly to the loss of water from pores of hydrates as well as to the first stage of dehydration and breakdown of tobermorite gel according to several authors [36]. In this temperature range, BP series performed better and showed higher residual strength compared to other series.

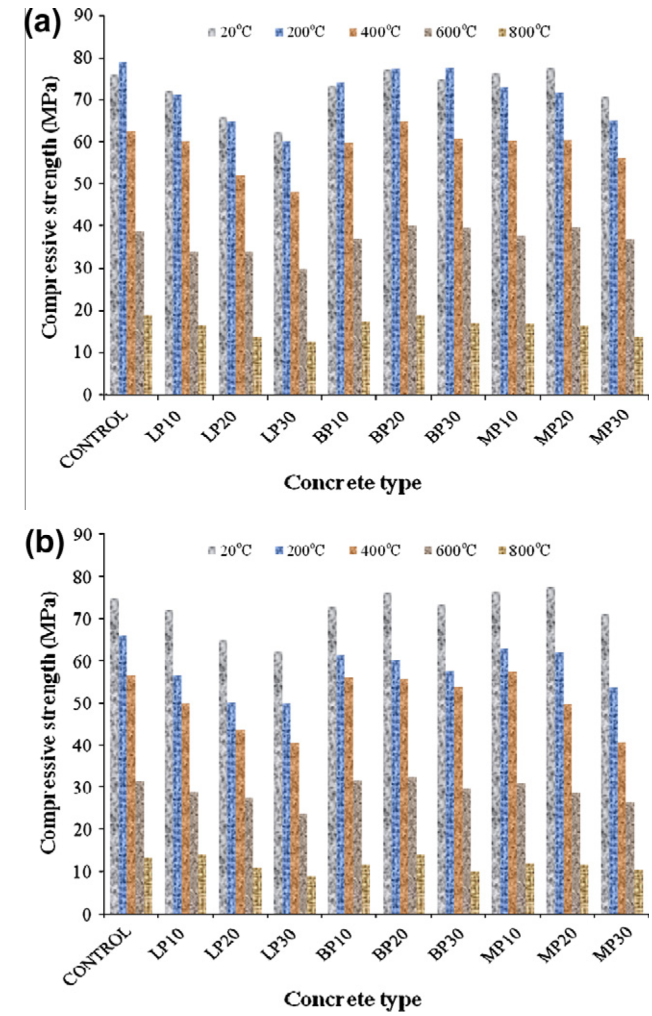

Fig. 4. Compressive strenth of (a) SCC mixtures without PP fibers and (b) SCC mixtures with PP fibers after exposure to various high temperatures.

A severe loss in strength was observed in the 400–600 °C temperature range. The strength loss was within the range of 47–53%. BP series performed better when compared to other series. The quick loss in compressive strength for SCC mixtures has been attributed to the dense microstructures in this type of concrete, which led to the buildup of high internal pressure during heating. Moreover, some researchers reported this strength loss is largely attributed to decomposition of calcium hydroxide, which is known to occur between 450 °C and 500 °C [37]. Furthermore, at high temperatures the bond between the aggregate and the paste is weakened, because the paste contracts following loss of water while the aggregate expands. On the other hand, at 573 °C, the allotropic transformation of quartz-α into quartz-β takes place with an expansion [38].

All the SCCs showed severe deterioration in the 600–800 °C temperature range and the average loss was 78% for concretes. LP, BP and MP series experienced extensive cracking and spalling and their residual compressive strength was less than control mixture. This is attributed to the presence and amount of filler additives in SCC mixtures that produced very denser transition zone between aggregates and paste due to their ultra-fine particles as filler materials. 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 filler additives than that of the control mixture [32]. Thus, greater strength losses are occurred in LP, BP and MP series. On the other hand, the decomposition of CSH gel was other reason for severe deterioration.

The comparison of Fig. 4a and b reveals that residual compressive strengths of SCCs containing PP fibers were obviously lower than those of concretes without PP fibers in all replacement ratios after exposure to elevated temperatures. The reason for such a difference could be microchannels which are randomly distributed in concrete because of melting of fibers at 162 °C. When the temperature exceeds 100 °C, the water begins to vaporize, usually causing a build-up of pressure within the concrete. The internal pressure inside the concrete forces the hardened concrete structure for releasing of vapor to the outer side. The internal vapor pressure can be released more easily in concretes containing PP fibers because of existence of microchannels developed by fibers. When melted fibers leaved from the concrete structure, fistulous microchannels are remained hollow. Then these channels decreases residual compressive strength [28]. Some authors carried out comprehensive investigations and reported on the effects of PP fibers elevated temperature on their strength properties and their findings are in line with this experiment [22,23,28]. The investigation on cement paste by Komonen and Penttala [39] have indicated that inclusion of PP fibers produces a finer residual capillary pore structure, decreases residual compressive strength. Poon et al. [40] have concluded that inclusion of PP fibers results in a quicker loss of the compressive strength and toughness of concrete after exposure to elevated temperatures (up to 800 °C).

3.4. The surface characteristics of samples

A thorough visual inspection was carried out to evaluate the visible signs of cracking and spalling on the surface of specimens after subjection of high temperature effect. No visible cracking or spalling was observed on samples in the 200–400 °C temperature range. Hairline cracks started to appear extensively at round 600 °C (Fig. 5a) and continued to grow until the final rise in temperature up to 800 °C (Fig. 5b). However, it was experienced a small amount of spalling at edges and corners of the specimens at 600 °C on some specimens and all the samples showed visible spalling at edges and corners at 800 °C. The cracks showed an increase with the rise of temperature and decreased with the increase of LP, BP and MP content. The concretes containing PP fibers experienced no extensive cracking and spalling. Because, the use of PP fiber reduced and eliminated the risk of the explosive spalling in all the SCCs. It may be because during the rapid temperature-increasing process, PP fibers melt and vaporize due to the lower melting point, which result in microchannels in the concrete. Thus, greater vapor tension in capillaries can be alleviated and released, which may be the reason why there was no explosive spalling in SSC with PP fibers [24].

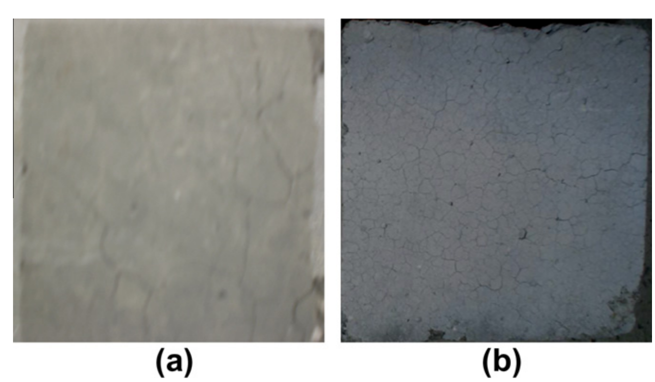

Fig. 5. Surface character of SCC samples without PP fibers after high temperature.

4. Conclusions

This study concerns the behavior of SCC at high temperatures. Specimens of various concretes compositions were made and subjected to different temperatures. Effects of high temperature on the properties of SCCs containing filler additives were studied. The loss in weight and compressive strength, the reduction in ultrasonic pulse velocity and observation of surface characteristics of samples were investigated. Some conclusions can be drawn from the experimental results:

- At higher replacement levels of LP, BP and BP further higher weight losses were observed. Higher weight losses were observed in LP series than BP and MP series. Weight losses for SCC mixtures in which containing filler additives with PP fibers were lower than without PP fibers in all replacement ratios. Loss in weight was observed for mixtures in the range of 1.24–9.07%. Expulsions of chunks or spalling of concrete from the surface layers were main reasons of weight loss.
- The UPV of heated SCC specimens decrease with an increasing temperature. As SCC mixtures were exposed to high temperature, LP series showed higher reduction of pulse velocity when compared to BP and MP series. The reduction of pulse velocity of SCC mixtures in which containing PP fibers were significantly higher than without PP fibers in all replacement ratios.
- SCCs lost a significant amount of their compressive strengths above 400 °C. BP series showed better performance than other series for all heating cycles. The residual compressive strengths of SCCs containing PP fibers were obviously lower than those of concretes without PP fibers in all replacement ratios after exposure to elevated temperature. The addition of PP fibers to SCCs had significant negative effect on the residual compressive strength of concrete. The inclusion of PP fibers produced a finer residual capillary pore structure, decreased residual compressive strength of SCC.
- According to visual inspection on the surface of specimens after subjection of high temperature effect, no visible cracking or spalling was observed on samples in the 200–400 °C temperature range. It was experienced a small amount of spalling and hairline cracks at 600 °C on some specimens and all the samples showed visible spalling and cracking at 800 °C. As the rate of temperature rise increases cracking and spalling become more pronounced. The concretes containing PP fibers experienced no extensive cracking and spalling.

References

[1] Yua Q, Taob Z, Wu YX. Experimental behaviour of high performance concrete-filled steel tubular columns. Thin-Walled Struct 2008;46:362–70.

[2] Siddique R. Properties of self-compacting concrete containing class F fly ash. J Mater Des 2011;32:1501–7.

[3] Sukumar B, Nagamani K, Raghavan RS. Evaluation of strength at early ages of self-compacting concrete with high volume fly ash. Const Build Mater 2008;22(7):1394–401.

[4] Melo KA, Carneiro AMP. Effect of Metakaolin's finesses and content in self-consolidating concrete. Const Build Mater 2010;24:1529–35.

[5] Liu M. Self-compacting concrete with different levels of pulverized fuel ash. Const Build Mater 2010;24:1245–52.

[6] Boukendakdji O, Kenai S, Kadri EH, Rouis F. Effect of slag on the rheology of fresh self-compacted concrete. Const Build Mater 2009;23:2593–8.

[7] Craeye B, De Schutter G, Desmet B, Vantomme J, Heirman G, Vandewalle L, et al. Effect of mineral filler type on autogenous shrinkage of self-compacting concrete. Cem Concr Res 2010;40:908–13.

[8] Sonebi M, Svermova L, Bartos PJM. Factorial design of cement slurries containing limestone powder for self-consolidating slurry-infiltrated fiber concrete. ACI Mater J 2004;101(2):136–45.

[9] Dinakar P, Babu KG, Santhanam M. Durability properties of high volume fly ash self compacting concretes. Cem Concr Compos 2008;30(10):880–6.

[10] Persson B. Fire resistance of SCC. Mater Struct 2004;37:575–84.

[11] Boström L. Self-compacting concrete exposed to fire. International RILEM symposium on self-compacting concrete. rilem publications SARL; 2003. p. 863–9.

[12] Xu Y, Wong YL, Poon CS, Anson M. Impact of high temperature on PFA concrete. Cem Concr Res 2001;31:1065–73.

[13] Janotka I, Mojumdar SC. Thermal analysis at the evaluation of concrete damage by high temperatures. J Therm Anal Calorim 2005;81(1):197–203.

[14] Tanyildizi H, Cevik A. Modeling mechanical performance of lightweight concrete containing silica fume exposed to high temperature using genetic programming. Const Build Mater 2010;24:2612–8.

[15] Fares H, Noumowe A, Remond S. Self-consolidating concrete subjected to high temperature: mechanical and physicochemical properties. Cem Concr Res 2009;39:1230–8.

[16] Liu X, Ye G, De Schutter G, Yuan Y, Taerwe L. On the mechanism of polypropylene fibres in preventing fire spalling in self-compacting and high-performance cement paste. Cem Concr Res 2008;38:487–99.

[17] Annerel E, Taerwe L, Vandevelde P. Assessment of temperature increase and residual strength of SCC after fire exposure. 5th International RILEM symposium on SCC; 2007. p. 715–20.

[18] Behnood A, Ghandehari M. Comparison of compressive and splitting tensile strength of high-strength concrete with and without polypropylene fibers heated to high temperatures. Fire Safety J 2009;44:1015–22.

[19] Kalifa P, Chene G, Galle C. High-temperature behavior of HPC with polypropylene fibers from spalling to microstructure. Cem Concr Res 2001;31:1487–99.

[20] Xiao J, Falkner H. On residual strength of high-performance concrete with and without polypropylene fibres at elevates temperatures. Fire Safety J 2006;41:115–21.

[21] Pliya P, Beaucour AL, Noumowé A. Contribution of cocktail of polypropylene and steel fibres in improving the behaviour of high strength concrete subjected to high temperature. Const Build Mater 2011;25:1926–34.

[22] Noumowé NA. Mechanical properties and microstruture of high strength concrete containing polypropylene fibres exposed to temperatures up to 200 °C. Cem Concr Res 2005;35:2192–8.

[23] Suhaendi SL, Takashi H. Effect of short fibers on residual permeability and mechanical properties of hybrid fibre reinforced high strength concrete after heat exposition. Cem Concr Res 2006;36:1672–8.

[24] Chen B, Liu J. Residual strength of hybrid-fiber reinforced high strength concrete after exposure to high temperature. Cem Concr Res 2004;34:1065–9.

[25] EFNARC. Specification and guidelines for self-compacting concrete. UK: EFNARC; 2002.

[26] RILEM TC 129-MHT. Test methods for mechanical properties of concrete at high temperatures – part 1: introduction; part 2: stress–strain relation: and part 3: compressive strength for service and accident conditions. Mater. Struct. 1995;28(181):410–4.

[27] ASTM C597-02. Standard test method for pulse velocity through concrete annual book of ASTM standards, vol. 04.02. Philadelphia; 2002.

[28] Yuksel I, Siddique R, Ozkan O. Influence of high temperature on the properties of concretes made with industrial by-products as fine aggregate replacement. Const Build Mater 2011;25:967–72.

[29] Kanéma TM, De Morais MVG, Noumowé A, Gallias JL, Cabrillac R. Experimental and numerical studies of thermo-hydrous tranfers in concrete exposed to high temperature. Heat Mass Transf 2007;44:149–64.

[30] Yang H, Lin Y, Hsiao C, Liu JY. Evaluating residual compressive strength of concrete at elevated temperatures using ultrasonic pulse velocity. Fire Safety J 2009;44:121–30.

[31] Tanyildizi H, Coskun A. The effect of high temperature on compressive strength and splitting tensile strength of structural lightweight concrete containing fly ash. Const Build Mater 2008;22:2269–75.

[32] Behnood A, Ziari H. Effects of silica fume addition and water to cement ratio on the properties of high-strength concrete after exposure to high temperatures. Cem Concr Compos 2008;30:106–12.

[33] Castillo C, Durrani AJ. Effect of transient high temperature on high strength concrete. ACI Mater J 1990;87(1):47–53.

[34] Dias WPS, Khoury GA, Sullivan PJE. Mechanical properties of hardened cement paste exposed to temperatures up to 700 °C. ACI Mater J 1990;87(2):160–6.

[35] Khoury GA. Compressive strength of concrete at high temperature: a reassessment. Magazine Concr Res 1992;44:291–309.

[36] Ye G, Liu X, De Schutter G, Taerwe L, Vandevelde P. Phase distribution and microstructural changes of SCC at elevated temperatures. Cem Concr Res 2007;37:978–87.

[37] Zhang B, Bicanic N. Residual fracture toughness of normal-and high-strength gravel concrete after heating to 600 °C. Mater J 2002;99(3):217–26.

[38] Fares H, Remond S, Noumowe A, Cousture A. High temperature behaviour of self-consolidating concrete: microstructure and physicochemical properties. Cem Concr Res 2010;40(3):488–96.

[39] Komonen J, Penttala V. Effect of high temperature on the pore structure and strength of plain and polypropylene fiber reinforced cement pastes. Fire Technol 2003;39(1):23–34.

[40] Poon CS, Shui ZH, Lam L. Compressive behaviour of fiber reinforced high-performance concrete subjected to elevated temperature. Cem Concr Res 2004;34(12):2215–22.