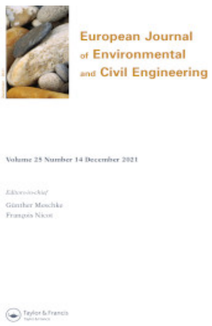

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Residual compressive strength of plain and fiber reinforced concrete after exposure to different heating and cooling regimes

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ABSTRACT

The article investigated the impact of different cooling regimes on the response of both plain and fibre reinforced concrete (FRC) after heating. A total of 256 standard concrete cylinders of normal strength concrete (NSC) and high strength concrete (HSC) were tested in compression after heating at 200 °C, 400 °C, and 600 °C. For each concrete grade, 32 specimens were prepared without fibres while 96 cylinders had fibres (steel, polypropylene (PP) and their hybrid) in the concrete mixture. The cooling regimes adopted for cooling the test specimens were water quenching and natural ambient cooling. Effect of studied parameters was evaluated for tested cylinders in terms of stress-strain characteristics, residual strength, modulus of elasticity, and failure modes. For both NSC and HSC, the reduction in strength increased significantly when the temperature was increased from 400 to 600 °C. At 600 °C, the use of steel fibres caused lower loss in compressive strength, elastic modulus and energy absorption as compared to the use of PP and hybrid fibres. The residual strength of water quenched concrete was more than the air cooled concrete because the heated specimens were kept submerged in water for 24 h, which helped in the rehydration of anhydrous cement products.

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Fibres; concrete; FRC; cooling regimes; elevated temperature

1. Introduction

The structural fire safety is a major concern for buildings and infrastructure. The fire damages to structures may make them non-functional (or unserviceable), thus requiring repair and strengthening for bringing them to life. Although concrete offers considerable resistance to fire, its mechanical properties are affected by the consequent physical and chemical changes due to heating.

The level of resistance offered by normal and high strength concretes (NSC and HSC) to fire is different due to the difference in their characteristics. Although reinforced concrete (RC) structures may survive even severe fires, the damage caused to the structures may necessitate either repair and strengthening or demolition and reconstruction. As the economic factors favour retrofitting of the fire damaged structure instead of its demolition, the crucial decision requires the assessment of the structural damage caused by fire. For assessing the fire damage, residual capacity of various structural elements is required to be estimated. Several researchers (Abbas et al., 2019; Al-Salloum et al., 2011; Elsanadedy, 2019; Khan & Abbas, 2015; 2016) have studied the influence of heating environments on the residual properties of NSC, HSC, and reactive powder concrete.

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Most of the early research on elevated temperature exposure was mainly on NSC. However, recently HSC, fibre-reinforced concrete (FRC), and lightweight aggregate concrete (LWAC) have also been investigated. The fire performance of LWAC has been reported to be better than NSC and HSC. One of the major concern for the exposure of HSC to fire is the explosive spalling that has been observed in experiments at temperatures varying from as low as 300 °C to up to 650 °C. The spalling of concrete is a critical issue in the fire behaviour of concrete as it exposes the inner concrete layers including rebars to the outside environment (Mindeguia et al., 2013). The exposure of concrete to elevated temperature causes free water available in concrete to evaporate and the burning of ingredient causes generation of gases which try to escape to outside environment. The structure of HSC being dense and less permeable, it does not allow the water vapours and gases to escape thereby leading to the pressure buildup, which is responsible for the explosive spalling of concrete. It was reported that the addition of polypropylene and steel fibres in concrete helps in enhancing the fire behaviour of HSC. The exposure of HSC, containing polypropylene fibres, to fire causes the fibres to melt at around 170 °C. The melting of fibres leaves voids, which provide routes for the escape of gases (generated during the heating of concrete) from the inside concrete mass without the development of excessive pressure. The use of steel fibres in producing HSC also helps in improving the fire resistance of HSC by increasing the concrete strength in tension, which helps in resisting the gas pressure and thus avoiding the spalling of concrete (Sharma et al., 2009).

The majority of past research on the properties of concrete after heating at elevated temperature was conducted on air cooled specimens. These experimental cooling conditions are quite different from the actual practices that are adopted in extinguishing fire such as the spraying of water. The water quenching of concrete leads to a thermal shock, which is responsible for severe degradation in the properties of concrete. Thus, there is a requirement for investigating the effect of different cooling schemes on the properties of different grades of concrete.

Understanding the performance of concrete exposed to heating and subsequent post-cooling stage is vital in assessing the residual properties of concrete. Nevertheless, there are limited studies on the effect of heating on the performance of concrete containing fibres e.g. polypropylene and/or steel fibres (Caggiano et al., 2016; Yap et al., 2020; Zhang et al., 2021). This study focuses on the influence of post-heating cooling regimes on the mechanical properties of both NSC and HSC. The effect of adding fibres in the concrete mixture on its resistance to high temperature was also studied. The crimped polypropylene, and hooked steel fibres were used in this research. The polypropylene fibres were used because unlike other polymeric fibres, they offer resistance to alkali, acid, and moisture attack, while providing adequate enhancements such as reducing plastic, and drying shrinkage. The steel fibres were used as they are significantly more effective for crack control. Two post-heating cooling regimes — namely water quenching and natural air cooling — were employed for cooling.

2. Related work

2.1. Influence of high temperature on plain and fibre reinforced concretes

Li et al. (Li et al., 2012) investigated the influence of elevated temperature environment on the properties of concrete. Both static and dynamic effects were considered. The critical temperature for the noticeable loss of compressive strength was 400 °C. However, the strength loss became more dramatic at 800 °C. Chen et al. (Chen et al., 2015) studied the effect of strain rate on NSC for elevated temperature exposures of 20 °C to 950 °C. Initially for temperature exposures of up to 400 °C, they reported concrete cracking and rapid propagation of cracks. For the temperature increase beyond 400 °C, the concrete cracking was less and the crack propagation was slow. Xiao et al. (Xiao et al., 2016) studied experimentally the strain rate effect on compression behaviour of HSC after exposing it to temperatures of up to 800 °C. They reported that the elastic modulus as well as the compressive strength of concrete are affected by strain rate.

Poon et al. (Poon et al., 2001) investigated the influence of heating on strength and durability of NSC and HSC having supplementary cementitious materials. The test results indicate best behaviour for concrete containing fly ash and ground granulated blast furnace slag (GGBFS) for elevated temperatures of up to 600 °C. They reported substantial loss of strength and permeability of HSC. The optimal percentages of cement replacement by GGBFS and fly ash in HSC were reported as 40% and 30%, respectively for minimum loss in strength and durability (measured in terms of permeability).

Bastami et al. (Bastami et al., 2011) conducted experiments for studying the impact of high temperature on the mechanical properties and potential for explosive spalling of HSC cylinders heated up to 800 °C. Studied parameters were the ratios of aggregate to cement, and water to cement. Both parameters were found to have substantial influence on concrete strength. At ambient temperature, as the water/cement (w/c) ratio increased, strength of HSC decreased; whereas, after exposure to elevated temperature, relative compressive strength increased with increasing w/c ratio.

Bayasi and Al Dhaheri (Bayasi & Al Dhaheri, 2002) studied the performance of PP FRC exposed to elevated temperature regimes. The peak flexural strength of PP FRC was found to decrease with increasing exposure temperature and duration. Moreover, exposure to temperatures below 100 °C does not significantly affect the flexural behaviour of PP FRC. Xiao and Falkner (Xiao & Falkner, 2006) conducted experiments for studying the mechanical properties of fibre reinforced high-performance concrete (HPC) at different elevated temperatures. The study showed no damaging effect of PP fibres on the residual strengths (compressive and flexural). Bangi and Horiguchi (Bangi & Horiguchi, 2012) conducted experiments to study the influence of geometry and fibre type on the behaviour of fibre-reinforced HSC at elevated temperature environments. The test results revealed that inclusion of organic fibres irrespective of their type caused substantial reduction in the pore pressure developed because of the exposure of concrete to the high temperatures. The effectiveness of fibres in pore pressure mitigation in order of decreasing influence were PP, polyvinyl alcohol, and steel fibres.

Novak and Kohoutkova (Novák & Kohoutková, 2017) studied the fire response of FRC at elevated temperatures. The tensile and compressive strengths of FRC were found to decrease with increasing temperature. Authors reported a compressive strength loss of 40% and 65% at the temperatures of 400 °C and 600 °C, respectively. The strength reduction was attributed to the increased porosity and cracks at high temperatures.

Varona et al. (Varona et al., 2018) performed experiments to study the influence of elevated temperature on concrete mixtures produced using limestone aggregates. Six concrete mixes of NSC and HSC having steel fibres were tested in compression and flexure. The increase in the aspect ratio of fibres was reported to have caused reduction in ductility at temperatures exceeding 650 °C.

Hachemi and Ounis (Hachemi & Ounis, 2015) studied experimentally the influence of elevated temperature on concrete produced using different types of coarse aggregates (natural and recycled brick aggregates) and varying w/c ratios. The test results revealed almost same or even better performance of concrete produced using recycled brick aggregates at elevated temperature. Hachemi and Ounis (Hachemi & Ounis, 2019) investigated the influence of sand types (calcareous and siliceous) and w/c ratio on the residual properties of concrete produced using these sands after exposure to temperature of up to 900 °C. Authors reported that effect of sand type on the residual properties of concrete after exposure to the elevated temperature was insignificant.

2.2. Effect of cooling regimes

The influence of cooling regimes after exposure to elevated temperature on the mechanical properties (compressive and splitting tensile strengths, fracture energy) of concrete has been less investigated in the literature (Botte & Caspeele, 2017; Peng et al., 2008; Rao & Kumar, 2015; Yaragal et al., 2012). Peng et al. (Peng et al., 2008) studied the effect of five cooling schemes after heating the specimens to elevated temperatures of 200 °C to 800 °C. The cooling schemes included ambient air cooling, water quenching, and water spray for three different durations. The ambient air cooling showed better performance with lesser reduction in residual properties.

The test results of NSC and HSC to elevated temperatures of 200 °C to 800 °C, and subsequent cooling by ambient air and water quenching are reported in a article by Rao and Kumar (Rao & Kumar, 2015). The article reported more loss in compressive strength in case of HSC as compared to NSC. Also, testing after air cooling of specimens resulted in more loss of strength than testing after water quenching.

In a study by Yaragal et al. (Yaragal et al., 2012), NSC cube specimens of size 100 mm were exposed to elevated temperatures varying from 150 °C to 550 °C. Six different cooling schemes were used including: furnace cooling, sand bath, air cooling, sprinkling water for 5 minutes, sprinkling water for 10 minutes, and sudden cooling. Authors concluded that the sudden cooling gives lowest strengths (compressive and splitting tension) due to the exposure to the thermal shock, whereas the furnace cooling leads to the highest residual strengths due to the gradual change in the gradient of heat.

Table 1. Details of test matrix*.

Cooling regime	Concrete type	Room temp NF	Room temp SF	Room temp PP	Room temp SF + PP	Temp = 200 °C NF	Temp = 200 °C SF	Temp = 200 °C PP	Temp = 200 °C SF + PP	Temp = 400 °C NF	Temp = 400 °C SF	Temp = 400 °C PP	Temp = 400 °C SF + PP	Temp = 600 °C NF	Temp = 600 °C SF	Temp = 600 °C PP	Temp = 600 °C SF + PP
Air cooling (AC)	NSC	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
	HSC	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
Water quenching (WQ)	NSC	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
	HSC	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
Total No. of specimens = 256																	

(No. of test specimens)

*NSC = normal strength concrete; HSC = high strength concrete; NF = no fibres; SF = steel fibres; PP = polypropylene fibres; SF + PP = hybrid fibres (steel + polypropylene).

Botte and Caspeele (Botte & Caspeele, 2017) investigated experimentally the influence of water quenching and water spraying after exposure to temperatures varying from 175 °C to 600 °C on the residual properties of concrete. The residual compressive strength was significantly influenced by the cooling methods. The water spraying was reported to be a better method of cooling as there was an additional strength loss of 38% in water quenched specimens. However, the effect of the two cooling regimes was found to reduce at higher temperatures.

Although the studies have shown the significance of fibres, especially the PP fibres, in the performance of concrete at elevated temperature, the effect of using hybrid of PP with steel fibres is not well established. The water spraying used in practice is difficult to simulate in laboratory because of the varying rate and duration of water spray. The effect of long duration of exposure of heated concrete to water quenching is also not known. This article is intended to investigate these issues. Thus, this article investigates experimentally the residual strength of fibre reinforced and plain concretes for different cooling regimes after heating the specimens to 200 °C, 400 °C, and 600 °C. Two grades of concrete, namely NSC and HSC, were employed in the study. The FRC was produced using PP fibre as well as a hybrid of steel and PP fibres. Residual compressive strength, stress-strain diagrams, and modes of failure are discussed.

3. Experimental program

3.1. Test matrix

A testing program was conducted in the current work to investigate the influence of different cooling regimes on the performance of plain and fibre reinforced concretes after heating with temperatures varying from 200 to 600 °C. Table 1 summarises the test matrix adopted in the study. It is worth mentioning here that each test cylinder was repeated four times in order to have more certainty in the experimental results. As seen in Table 1, a total of 256 concrete cylinders of 150 × 300 mm size were cast. The main variables in the testing program are: (i) concrete grade (normal vs high strength), (ii) existence of fibres in the concrete mix (plain vs fibre reinforced concrete), (iii) type of fibres and their combination (steel fibres alone, polypropylene fibres alone, and hybrid fibres with a mix of steel and polypropylene fibres), (iv) exposure temperature (room temperature of 26 °C, 200 °C, 400 °C, & 600 °C), and (v) cooling regime (natural air cooling versus water quenching). As seen in the table, half of the concrete specimens were prepared using normal strength concrete mixture; whereas the other half (128 specimens) were made of high strength concrete. Out of the 256 cylinders, 64 specimens were prepared without fibres and the remaining 192 cylinders had fibres in the concrete mixture.

3.2. Mixture proportions and material properties

The quantities of ingredients used in preparing normal and high strength concrete mixtures are shown in Table 2. The limestone coarse aggregates were used. The particle size distribution of fine and coarse aggregates are shown in Figure 1. It should be noted that superplasticizers were not utilised in the normal strength concrete mix; however, the high strength concrete was produced using superplasticizers. It should be also mentioned that in the designation of concrete mixtures used in Table 2, “Mix1 (M1)” is

Table 2. Mix proportions for normal and high strength concrete*.

	Mix1 (M1)	Mix2 (M2)
Material	Weight (kg/m^3)	Weight (kg/m^3)
Cement	370	650
Crushed sand	300	264
Silica sand	445	528
Coarse aggregate (Nominal size = 10 mm)	330	770
Coarse aggregate (Nominal size = 20 mm)	765	
Water	192.5	162.5
Gli-110 (Super-plasticizer)	-	3 Liters

*Mix1 (M1) is for normal strength concrete, and Mix2 (M2) is for high strength concrete.

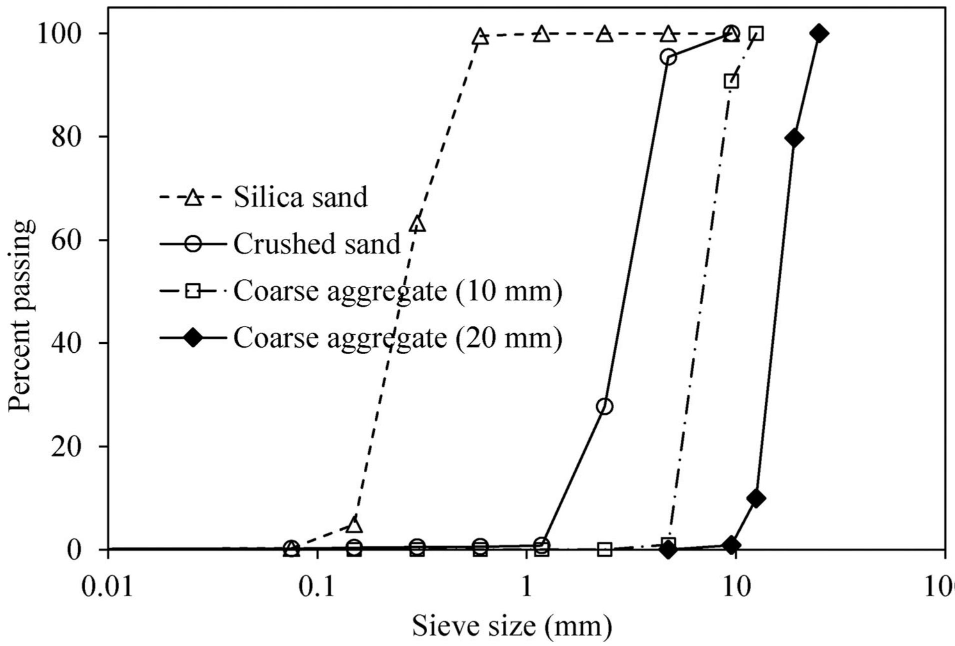

Figure 1. Particle size distribution of fine and coarse aggregates.

Table 3. Physical and mechanical properties of fibres.

	Fiber type	
Properties	Steel (SF)	Polypropylene (PP)
Length (mm)	60	50
Shape	Hooked ends	Crimped
Section dimensions (mm)	$\phi = 0.75$ (Circular)	1.0×0.6 (Rectangular)
Specific gravity	7.85	0.90
Tensile strength (MPa)	1225	550
Modulus of elasticity (GPa)	200	4.0

used for normal strength concrete, while “Mix2 (M2)” stands for HSC. The 28-day specified compressive strength was, respectively, 30 MPa and 60 MPa, for normal and high strength concretes.

In the production of mixtures of FRC, polypropylene (PP) and hooked-end steel fibres were utilised. For PP fibres, the tensile modulus of elasticity is 4 GPa and the tensile strength is 550 MPa. However, the steel fibres have a tensile modulus of elasticity of 200 GPa and a tensile strength of 1225 MPa. The PP fibres have dimensions of 50 mm length $\times$ 1 mm width $\times$ 0.6 mm thickness. PP and steel fibres have specific gravity of 0.9 and 7.85, respectively. Table 3 shows the properties of used fibres. Percentage of steel, polypropylene or hybrid fibres by volume (or by weight) used in the NSC and HSC mixtures are given in

Table 4. Fibre percent in different concrete mixes.

	Percentage of fibre by volume (by weight)			Amount of fibres added in mix (kg/m^3)	
Concrete mix	Polypropylene (PP)	Steel (SF)	Total	PP	SF
M1-P0S0	0.0 (0.00)	0.0 (0.00)	0.0 (0.00)	0.0	0.0
M1-P0S1	0.0 (0.00)	0.6 (1.96)	0.6 (1.96)	0.0	14.4
M1-P1S0	0.2 (0.29)	0.0 (0.00)	0.2 (0.29)	4.8	0.0
M1-P1S1	0.2 (0.29)	0.6 (1.96)	0.8 (2.25)	4.8	14.4
M2-P0S0	0.0 (0.00)	0.0 (0.00)	0.0 (0.00)	0.0	0.0
M2-P0S1	0.0 (0.00)	0.6 (1.96)	0.6 (3.05)	0.0	14.4
M2-P1S0	0.2 (0.00)	0.0 (0.00)	0.2 (1.96)	4.8	0.0
M2-P1S1	0.2 (0.29)	0.6 (0.00)	0.8 (2.25)	4.8	14.4

Table 4. In the designation of concrete mixtures in Table 4, the acronyms “M1” and “M2” stand for normal and high strength concrete mixtures, respectively. The acronyms “P0S0”, “P0S1”, “P1S0”, and “P1S1” designate, in turn, mixtures with: no fibres, steel fibres alone, polypropylene fibres alone, and steel/polypropylene hybrid fibres.

3.3. Specimen preparation

In preparation of concrete cylinders, concrete mixture was gradually cast into the moulds to alleviate segregation and concrete was vibrated carefully using a vibrator in order to mitigate the formation of voids with the specimen. A levelled concrete surface was ensured by finishing the top surface of the specimen using a steel trowel. The specimens were cured by immersing in a water tank for the entire period of 28 days.

3.4. Heating of specimens

Upon their removal from the curing tank, cylinder specimens were kept to dry in air for a period of 120 days before heating. This process was carried out to minimise the moisture in order to control the shrinkage strain and explosion that may occur due to the sudden increase in temperature. The specimens were exposed to different elevated temperatures with the help of a large-scale electrical oven having internal dimensions of $100 \times 100 \times 100$ cm. In the oven, specimens reached their target high temperature at a rate of 8 °C/min, which was the maximum heating rate that could be achieved by the oven. It is worth mentioning that the heating rate is in the range of the rates (1 to 10 °C/min) adopted in several past studies (Botte & Caspeele, 2017; Elsanadedy, 2019). Specific time versus temperature curves employed for each temperature exposure are presented in Figure 2. Presented in Figure 2 is also the European ISO 834-1999 (ISO. , 1999) standard fire curve. It is explicable from Figure 2 that the heating regime used in current study was at a rate that is slower than the standard fire curve. Nevertheless, this should not be considered critical as the standard fire testing does not necessarily represent the actual concrete heating in a real structure in a real fire event. The inside oven temperature was recorded with the help of thermocouples. Test cylinders were heated to high temperatures of 200 °C, 400 °C, and 600 °C with a soaking period of 3 h for ensuring uniform heating of inside the specimens. In order to ensure uniform exposure to the elevated temperature during heating, the specimens were not stacked and the specimens were kept at uniform spacing. After each heating exposure, the test cylinders were cooled at different cooling regimes.

3.5. Cooling regimes

Two different cooling regimes were used to cool the specimens that had been taken out from the oven. The first cooling regime was to let the specimens cool down at ambient temperature (26 °C) for a period of 24 h before it gets tested (Air Cooling process). For the second cooling regime, the heated cylinders were quenched by immersing in a water tank for 24 h, and then they were left out of the tank and kept in natural air for one month before the compressive strength test (Water Quenching method). The submergence of specimens in water for 24 h represent the limiting case of water spray on fire exposed concrete for long duration. Although the rest periods in the two schemes of cooling are different, the adopted procedure ensured similar moisture conditions at the time of testing for being able to compare

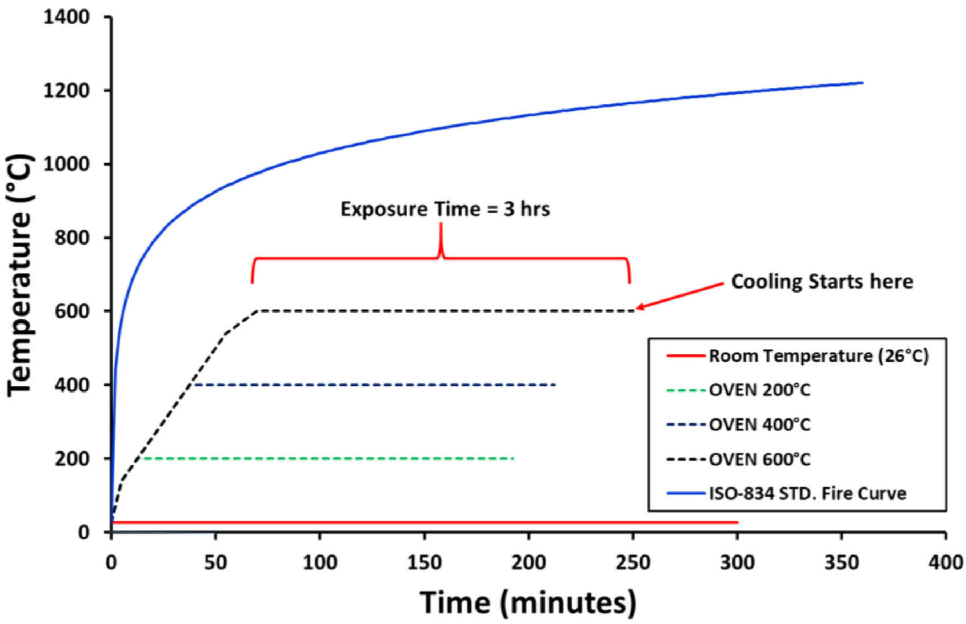

Figure 2. Individual time-temperature curves used in this research.

the residual strength of concrete for the two schemes. The humidity in the atmosphere being quite low, the absorption of moisture from air during the rest period is expected to be insignificant. The air cooling and water quenching methods were similar to the methods used in an earlier study (Abbas et al., 2017).

3.6. Testing procedure

In order to ensure that the cylinders are completely flat under the compression testing machine, the top surface was capped using sulphur. In order to measure the axial strain during the compression test, a compressometer comprising of two LVDTs (180° apart) attached to the specimen was utilised. Cylinders were exposed to uniform uniaxial compression up to failure and the concrete compressive strength was measured as per the procedure of ASTM C39 (ASTM, 2010).

4. Discussion of experimental results

In this section, the test results of different concrete mixtures are presented in terms of: effect of elevated temperature exposure on specimens' colour and structure, residual concrete strength after elevated temperature exposure in addition to axial stress-strain characteristics for heated specimens. These results are discussed below.

4.1. Effect of heating on cracking, spalling and surface color

Summary of post-heat view is shown in Figures 3 and 4 for NSC and HSC specimens, respectively. Up to the temperature of 600 °C, there was a slight apparent visual discolouration in the concrete. For specimens made of NSC, no visible damage in terms of cracking or spalling was noticed at the temperature of 200 °C, whereas at 400 °C and 600 °C, thermal cracking was noticed in concrete with no fibres (M1-P0S0), as seen in Figure 3. Similar observations were reported elsewhere for concrete under high temperature exposure (Al-Salloum et al., 2016; Elsanadedy et al., 2017; Freskakis et al., 1979). However, for mixtures with fibres (M1-P0S1, M1-P1S0, and M1-P1S1), thermal cracks were not identified on the surface (see Figure 3), as the addition of steel and PP fibres in concrete specimens produced a bridging effect between cracks.

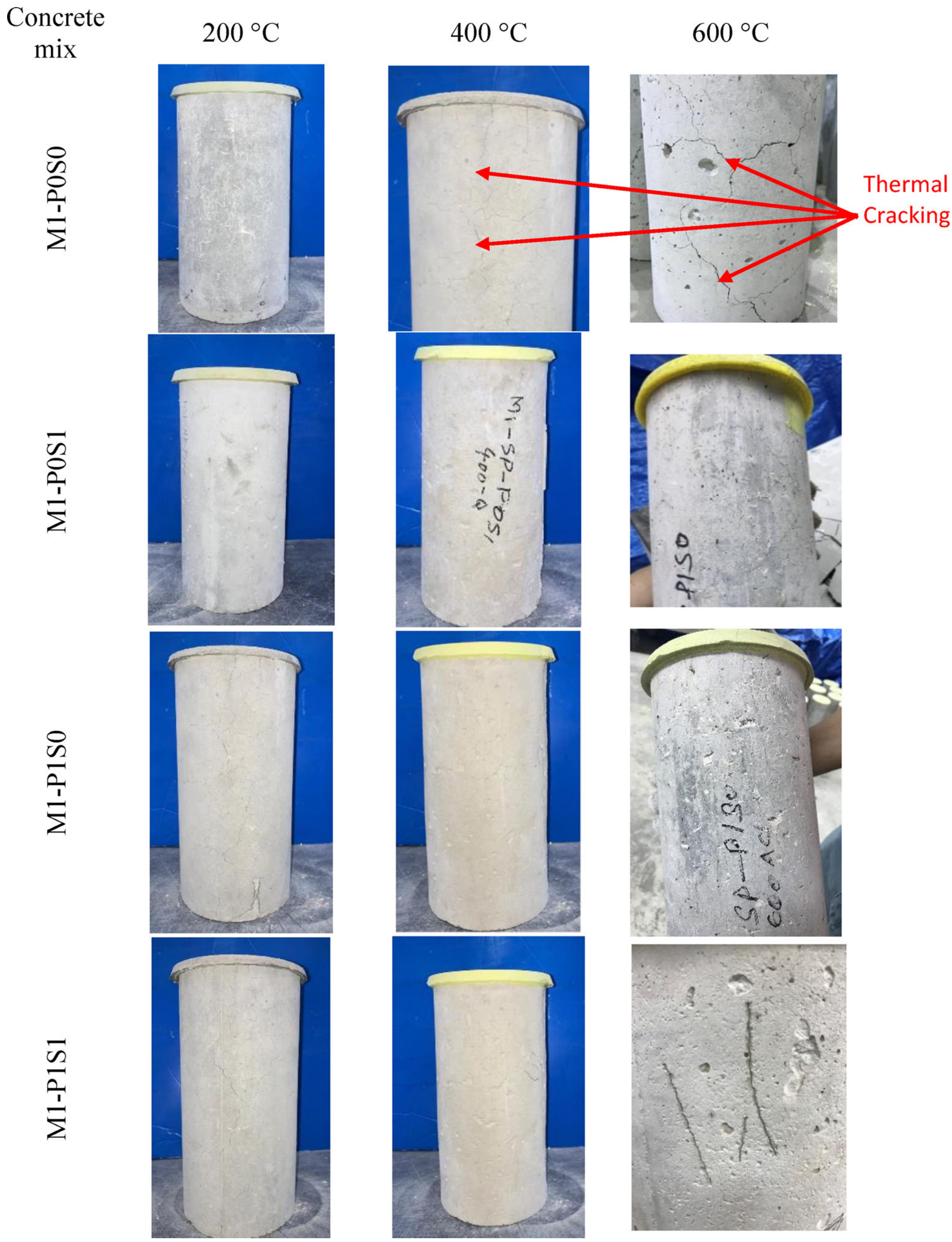

Figure 3. Post-heat view of NSC specimens.

For specimens made of HSC, no damage was evident for the exposure temperature of 200 °C. However, for HSC specimens containing no fibres (M2-P0S0), explosive spalling was noticed at 400 °C and 600 °C (Figure 4), which is primarily because of the denser microstructure of HSC. The low permeability of HSC does not allow the escape of water vapour, and therefore leads to increase in the pore pressure in the cementitious matrix, which is primarily accountable for the explosive spalling in high strength concrete. Yet, for HSC specimens M2-P0S1, M2-P1S0, and M2-P1S1, the addition of fibres in concrete mixtures showed improvement in spalling at high temperatures of 400 °C, and 600 °C. Polypropylene fibres, melting at about 170 °C, have been found effective in controlling the concrete spalling. This is because the

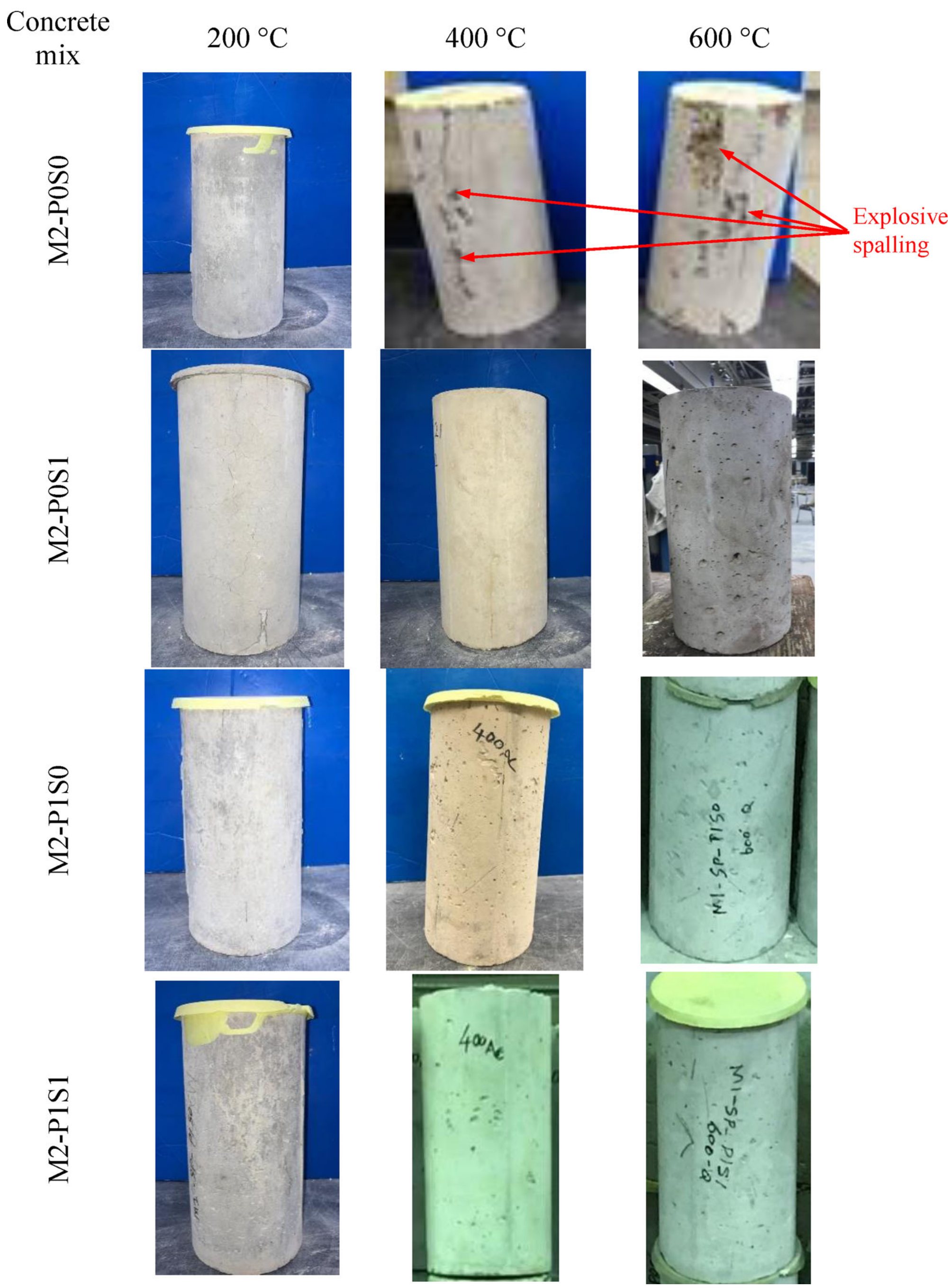

Figure 4. Post-heat view of HSC specimens.

melting of PP fibres generates supplementary capillary pore network within the concrete, thus allowing the relief of the water steam produced by the dehydration reactions (Phan, 2008; Varona et al., 2018).

4.2. Mode of failure

Figures 5 and 6, respectively, present representative samples of failure modes as a result of compression tests on NSC and HSC cylinders after their exposure to heating-cooling regimes. For specimens with or

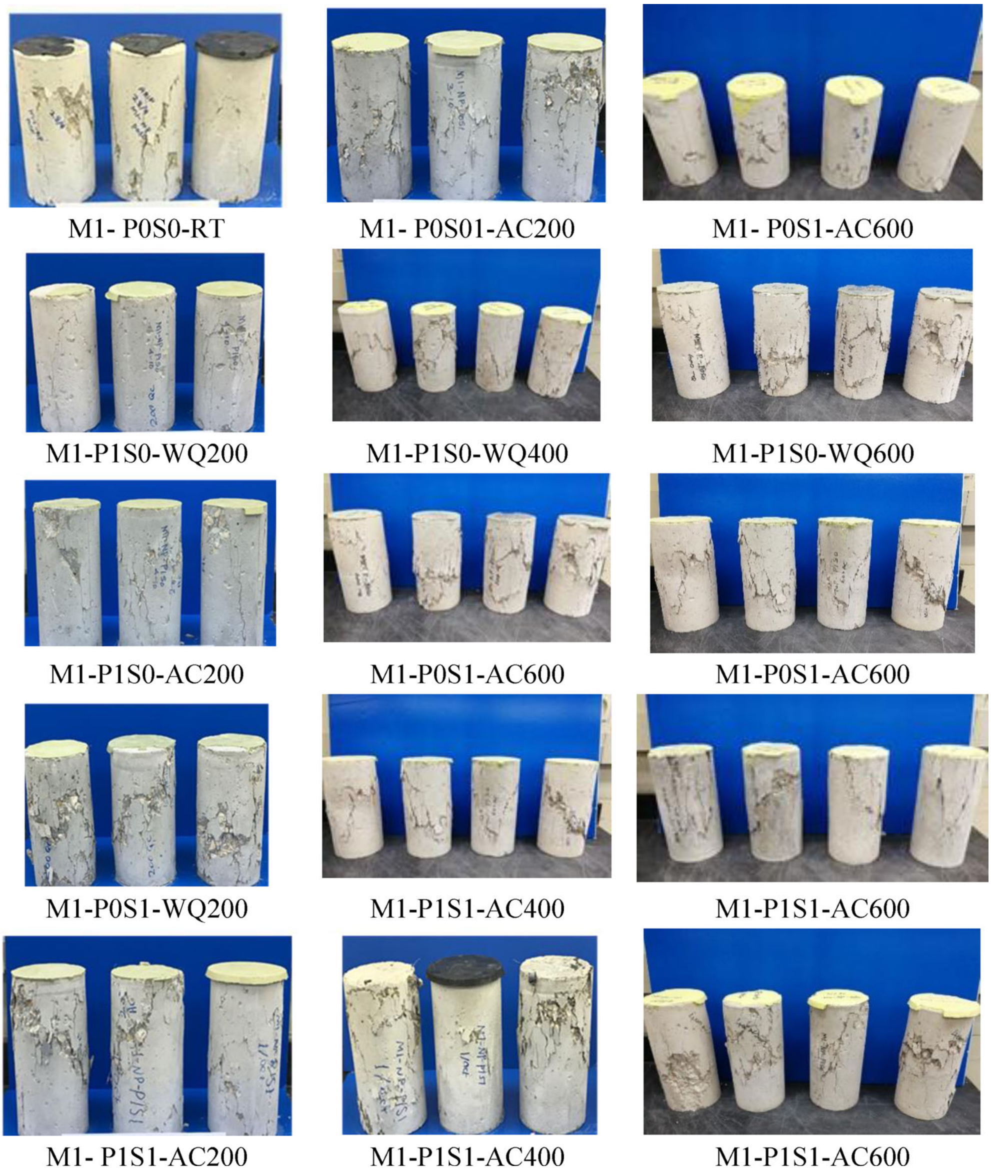

Figure 5. Failure mode of representative NSC specimens.

without fibres and tested without preheating (room temperature), it was generally noted that failure of HSC under compression loading was more brittle and explosive than NSC. However, for preheated specimens without fibres, and exposed to 200 °C, failure of HSC specimens was almost same as that for unheated specimens; however, after being exposed to 400 °C or 600 °C, failure became less explosive/brittle. For HSC specimens with PP fibres, and preheated at 200, 400, or 600 °C, the melting of the fibres and the consequent formation of porous media in the concrete core led to the ductile failure of specimens, as noted by Xiao and Falkner (Xiao & Falkner, 2006). For HSC specimens containing steel fibres alone, and preheated at 200 °C, failure was almost same as specimens without fibres. However, when they were preheated at 400 °C, or 600 °C, the failure became more ductile than specimens without fibres. Also, HSC containing steel fibres alone was more ductile than specimens with PP fibres. The failure mode of preheated HSC specimens with hybrid fibres was something in between steel fibres alone and PP fibres.

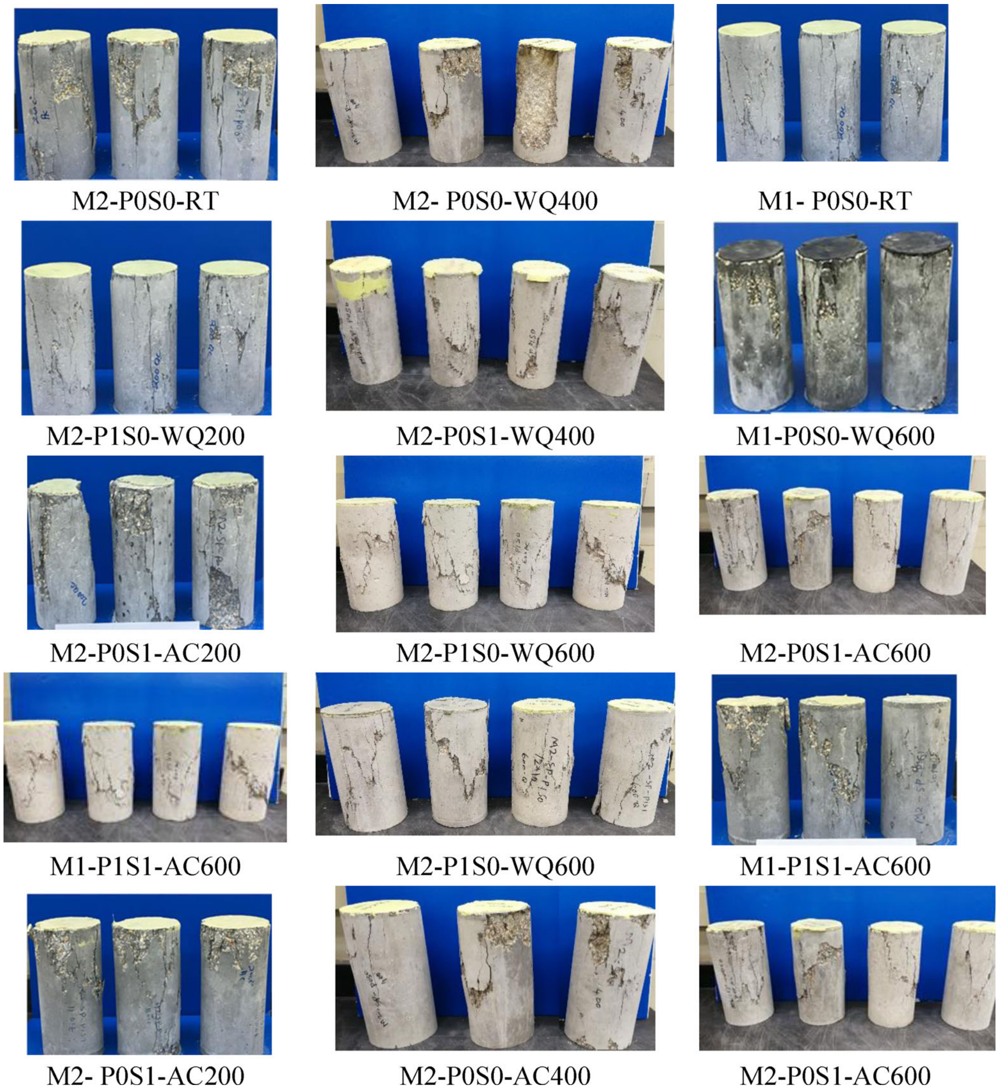

Figure 6. Failure mode of representative HSC specimens.

4.3. Residual compressive strength

As mentioned previously, all specimens were subjected to compression load after they were exposed to heating-cooling regimes. Table 5 shows summary of the test results for all concrete specimens in terms of residual compressive strength after heating. Percentage loss in compressive strength due to heating (with respect to their values at room temperature) is also given in Table 5. The experimental results of the repeated cylinders had small variation and the values presented in Table 5 are the average of the four cylinders. It is clearly evident that for all NSC and HSC concretes with and without fibres, the residual compressive strength decreases as the exposure temperatures increases. This is attributed to the loss of the moisture content and the fragmentation of the hydrated cement paste. From the table, it is identified that adding steel fibres alone enhanced compressive strength at room temperature by about 31% and 28% for NSC and HSC specimens, respectively. Enhancement in the compressive strength at room temperature because of the inclusion of PP fibres alone was limited to 6% for NSC cylinders; however, it reduced the compressive strength at room temperature for HSC specimens by about 3% (see Table 5). The incorporation of hybrid fibres (steel + PP) enhanced the compressive strength at room temperature by about 28% and 30% for NSC and HSC specimens, respectively. The high increase in the compressive

Table 5. Summary of test results of different concrete mixes**.

		Compressive strength of concrete* (MPa)						
			200 °C		400 °C		600 °C	
	Mix	Room temp.	AC	WQ	AC	WQ	AC	WQ
Normal strength concrete	M1-P0S0	32.4	26.8 (17.3%)	25.1 (20.1%)	24.5 (24.2%)	24.0 (25.9%)	13.0 (59.9%)	19.9 (38.6%)
	M1-P0S1	42.4	38.6 (9.0%)	37.7 (11.9%)	35.3 (16.7%)	33.2 (21.3%)	24.3 (42.6%)	30.5 (28.0%)
	M1-P1S0	34.5	30.6 (11.0%)	30.4 (11.1%)	28.7 (16.5%)	30.1 (12.3%)	14.4 (58.1%)	26.3 (23.5%)
	M1-P1S1	41.4	37.4 (9.7%)	38.7 (6.5%)	30.5 (26.3%)	30.1 (27.2%)	18.5 (55.2%)	30.9 (25.3%)
High strength concrete	M2-P0S0	63.3	53.2 (16.0%)	54.7 (13.6%)	38.7 (38.9%)	41.7 (34.3%)	32.7 (48.2%)	34.6 (45.3%)
	M2-P0S1	81.3	73.9 (9.1%)	74.4 (8.3%)	59.1 (27.3%)	61.1 (24.8%)	48.9 (40.8%)	52.4 (35.3%)
	M2-P1S0	61.2	55.1 (9.9%)	55.4 (9.5%)	42.7 (30.0%)	50.2 (17.9%)	30.8 (49.7%)	38.1 (37.9%)
	M2-P1S1	82.3	74.4 (9.5%)	74.7 (9.2%)	59.6 (27.6%)	64.4 (21.8%)	42.3 (48.6%)	48.2 (41.5%)

**AC = air cooling; WQ = water quenching.
*Value within brackets is the percentage decrease with respect to room temperature.

strength of concrete having steel fibres is due to the higher aspect ratio of steel fibres (i.e. 80) used in this study, which plays a significant role in efficiently utilising the strength of fibres. The range of increase in the compressive strength is in conformity with the past studies (Duzgun et al., 2005; Song & Hwang, 2004; Thomas & Ramaswamy, 2007; Yazıcı et al., 2007), wherein the incorporation of steel fibres in concrete is reported to have caused 8–37% increase in the compressive strength of concrete.

It is generally noted that adding of fibres in the concrete mixture reduced substantially the loss in the compressive strength owing to elevated temperature exposure. As discussed previously, fibres were able to control thermal cracking in NSC specimens and explosive spalling in HSC cylinders, and as a result, the damage caused by elevated temperature exposure in FRC specimens is considerably less than that in plain concrete specimens. Hence, the loss in the residual compressive strength of post-heated FRC cylinders are considerably less than plain concrete specimens.

The compressive strength results given in Table 5 indicate that air cooling of specimens generally resulted in more loss of strength compared to that of water quenching, especially for the exposure temperature of 600 °C. This may be attributed to keeping the heated specimens in the quenching water tank for about 24 h upon their removal from the oven, which aided in the hydration of anhydrous phases (owing to loss of water in the pores). This results in the formation of hydrates with improved bonding properties (Fares et al., 2010). In case of NSC specimens subjected to 600 °C, the percentage reduction in compressive strength was found to vary from 42.6% to 59.9% and from 23.5% to 38.6% for air cooling and water quenching, respectively. However, for HSC cylinders exposed to 600 °C, the percentage loss in strength varies from 40.8% to 49.7% and from 35.3% to 45.3% for the case of air cooling and water quenching, respectively. The range of percentage reduction in compressive strength is within the range reported in literature for plain and fibre reinforced (steel and steel + PP fibres) concrete exposed to 600 °C (Chen & Liu, 2004; Elsanadedy, 2019).

Conclusively, it is generally noted that both plain and fibre reinforced concretes lose a significant amount of their compressive strength, ranging from 23.5% to 59.9% for NSC and from 35.3% to 49.7% for HSC, once they are heated above 400 °C as seen in Table 5. However, after heating at 200 °C, the reduction in the strength is marginal for FRC (it varied from 11.0% to 15.4% for NSC and from 9.1% to 16% for HSC). The same findings were also observed by other researchers (Lie, 1992; Shaikh & Taweel, 2015; Sukontasukkul et al., 2010), where the FRC strength decreased slightly, when it was exposed to high temperature below 400 °C, but when it was exposed to more than 400 °C, the loss in residual strength was significant.

4.4. Stress-strain curves

One of the key properties needed for the assessment of the overall behaviour of concrete structures under fire condition is the stress-strain relationship for concrete. For NSC and HSC specimens tested in this study, axial stress versus axial strain curves were generated, as seen, respectively, in Figures 7 and 8. In calculating the axial stress for test specimens, the axial load was divided by the initial cross-sectional area of the cylinder. The average axial displacement recorded by LVDTs was divided by the gage length to get the axial strain.

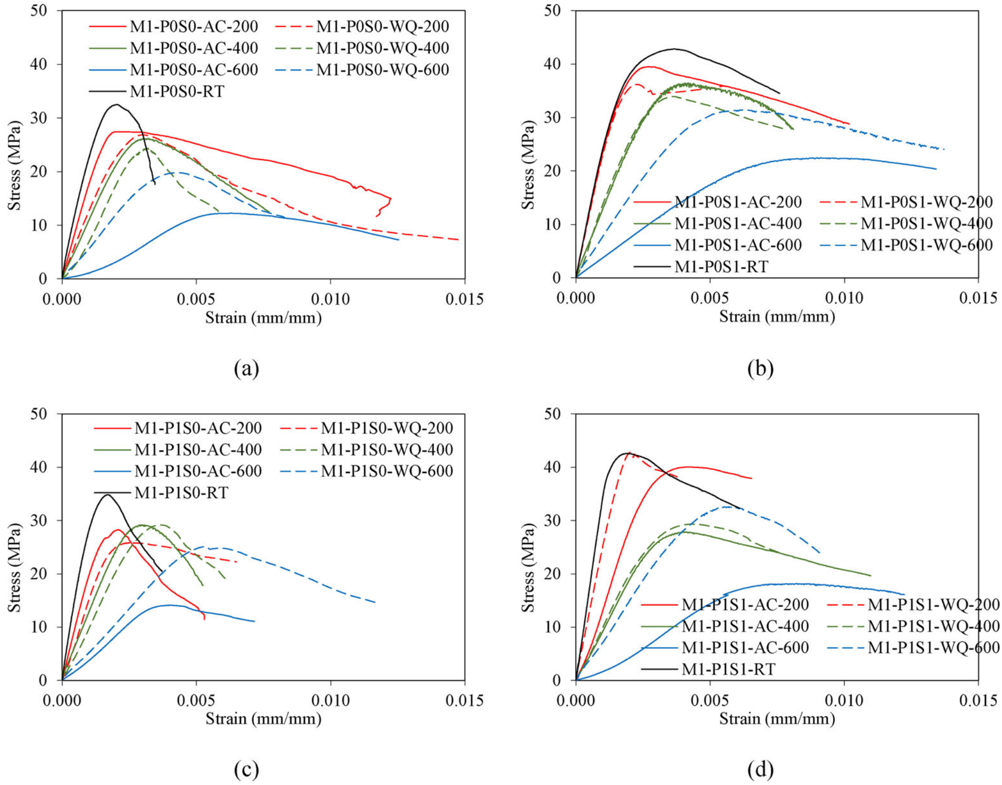

Figure 7. Stress-strain curves for NSC specimens: (a) Case of no fibres; (b) Case of steel fibres alone; (c) Case of PP fibres alone; (d) Case of hybrid (steel + PP) fibres.

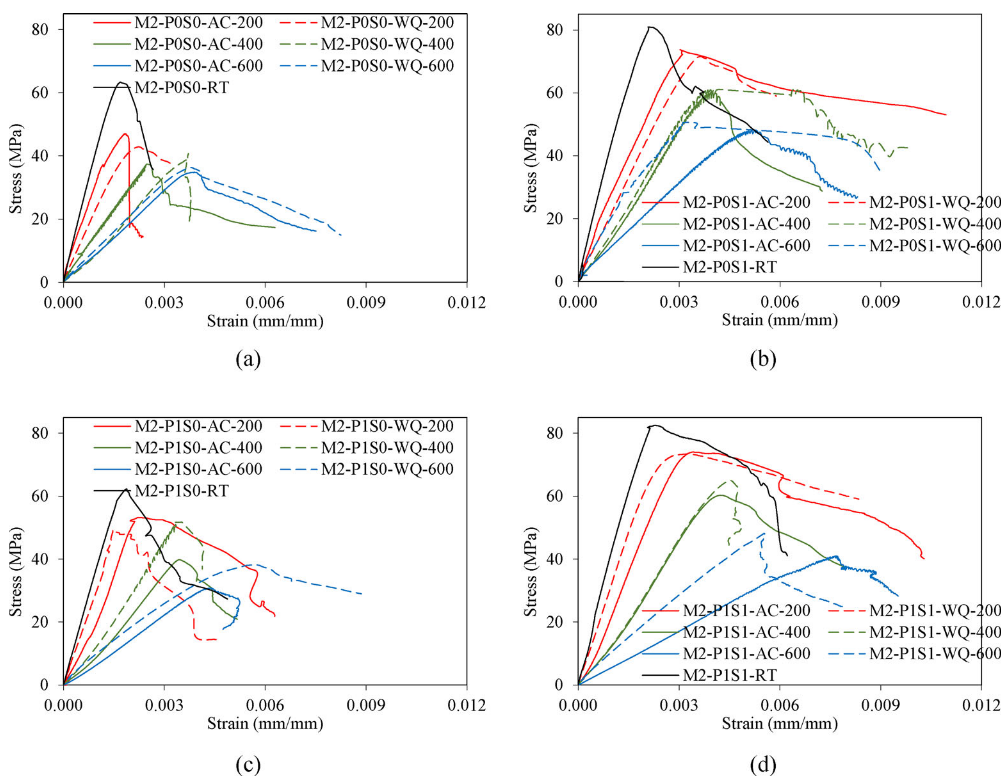

Figure 8. Stress-strain curves for HSC specimens: (a) Case of no fibres; (b) Case of steel fibres alone; (c) Case of PP fibres alone; (d) Case of hybrid (steel + PP) fibres.

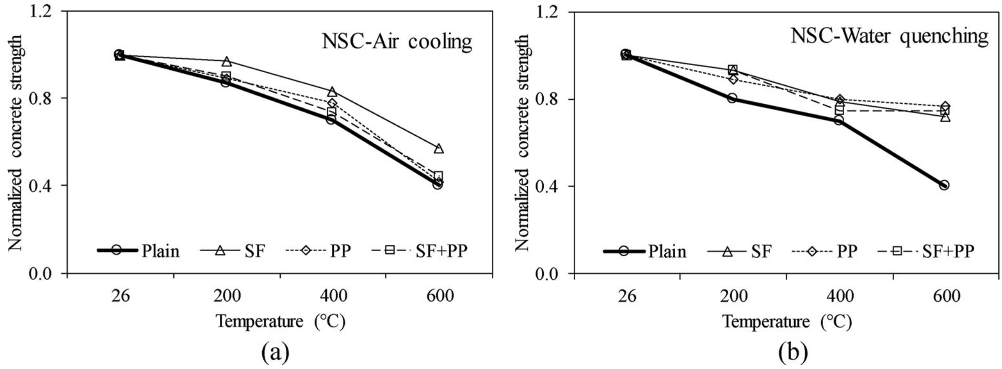

Figure 9. Effect of type of fiber on normalised concrete strength for NSC specimens: (a) Case of air cooling; (b) Case of water quenching.

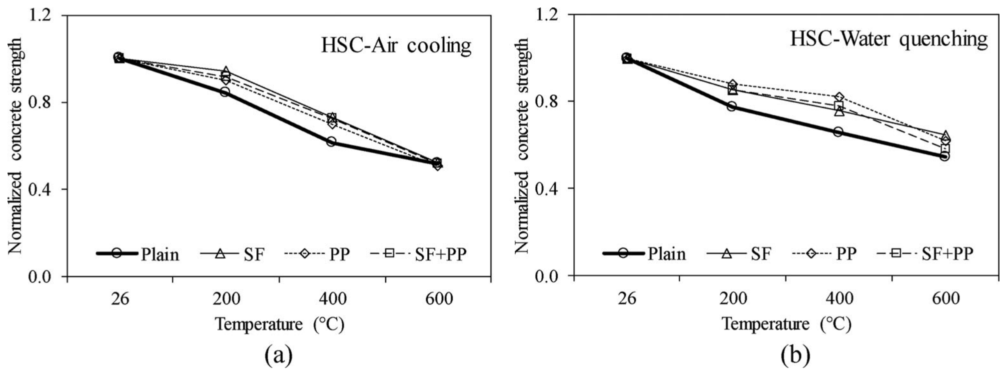

Figure 10. Effect of type of fiber on normalised concrete strength for HSC specimens: (a) Case of air cooling; (b) Case of water quenching.

The stress-strain relationships for different elevated temperature exposures show that the modulus of elasticity decreases with increase in the exposure temperature from ambient to 600 °C, as illustrated in Figures 7 and 8. The stress-strain curves reveal that for both plain and fibre reinforced concretes exposed to 600 °C, and cooled down under air cooling condition, the loss of stiffness is more as compared to the reduction in compressive strength. It is also noted that concretes having steel fibres exhibited better energy absorption capacity (represented by area under stress-strain curve of specimen) and elastic modulus after high temperature exposure, as compared with case of no fibres and cases of PP and hybrid fibres. This is because steel fibres have higher mechanical properties in terms of strength and elastic modulus than PP fibres and can also withstand higher temperatures. However, PP fibres may melt during the elevated temperature exposure. Also, the reduction in energy absorption capacity and modulus of elasticity due to heating was less for concretes containing hybrid fibres as compared to concretes having PP fibres alone. This is because adding steel fibres counteracted the weakness of the PP fibres (i.e. tensile strength and elastic modulus); whereas, PP fibres were able to reduce the porosity of the concrete mix (Kalifa et al., 2001).

4.5. Effect of type of fibre

In order to study the influence of type of fibres and their combination on the performance of test specimens after high temperature exposure, the exposure temperatures were plotted versus the normalised compressive strength of concrete (i.e. the ratio of the residual compressive strength of concrete after being exposed to elevated temperature to the compressive strength at ambient temperature) for different fibre types, as seen in Figures 9 and 10 for NSC and HSC specimens, respectively. These figures

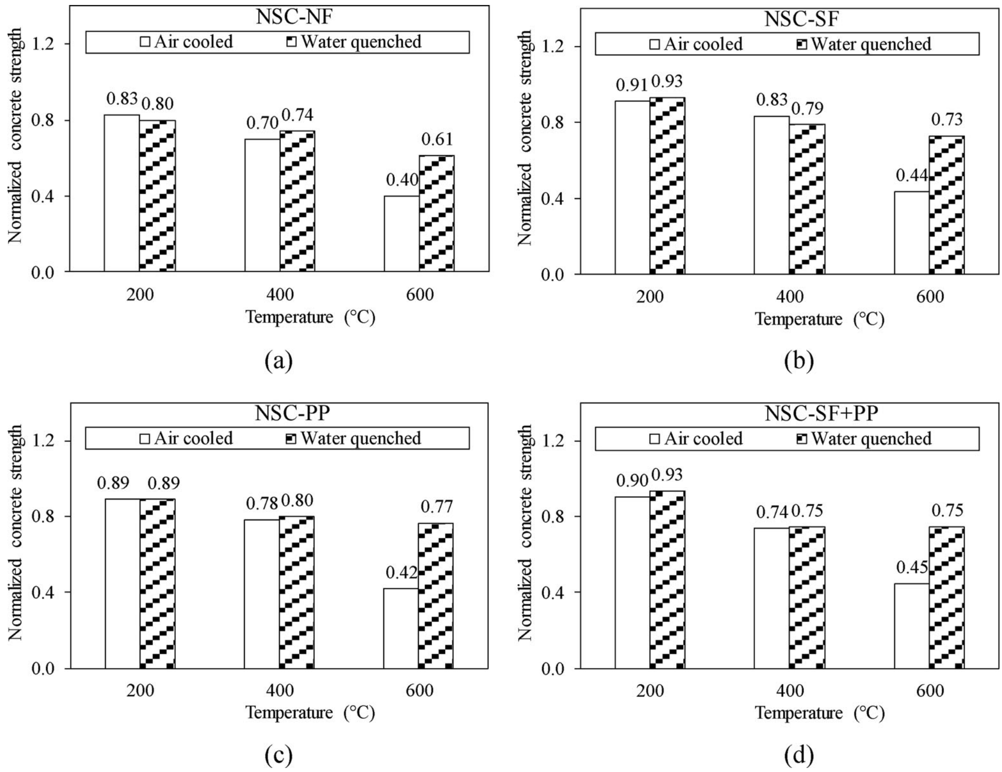

Figure 11. Effect of cooling regimes on normalised concrete strength for NSC specimens: (a) Case of no fibres; (b) Case of steel fibres alone; (c) Case of PP fibres alone; (d) Case of hybrid (steel + PP) fibres.

clearly show that the residual concrete strength is considerably affected by the addition of fibres in both NSC and HSC. Adding fibres in the concrete mixture reduced substantially the loss in its strength because of exposure to high temperatures. Hence, the reduction in the residual strength of post-heated FRC cylinders are considerably less than plain concrete specimens for both concrete grades. It is generally noted from Figures 9(a) and 10(a) that, for air cooling condition, the type of fibres in the order of decreasing efficiency are: steel fibres alone, hybrid (steel + PP) fibres, and lastly PP fibres alone. The steel fibres are the best due to the bridging effect. However, specimens cooled down using water quenching showed different performance as the type of fibres in the order of decreasing efficiency are: PP fibres alone, hybrid fibres, and lastly steel fibres alone (see Figures 9(b) and 10(b)). The better behaviour provided by PP fibres alone is attributed to melting of PP fibres at high temperature which created channels within the concrete media (Komonen & Penttala, 2003). This in turn allowed for water passage inside the channels, which aided in the rehydration of the anhydrous cement products (Kalifa et al., 2001; Peng et al., 2008; Phan, 2008).

4.6. Effect of cooling regime

So as to investigate the impact of cooling regimes on the performance of test specimens after high temperature environments, the exposure temperatures were plotted versus the normalised compressive strength for air cooling and water quenching, as seen in the bar charts in Figures 11 and 12 for NSC and HSC specimens, respectively. It is observed from these figures that the cooling methods affect the residual concrete strength. For NSC specimens, this effect is significant for the exposure temperature of 600 °C with the water quenching providing a considerably higher residual strength than air cooling by about 53% to 83% (Figure 11 and Table 5). However, the effect is marginal for temperatures of 200 and 400 °C for which the difference in residual strength for the two cooling regimes ranges from 0% to 5.7% (Figure 11 and Table 5). For HSC specimens, the cooling regime has a little impact on the residual

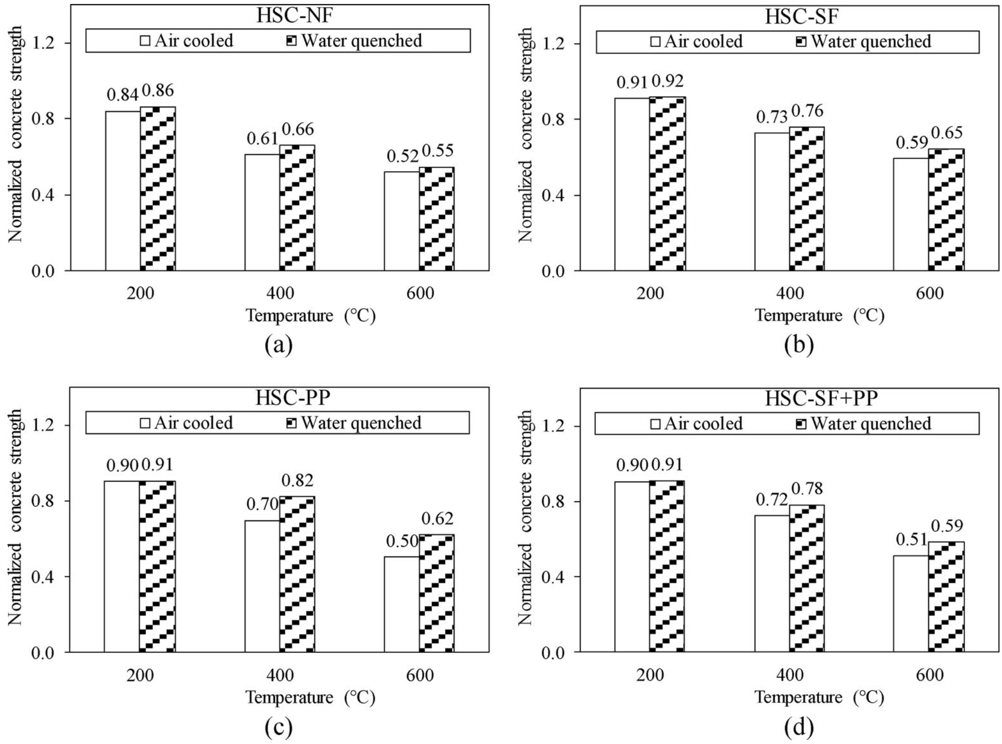

Figure 12. Effect of cooling regimes on normalised concrete strength for HSC specimens: (a) Case of no fibres; (b) Case of steel fibres alone; (c) Case of PP fibres alone; (d) Case of hybrid (steel + PP) fibres.

concrete strength for the three exposure temperatures, as presented in Figure 12. The water quenching provided a slightly higher residual strength than air cooling by about 1.1% to 17.1% (Figure 12 and Table 5). The higher residual strength for water quenched specimens than naturally cooled specimens could be attributed to keeping the heated specimens in the quenching water tank for about 24 h upon their removal from the oven (specimens were then left out of the tank and kept in the lab environment for almost one month prior to compression testing), which aided in the hydration of anhydrous parts (owing to loss of water in the pores). This results in the formation of hydrates with improved bonding properties (Fares et al., 2010). Moreover, water quenching resulted in a denser microstructure than natural air cooling. This is partly due to the re-hydration of the phases that were generated from the disintegration of hardened cement mortar in the concrete at elevated temperatures (Komonen & Penttala, 2003). The less enhancement caused by water quenching of HSC specimens may be attributed to the dense microstructure and in turn the less porosity of the high strength concrete media, as compared to NSC specimens, which had little effect on the rehydration of the anhydrous cement products.

It should be noted that the results of this research are in line with the outcome of Rao and Kumar (Rao & Kumar, 2015), in which the water quenched specimens gave more residual strength than air cooled specimens. Accounting for the developed microcracks and the porous microstructure, more water may be absorbed by the concrete at elevated temperature during the quenching process. Nevertheless, the results of current study contradict with the conclusions of other researchers (Botte & Caspeele, 2017; Chan et al., 2000; Luo et al., 2000; Peng et al., 2008; Poon et al., 2001; Yaragal et al., 2012). In their study, air cooling provided more residual strength than water quenching. The reason is that in their study the heated specimens were removed out of the water tank quickly after quenching and there was not enough time for the heated concrete to absorb water to help in the hydration of anhydrous phases of cement and the thermal shock caused by quick cooling produced a more reduction in strength than in the case without thermal shock (gradual cooling) (Chan et al., 2000). However, in current study, and as stated previously, heated cylinders were kept in the quenching water tank for 24 h following their removal from the oven. In brief, details of the quenching process have a major impact on the deterioration of concrete strength when exposed to elevated temperature. While rapid removal of heated specimens out of the quenching tank may result in more loss of residual strength than natural air cooling, keeping the heated concrete specimens in the water tank for longer duration before their removal may provide more residual strength than air cooling.

5. Conclusions

Influence of different cooling regimes on the residual strength of plain and fibre reinforced normal and high strength concretes following their exposure to the temperatures of 200, 400, and 600 °C were experimentally investigated. The prime conclusions of the experimental study can be summarised as follows:

1. At ambient temperature, adding volume fractions of 0.2% PP fibre, 0.6% steel fibre and 0.8% of hybrid fibres (steel and PP) increased the compressive strength of NSC by 6%, 31%, and 28%, respectively, while the increase in strength of HSC was 0%, 28% and 30% with the same fibre addition.
2. For both NSC and HSC specimens with or without fibres, no visible damage in terms of cracking or spalling was noticed at exposure temperature of 200 °C. For concretes containing no fibres, at 400 °C and 600 °C thermal cracking was observed on the surface of NSC specimens while explosive spalling was noticed for HSC cylinders. However, for mixtures with fibres, neither thermal cracks nor explosive spalling were depicted at exposure temperatures of 400 °C and 600 °C and the addition of fibres have been proven to control the cracking (or spalling) of concrete.
3. For both NSC and HSC specimens with or without fibres, the critical temperature for the noticeable reduction in compressive strength was 400 °C, and the reduction in strength became more dramatic when the temperature was increased from 400 to 600 °C.
4. Steel fibre-reinforced concretes showed lower compressive strength loss in addition to better elastic modulus and energy absorption capacity (area under stress-strain diagram) following their exposure to elevated temperature of 600 °C, in comparison with case of no fibres and cases of PP and hybrid fibres. This is because steel fibres have higher mechanical properties in terms of strength and elastic modulus than PP fibres and can also withstand higher temperatures. However, PP fibres may melt during the elevated temperature exposure. Also, the reduction of energy absorption capacity and modulus of elasticity due to heating was less for concretes containing hybrid fibres as compared to concretes with PP fibres alone.
5. Two cooling regimes have been investigated: air cooling versus water quenching. It is generally concluded that the reduction in concrete strength after high temperature exposure greatly relies on the type of cooling regime especially for NSC specimens at temperature of 600 °C. It is also concluded that details of the quenching process have a major impact on the deterioration of compressive strength of concrete after elevated temperature exposure. While rapid removal of heated specimens out of the quenching tank may result in more loss of residual strength than natural air cooling, keeping the heated concrete specimens in the water tank for longer duration before their removal may provide more residual strength than air cooling.

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Disclosure statement

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