Construction and Building Materials 41 (2013) 296–302

Contents lists available at SciVerse ScienceDirect

Construction and Building Materials

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

Residual mechanical characteristics and spalling resistance of fiber reinforced self-compacting concretes exposed to elevated temperatures

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HIGHLIGHTS

- ▶ We examined the performance at elevated temperatures of two normally vibrated concretes and six self compacted concretes.
- ▶ The strength classes of the mixtures were C25/30 and C30/37.
- ▶ Polypropylene fibres with a length of 6 and 12 mm were used to produce fibre reinforced SCC.
- ▶ The spalling tendency was increased for specimens of higher strength class irrespective of the mixture type (SCC or NVC).
- ▶ Both 6 m and 12 mm fibres had the same positive effect since all fiber reinforced SCC mixtures did not perform any spalling.

ARTICLE INFO

Article history:
Received 20 February 2012
Received in revised form 6 November 2012
Accepted 22 November 2012

Keywords:
Spalling
Resistance at elevated temperatures
Mechanical characteristics
Polypropylene fibres

ABSTRACT

The study presented in this paper concerns the effect that polypropylene fibres have on the properties of SCC of different strength classes when exposed to elevated temperatures. A total of six different SCC and two normal concrete mixtures were produced. The strength classes of the mixtures were C25/30 and C30/37.

The specimens produced were placed at the age of 120 days in an electrical furnace and the heat was applied with a rate of 5 °C/min. The tested temperatures were 300 °C and 600 °C. Once reached, the maximum temperature was maintained for 1 h. Then the specimens were naturally cooled down to ambient temperature in the furnace. The properties measured after heat exposures were the compressive strength, splitting tensile strength, water capillary absorption and ultrasonic pulse velocity.

It was noticed that, the spalling tendency was increased for specimens of higher strength class C30/37 irrespective of the mixture type (SCC or NVC). Such an explosive behavior was not observed when polypropylene fibers were added in the mixtures; however, in this case the residual mechanical characteristics of concretes were significantly reduced.

1. Introduction

Self-compacting Concrete (SCC) is a type of concrete developed through the last 15 years. It is widely used in different applications ranging from housing to large infrastructures, such as bridges and tunnels. SCC can spread into place under its own weight and fill restricted sections without the need of mechanical consolidation, improving this way the working environment, reducing the manpower need for casting and increasing the speed of construction and the quality of cast structures [1]. SCC is usually considered as a special type of high-performance concrete produced with higher amounts of filler materials and lower water/binder ratios as compared with other concretes. Thus porosity of SCC is usually reduced and the material is characterized by a high resistance to fluid diffusion. This fact is responsible for the superior durability usually observed on SCC [2–10]. On the other hand concrete mixtures of high diffusion resistance are usually considered as more vulnerable to fire attack [11,12]. Concrete has in general good fire resistance. Usually, its residual compressive strength is slightly reduced after fire exposure up to 300 °C [4,13–15] although some researchers reported that concrete's residual compressive strength decrease may be very important even for temperatures lower than 200 °C [16,17]. There is, however, a phenomenon that decreases the fire resistance of concrete which is named spallling. According to Khoury and Anderberg [18] spalling, in its most general form, is defined as the violent or non-violent breaking off of layers or pieces of concrete from the surface of a structural element when it is exposed to high and rapidly rising temperatures as experienced in fires. There are four types of spalling: Explosive, surface, aggregate

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http://dx.doi.org/10.1016/j.conbuildmat.2012.11.093

and corner spalling. The most important of these is explosive spalling which occurs violently and results in serious loss of material.

The two most common explanations of the origin of spalling are internal pore pressure and thermal stress. Internal pore pressure caused by heating of water trapped in the concrete leads to tensile failure while restrained thermal expansion causes mechanical stresses which result in spalling [19]. According to Khoury and Anderberg [18], pore pressure spalling may apply by itself only for small unloaded specimens, as the specimens used in this research.

It is important to consider, when comparing different spalling theories, whether the theory deals with one-side exposure of concrete or exposure from more than one side. The mechanism of fire spalling probably depends on the type of exposure due to the fact that the stresses in the cross-section and escape routes for moisture in the pore system depend on the geometry of the elements. In multi sided exposure, where the moisture flow towards the centre of the cross-section it meets a similar flow from the opposite side, and thus the role of moisture in prompting spalling is amplified relative to that of one-sided exposure [20].

The main reason for concrete's spalling at elevated temperatures was considered to be the internal pore pressure buildup due to the vaporization of the free and chemically bound water [21]. In concrete mixtures with finer pore structure, such as HPC, this internal pressure is not released, thus leading to spalling of concrete surface [13,22–26]. Recent studies reported that pressure in itself is not the only factor impacting on the propensity of concretes to spall. Experimental results revealed that concrete spalling does not start because of pore pressure, but mostly due to internal cracking, that releases the pressure during fast heating [20,27].

Spalling behavior of certain concretes under fire conditions is a reason for inhibiting their use in structures where increased fire resistance is required for safety reasons, such as high rise buildings and tunnels. A lot of research has been carried out in order to model the spalling tendency of HPC and to propose some alternative solutions such as different mixture proportions or use of materials that provide a passive or active protection against spalling. Among the proposed solutions, the addition of polypropylene fibres seems to be an effective one [28–33]. It was reported [34] that polypropylene melts at 160–168 °C whereas HPC spalls when the air temperature ranges between 190 and 250 °C. Melting of polypropylene fibres creates an additional pathway for release of internal vapor stresses at higher temperatures. Eurocode 2 [35] recommends including more than 2 kg/m^3 of monofilament polypropylene fibres in HSC to reduce spalling but the size of the fibres is not specified. Many researchers reported that concrete spalling may be avoided when adding even smaller amount of fibres [32,36–38].

Recent research [39] has shown that for the same w/powder ratio, the porosity and pore size distribution of SCC are very similar to these of high performance concrete. This means that when self-compacting concrete is exposed to elevated temperatures, it might have the same risk (i.e. explosive spalling) as high performance concrete. But the phase composition of SCC and HPC is different as observed by SEM and DTA/TGA measurements. In the case of limestone as filler in SCC concrete, the limestone particles are almost not decomposed up to a temperature of 700 °C and the weight loss of SCC is much smaller than that of HPC before this temperature [40].

In this paper the mechanical characteristics of eight self-compacting and normally vibrated concretes subjected to elevated temperatures up to 600 °C were experimentally investigated. The initial effort was to produce self-compacting concretes with cement and water content as close as possible to the quantities used for the production of NVC mixtures of the same strength class. Polypropylene fibres with length of 6 mm and 12 mm were added in four SCC.

2. Experimental program

2.1. Materials

Eight different concrete mixtures – six self-compacting concretes (SCCs) and two normally vibrated concretes (NVCs) were produced. The concretes belong to two strength classes, C25/30 and C30/37, according to EN206-1 [41]. Concretes were prepared using two classes of Blended Portland Cement, i.e. CEM II A-M/42.5N and CEM II A-M/32.5N according to European standard EN 197-1 [42]. The initial effort was to keep the cement dosage and water content stable among SCC and NVC of the same strength class. The coarse aggregates consisted of crushed granite with maximum size of 16 mm. The fine aggregates used were natural river sand and crushed limestone sand. All SCC mixtures were produced with crushed limestone sand only in order to increase the content of fine materials. Limestone filler was also added in SCC mixtures. SCCs were prepared and tested in fresh condition according to the specifications of EFNARC [43]. Chemical composition of cements and limestone filler are presented in Table 1. Polypropylene fibres (PPFs) with a length of 6 mm and 12 mm at a dosage of 1 kg/m^3 were also used to produce fibre reinforced SCC of both strength classes. Physical and mechanical properties of PP fibres are presented in Table 2. A high range water reducing carboxylic ether polymer admixture was added at different dosages in order to achieve a slump of 190–200 mm in the case of NVCs, or to achieve self compactibility in the case of SCCs. The proportions as well as the properties of fresh mixtures are presented for all concretes prepared in Table 3.

2.2. Mechanical tests and type of specimens

The specimens prepared were 150 mm (edge) cubes and 150 × 300 mm cylinders. Six 150 mm cubes for each mixture were cured in a curing chamber (T = 20 °C, RH = 98%) and used for measuring the 28 days compressive strength and the water capillary absorption. All other specimens (150 mm cubes and 150 × 300 mm cylinders) were used for heat tests. They were initially cured for the first 14 days in the curing chamber. From this age onwards they were placed in the laboratory air environment (relative humidity = 50–60% and temperature = 20 ± 2 °C) where they remained until the test age.

2.3. Heat testing

At the age of 120 days specimens were placed in an electrical furnace with heat applied at a rate of 5 °C/min until the desired

Table 1
Chemical composition of cement and limestone filler.

	CEM II/A-M 42.5 N	CEM II/A-M 32.5 N	Limestone filler
SiO_2	22.71	23.85	17.79
Al_2O_3	6.06	5.22	1.57
Fe_2O_3	3.43	4.13	1.62
CaO	58.87	58.2	44.24
MgO	1.67	3.2	4.04
SO_3	2.65	3.3	3.02
K_2O	1.18	0.68	–
Na_2O	0.43	0.32	–
TiO_2	0.28	0.24	0.17
P_2O_5	0.09	0.06	0.02
SrO	0.03	0.03	–
Cr_2O_3	0.01	0.02	–
ZnO	0.01	0.01	–
SG (g/cm^3)	3.15	3.10	2.65
Blaine (cm^2/g)	4050	3760	2739

Table 2
Physical and mechanical properties of PP fibres.

Specification	PP fiber
Purity (%)	100
Elongation at failure (%)	29
Diameter (μm)	25
Length (mm)	6/12
Color	White
Tensile strength (MPa)	400
Melting point (°C)	160

temperature was reached. Before heat testing three cubes were dried at 105 °C until constant mass. The moisture content was then determined in the following way:

$$w = (m_o - m_d)/m_d$$

where m_d is the mass of the test specimen after drying at 105 °C and m_o is the mass of the test specimen before drying.

Moisture content ranged between 3% and 4% for all mixtures. In the electrical furnace the maximum temperature of 300, or 600 °C was maintained for 1 h after reaching the target temperature. Specimens were then allowed to cool in the furnace and tested for compressive strength (cube specimens), splitting tensile strength (cylindrical specimens) and pulse velocity (cube specimens). Control tests were also performed on specimens cured at room temperature (20 °C). Residual compressive strength was determined as the mean value of three cubes tested per temperature, whereas splitting tensile strength was determined as the mean value of two tested cylinders. Pulse velocity measurements were determined as the mean value of six measurements (two opposite sides of the cubes used for compressive strength measurements) at any temperature. Pulse velocity measurements were performed according to ASTM C-597-09 [44]. The capillary water absorption, measured before heat testing according to the procedure described by RILEM TC116 [45], was determined as the mean value of three cubes.

Spalling tendency of tested concretes was also assessed. According to [18] there are two forms of explosive spalling, both influenced by external loading; pore pressure spalling and thermal stress spalling. They act singly or on combination depending upon the section size, the material, and the moisture content. Pore pressure spalling may apply by itself only for small unloaded specimens, as the specimens used in this research.

3. Results and discussion

3.1. Residual compressive strength

Residual compressive strength is presented for all mixtures in Fig. 1a and b. Compressive strength of NVC is linearly reduced until 600 °C. Spalling occurred above 500 °C for the mixture NVC25/30 and destroyed some cylindrical and cubic specimens. However, in the case of NVC30/37 mixture explosive spalling occurred above 250 °C and was more violent leading to destruction of more cubes and cylinders (Fig. 2). Compressive strength of SCC mixtures was also linearly reduced, and it can be said that strength reduction illustrated parallel to the one observed on NVC mixtures of the same strength category. SCC 2 also suffered explosive spalling. However this occurred above 500 °C and resulted to less damages (Fig. 2b). Spalling behaviour of all concretes is presented in Table 4.

The influence of polypropylene fibres on residual compressive strength of concretes is illustrated in Fig. 1a and b. As it was mentioned above, polypropylene fibres melt at 160–168 °C. The melted fibres, which are in liquid state, pass through the pores around them. This movement will break the connection among hydrated products [39]. With higher temperature, the melted fibres will absorb more energy and vaporize. Thus their remains (the fiber channels) and the flow path are connected with each other and form a more connective pore network aiding the internal vapour pressure to expand [39,46]. This found to be crucial for SCC mixtures of the higher strength class C30/37. Formation of additional pores led to rapid reduction of residual strength especially at the temperature range of 100–300 °C but no spalling was observed at any temperature tested. All SCC mixtures produced with polypropylene fibres performed a more sharp decrease of their residual compressive strength after treated at both target temperatures (Fig. 1a and b). These results are in agreement with findings of other researchers [47,48]. It should also be noted that the length of fibres – 6 or 12 mm – did not influenced the results since all SCC mixtures produced with polypropylene fibres presented the same trend. Residual values of compressive strength of all mixtures is generally in good agreement with the values proposed in EC4. Pamonte and Gambarova [49] recently performed an extended research targeting to compare the residual compressive strength of SCC mixtures as reported in different projects [15,50–53]. They also concluded that in most cases the residual strength curve was close to the values proposed in EC4.

For all the tested temperatures, the residual compressive strength of SCC mixtures without fibres was higher than the one

Table 3
Mix design characteristics of self-compacting concretes and normally vibrated concretes.

Mix design (kg/m^3)	SCC 25/30 SCC 1	SCC 30/37 SCC 2	SCC 25/30 + PPF 6 mm SCC 3	SCC 30/37 + PPF 6 mm SCC 4	SCC 25/30 + PPF 12 mm SCC 5	SCC 30/37 + PPF 12 mm SCC 6	NC 25/30 NVC 1	NC 30/37 NVC 2
CEM II 32.5N	300	305	300	305	300	305	300	305
CEM II 42.5N	50	130	50	130	50	130	50	130
Coarse aggregates	800	800	800	800	800	800	850	760
Sand	945	880	945	880	945	880	980	1010
Limestone filler	50	50	50	50	50	50	–	–
Water	195	191	195	191	195	191	195	191
Sup/er 1	5.74	5.00	5.74	5.00	5.74	5.00	–	–
Sup/er 2	–	1.74	–	1.74	–	1.74	5.03	5.42
Retarder	1.050	–	1.050	–	1.050	–	–	–
VMA	1.050	–	1.050	–	1.050	–	–	–
PP fibers	–	–	1.00	1.00	1.00	1.00	–	–
W/C	0.56	0.44	0.56	0.44	0.56	0.44	0.56	0.44
Slump (mm)	750	700	710	680	680	685	19	20
T_{50} (s)	1.82	2.68	2.8	2.59	2.42	2.51	–	–
L-BOX (H_1/H_2)	1	0.95	0.95	0.95	0.80	0.75	–	–
f_{c28} (MPa)	40	56.6	39.6	55.4	40.3	54.2	36.5	48.6

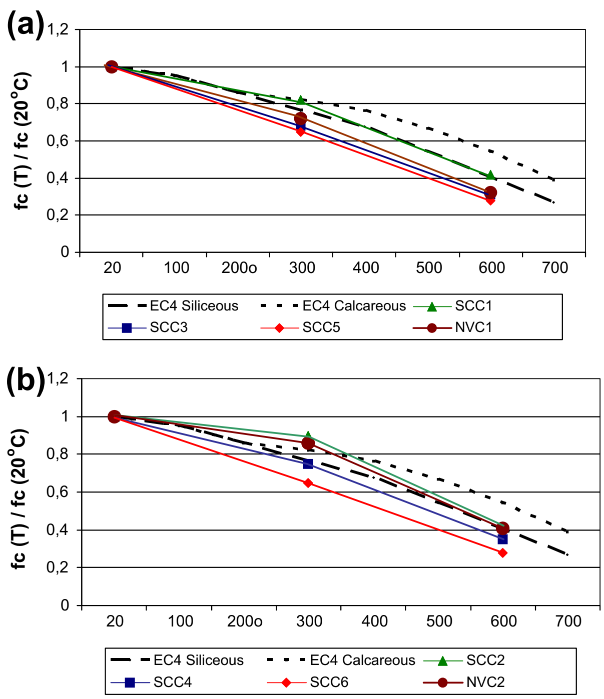

Fig. 1. Residual compressive strength of self-compacting and normally vibrated concretes.

measured on NVC of the same class. The same conclusion results from the research of Ye et al. [54], who reported that concrete specimens produced with SCC performed better stability below 700 °C as compared with NVC specimens prepared with the same water content.

According to Chan et al. [55], there are three temperature ranges from the viewpoint of compressive strength loss: 20–400 °C, 400–800 °C and 800–1200 °C. Chan et al. investigated the behavior of three grades of concretes (one normal strength concrete – NSC – and two high strength concretes – HSC) prepared with ordinary portland cement. At 90 days specimens from each batch were heated in an electric furnace to temperatures of 400, 600, 800, 1000 and 1200 °C respectively. The peak temperature was maintained for 1 h and then the specimens were left in the furnace until they were cooled to ambient temperature. They concluded that for all types of concretes, only a small part of the original compressive strength was lost up to 400 °C, between 1% and 10% for HSC and 15% for NSC. Bamonte and Gambarova [49] produced three self-compacting concretes with compressive strength of 51, 82 and 90 MPa. They reported that the loss of original compressive strength at the low temperature area (20–400 °C) ranged between 18% and 45% for concretes tested at 200 °C and 400 °C respectively. Similar results were also presented for the SCC mixtures tested in the present research. It appeared that the residual compressive strength at the temperature of 300 °C ranged between 0.62 and 0.90 of the original strength (measured at 20 °C), whereas no spalling was observed at any of the SCC or NVC mixtures. The most severe loss of compressive strength occurred for both SCC and NVC mixtures at the temperature range between 300 and 600 °C.

According to Neville [56] permeability of concrete is controlled by the capillary porosity of hardened cement paste. The pores relevant to permeability are those with a diameter of at least 120 or 160 nm and have to be continuous. Reinhardt and Stegmaier [51] produced eight different SCC mixtures and one reference conventional concrete and performed heat tests according to the time temperature curve described in ISO 834. The maximum temperature reached was 1080 °C after 120 min. They concluded that as the matrix of the concrete mixtures gets denser, their behaviour after heated at high temperatures gets worse: there was a clear trend that the residual compressive strength of all concrete mixtures tested in their research increased when the w/c also increased. The relationship between w/c and propensity for explosive spalling was also reported by Phan and Carino [57]. It has been theorized [13–21,58,59] that the higher susceptibility of high strength concretes to explosive spalling is due, in part, to their lower permeability, which limits the ability of water vapour to escape from the pores.

The concrete mixtures investigated in this study were of different permeability categories since they were produced with different cement contents and different w/c. The capillary water absorption is presented for all mixtures in Fig. 3a and b. Both NVC and SCC of the lower class C25/30 were produced with high w/c, which resulted in great water absorption values, and for this reason danger for spalling was low; only some cylindrical specimens of NVC were destroyed. On the contrary, explosive spalling occurred for both SCC and NVC of the higher strength class without fibres. PPF–SCC mixtures of both strength classes produced with 6 mm and 12 mm fibres were characterized by higher water permeability, probably due to less effective self-compaction. This additional porosity, in combination with the pathway formed after fibres melt, resulted to better spalling behaviour, but was also responsible for the reduced residual strength measured.

3.2. Residual tensile strength

The ratio of residual tensile strength of all self-compacting and normally vibrated concrete specimens as compared to the tensile strength at room temperature (20 °C) is shown in Fig. 4a and b. The sharp loss of tensile strength after heating at 300 °C is different from the more gradual loss of compressive strength. Such a sharp

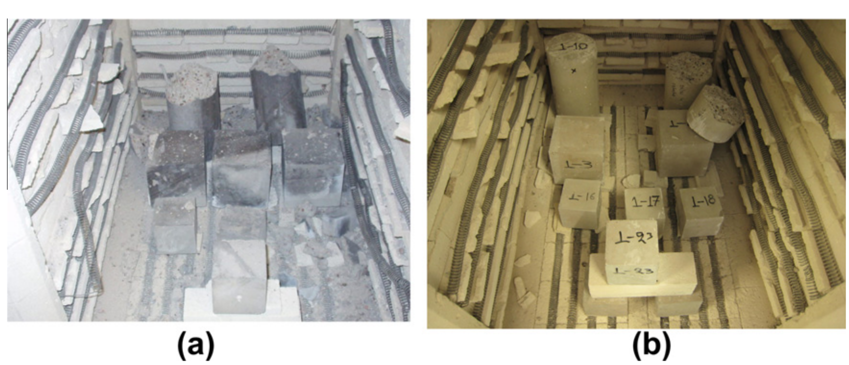

Fig. 2. Explosive spalling after heating at 600 °C for: (a) NVC2 and (b) SCC2 mixtures.

Table 4
Spalling of self-compacting concretes and normally vibrated concretes.

	SCC 25/30 SCC 1	SCC 30/37 SCC 2	SCC 25/30 + PPF 6 mm SCC 3	SCC 30/37 + PPF 6 mm SCC 4	SCC 25/30 + PPF 12 mm SCC 5	SCC 30/37 + PPF 12 mm SCC 6	NC 25/30 NVC 1	NC 30/37 NVC 2
300 °C								
Explosive spalling of cylinders	No	No	No	No	No	No	No	Yes
Explosive spalling of cubes	No	No	No	No	No	No	No	Yes
600 °C								
Explosive spalling of cylinders	No	Yes	No	No	No	No	Yes	Yes
Explosive spalling of cubes	No	No	No	No	No	No	Yes	Yes

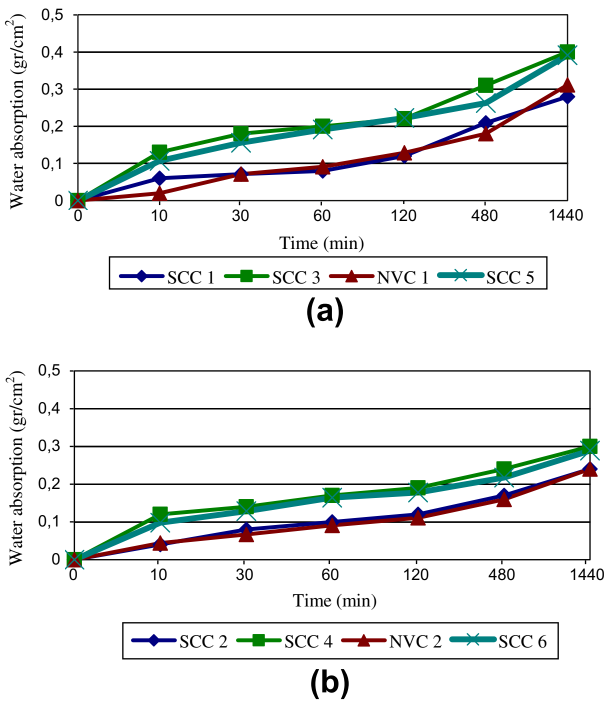

Fig. 3. Capillary water absorption of different self-compacting and normally vibrated concretes.

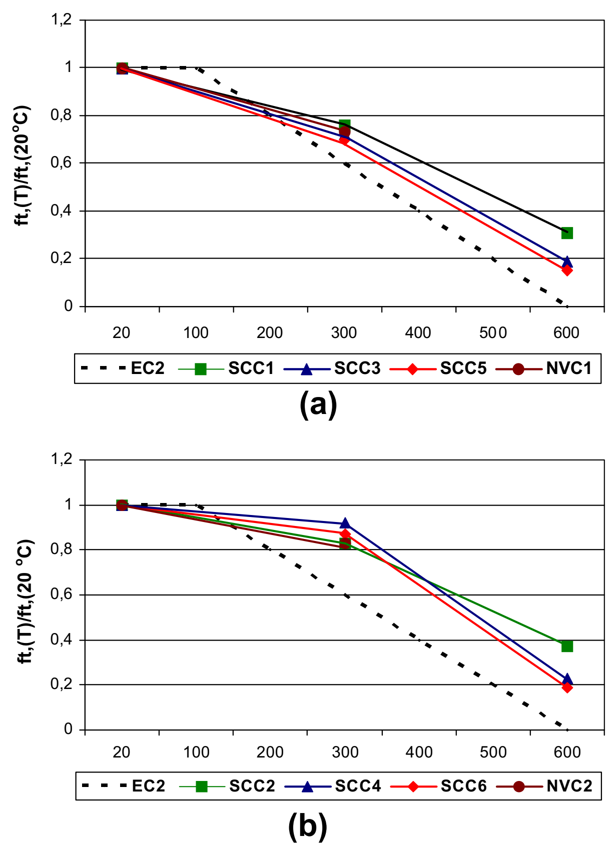

Fig. 4. Ratio of residual splitting tensile strength after peak temperature ($f_{ct(T)}$) to the splitting tensile strength at room temperature ($f_{ct(20)}$) of self-compacting and normally vibrated concretes.

decrease was also reported by Chan et al. [55] and Khalig and Kondur [60]. They attributed this phenomenon to the macro and micro-cracks produced in the specimens due to the thermal incompatibility within the concrete [13,59]. It was also reported that the majority of these cracks were formed above 300 °C [61,62]. Thus both residual compressive and tensile strength were further reduced beyond this temperature (Figs. 1 and 4). However additional cracks have a more detrimental effect in tension properties (tension zone of concrete) thus residual tensile strength was more sharply reduced above 300 °C than residual compressive strength.

It was also observed in this research that relative splitting tensile strength $f_{ct}(T)/f_{ct}(20)$ was reduced up to 300 °C following a similar path for all SCC and NVC mixtures of the lower strength class C25/30 (Fig. 4a). Among concrete mixtures tested SCC3 and SCC5 were more susceptible in reducing their relative splitting tensile strength at temperatures above 300 °C due to melting of fibres. NVC1 suffered explosive spalling and some cylindrical specimens were deteriorated.

Concerning the $f_{ct}(T)/f_{ct}(20)$ of the higher strength category C30/37 mixtures, SCCs performed a smaller reduction of their relative strength than NVC of the same category did. After exposed to 600 °C SCC2 mixture retained 37% of its initial strength whereas SCC4 mixture retained only 23% (Fig. 4a and b) and SCC6 only 19%. Once again explosive spalling occurred above 300 °C for NVC2 mixture, and all specimens intended to be measured for splitting tensile strength were totally deteriorated.

Residual splitting tensile strength for polypropylene fibres SCC mixtures was significantly reduced beyond 600 °C. This was valid for all for mixtures produced, irrespective of the length of the fibres. Additional porosity formed after melting of fibres at 160 °C in combination with the development of micro and macro cracks due to thermal stresses were responsible for that [60]. However the residual splitting tensile strength for SCC 4 and SCC6 mixtures after 300 °C was higher than the one measured on SCC2 and NVC2. It is believed that the additional porosity of these mixtures in combination with the pathway formed after fibres melt favourite the release of additional stresses originated from vaporization of water at the low temperature area. Formation of micro cracks was therefore limited as compared with mixtures produced without fibres. Liu et al. [39] also found that microcracking showed a higher occurrence at 300 °C for samples without the addition of PP fibres.

3.3. Residual pulse velocity

Residual pulse velocity of all concretes after different peak temperatures compared to the pulse velocity at air temperature (20 °C) is plotted in Fig. 5. A decrease in velocity indicates the initiation of cracks in concrete specimens and an increase in porosity. Factors that cause this type of failure [26] are: (a) the thermal stresses induced by thermal gradients, (b) the thermal incompatibility between cement paste and aggregates at high temperature (c) the decomposition of calcium hydroxide (CH) in the cement paste and (d) the calcination of limestone aggregates or (as in this research) the phase transformation of quartz aggregates at elevated temperature. Siliceous aggregates containing quartz, such as granite aggregates used in this study, can cause distress in concrete at about 573 °C because transformation of quartz from α to β form is associated with a sudden expansion of the order of 0.85% [58].

Residual pulse velocity $V(T)/V(20)$ is reduced almost linearly from 20 °C to 600 °C in both SCC and NVC of the lower strength category C25/30 (Fig. 5a). The same trend was also observed in SCC and NVC mixtures of category C30/37 but only for temperatures until 300 °C. Explosive spalling occurred above those temperatures and there was only one cube left from NVC2 mixture at 600 °C (Fig. 5b). Pulse velocity is therefore plotted with dashed line at this temperature. It should be noted that both SCC and NVC follow the same trend in reducing their residual pulse velocity, especially at the low temperature area. This means that initiation and propagation of cracks is only depended on the strength category, i.e. on the cement content and w/c. Addition of fibres resulted to additional pores after melting temperatures, thus to lower residual velocity measurements, even from the low temperature area. The residual pulse velocity at 300 °C compared to the pulse velocity at air temperature was measured equal to 0.68, 0.66, 0.70 and 0.68 for SCC3, SCC5, SCC4 and SCC6 respectively. The respective values measured for SCC1, NVC1, SCC2 and NVC2 were 0.79, 0.74, 0.87 and 0.79 (Fig. 5).

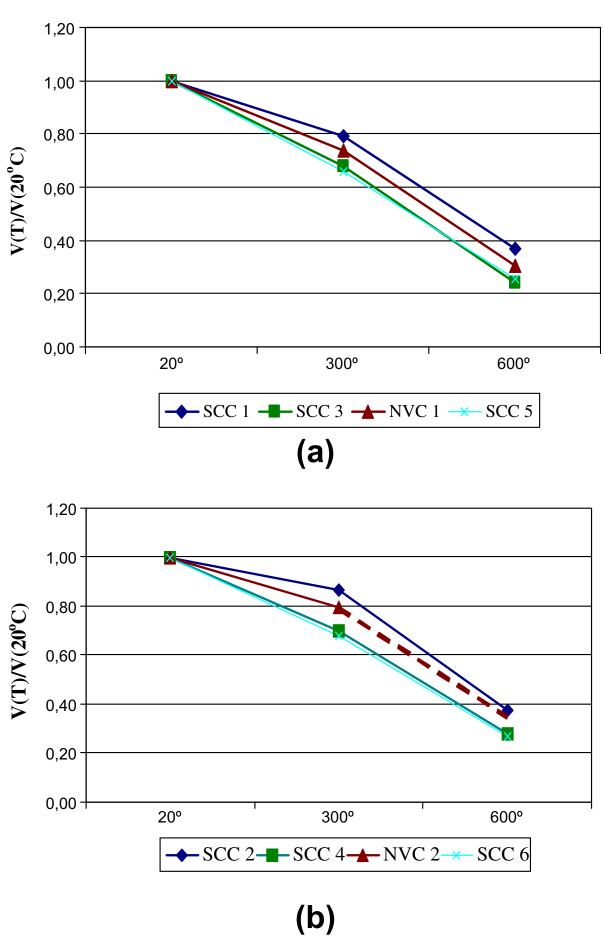

Fig. 5. Ratio of residual pulse velocity after peak temperature ($f_{ct(T)}$) to the pulse velocity at room temperature ($f_{ct(20)}$) of self-compacting and normally vibrated concretes.

4. Conclusions

Self-compacting concretes tested in the present study had an explosive spalling tendency almost similar to the one of normally vibrating concretes of the same strength class. The residual mechanical properties tested in this research (residual compressive strength and splitting tensile strength) in self-compacting concretes and normally vibrating concretes belonging in the same strength class were affected by the same way. Influence of elevated temperatures found to be more detrimental to splitting tensile strength of all mixtures tested in this research.

The influence of adding fibre reinforcement on the performance of concrete at high temperatures was twofold. On the one hand, they reduced slump flow and L-box values of SCCs thus the compaction got more difficult. The total porosity was slightly increased and this led to increased permeability, which reduced the risk for explosive spalling. On the other hand polypropylene fibres melt at temperatures above 160 °C creating this way an additional pathway in the interior of concrete structure.

Polypropylene fibre reinforced SCC mixtures were not destroyed at any of the temperature achieved in this research. Additions of this type of fibres increased the spalling resistance of SCC mixtures. Both 6 mm and 12 mm long fibres tested in this research had the same positive effect. However they had negative effect on concrete's residual mechanical properties since they significantly decreased the residual compressive strength and tensile strength of concrete. It is therefore recommended to use polypropylene fibres as part of a total spalling protection design method in combination with other materials such as external thermal barriers.

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