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Effect of high temperatures on high performance steel fibre reinforced concrete

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Abstract

After being subjected to different elevated heating temperatures, ranging between 105 °C and 1200 °C, the compressive strength, flexural strength, elastic modulus and porosity of concrete reinforced with 1% steel fibre (SFRC) and changes of colour to the heated concrete have been investigated.

The results show a loss of concrete strength with increased maximum heating temperature and with increased initial saturation percentage before firing. For maximum exposure temperatures below 400 °C, the loss in compressive strength was relatively small. Significant further reductions in compressive strength are observed, as maximum temperature increases, for all concretes heated to temperatures exceeding 400 °C. High performance concretes (HPC) start to suffer a greater compressive strength loss than normal strength concrete (NSC) at maximum exposure temperatures of 600 °C. It is suggested that HPC suffers both chemical decomposition and pore-structure coarsening of the hardened cement paste when C–S–H starts to decompose at this high temperature. Strengths for all mixes reached minimum values at 1000 or 1100 °C. No evidence of spalling was encountered. When steel fibres are incorporated, at 1%, an improvement of fire resistance and crack [F.M. Lea, Cement research: retrospect and prospect. Proc. 4th Int. Symp. On the Chemistry of Cement, pp. 5–8 (Washington, DC, 1960).] resistance as characterized by the residual strengths were observed. Mechanical strength results indicated that SFRC performs better than non-SFRC for maximum exposure temperatures below 1000 °C, even though the residual strength was very low for all mixes at this high temperature. The variations with colour, which occured, are associated with maximum temperatures of exposure.

Keywords: High performance concrete; Steel fibre reinforced concrete; Saturation level; Mechanical properties; High temperature

1. Introduction

Fire represents one of the most severe risks to buildings and structures. A limited range of relevant studies has been previously carried out, especially for both high performance concrete and concretes incorporating steel fibres [2,3]. This paper reports a study of effects on, and the differences in, the mechanical properties of normal strength concrete (NSC) and high performance concrete (HPC) subjected to different maximum temperatures and with different initial saturation percentages. In addition, the effect of including 1% of steel fibre reinforcement was investigated for both NSC and HPC.

Steel fibre reinforced concrete (SFRC) has various excellent properties as a composite material; for instance, flexural, tensile and shear strength, toughness, impact resistance, crack resistance and resistance to frost damage can be improved by the use of steel fibre. SFRC has been commonly used in industry for tunnel lining and road paving. However, the main contribution of a small percentage of fibres is to increase the toughness of concrete. Throughout a concrete mix with steel fibres distributed in all directions, micro cracks which appear due to shrinkage as water evaporates from the concrete or due to applied loading, intersect with steel fibres which block their growth and provide higher tensile capacity. Although steel fibre may not offer any obvious advantage from a fire-endurance point of view, previous work [4] has shown that steel fibres can affect the spread of cracking, and hence potentially improve the performance of concrete, after exposure to high temperatures.

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Table 1
Properties of cement

Chemical composition (% by weight)		Physical properties	
CaO	66.90	Fineness (m^2/kg)	335.00
SiO_2	22.00	Specific gravity	3.17
Al_2O_3	5.70	Standard consistency (%)	31.00
Fe_2O_3	3.30	Setting (min)	
MgO	1.00	Initial	80.00
SO_3	2.50	Final	125.00
Na_2O (sodium oxide)	0.47	Soundness (mm)	0.10
Bogue compound composition (%)		Compressive strength (N/mm^2)	
C_3S	54.90	2 days	22.70
C_2S	21.70	7 days	40.70
C_3A	9.50	28 days	58.90
C_4AF	10.00		

For fibre content higher than 1.5% by volume of concrete, however, the improvement in mechanical properties may be insignificant or reduced. Many of the current applications of fibre reinforced concrete involve around a 1% content and thus the 1.0% figure was chosen for this research.

Limited information also exists on the performance of high performance concrete (HPC), including the influence of steel fibres in HPC. In fact, with the further development and usage of HPC, doubts about the fire resistance of HPC have emerged. For this reason HPC comparisons with NSC were included in the study.

2. Previous research

Since the work of the research pioneers, Lea and Stradling [5,6], who in the 1920s investigated the influence of high temperatures on concrete strength, a number of research studies related to the fire resistance of concrete have been carried out. Initially, research paid attention to the chemical and physical changes within the concrete, such as the decomposition of calcium hydroxide ($Ca(OH)_2$), the incompatibility at the aggregate–cement paste boundary and the crystal transformation of quartz (SiO_2). Since 1970, the influences of different environmental and material factors on the fire resistance of concrete have been investigated, including measurements following the employment of thermally stable aggregates for concrete subjected to high temperatures.

The actual behavior of concrete exposed to high temperatures is dependent on many factors, including constituent materials and the environmental factors: rate of heating, maximum temperature attained, duration of exposure at the maximum temperature, method of cooling after the maximum temperature is reached, post-cooling treatment and the level of applied load [7,8]. The material factors include the types of aggregates, the types of mineral admixtures and the saturation level of the concrete.

Heating rate and maximum temperature reached are the two main environmental factors that have a significant influence on concrete properties. Under heating, the dehydration of the C–S–H phase, the thermal incompatibility between the aggregates and cement paste, and the pore pressure within the cement paste are the main detrimental factors [7–10].

High temperatures, in general, cause deterioration in properties such as compressive strength, flexural strength, modulus of elasticity, bond with reinforcement. An additional specific characteristics of HPC is a tendency towards explosive spalling at high temperatures. It is probable that the dense hardened cement paste (HCP) prevents free water from escaping, causing considerable internal vapor pressure, which often results in spalling.

Experimental results which report on the influence of moisture of concrete on strength are very limited. In fact, fire resistance depends on many factors as stated above. It can be stated more generally that moisture is a most important factor for determining the structural behavior of HPC at higher temperatures. The higher the rate of rise in temperature and the lower the permeability of the concrete, the greater the risk to HPC of explosive spalling. As is discussed below, the strength loss of concrete after exposure to higher temperatures has been found greater for initially saturated concrete than for initially dry concrete.

Past work has shown that there is also a progressive decrease in the modulus of elasticity after heating concrete up to between 50 and 800 °C [11]. The extent of the decrease in the modulus depends on the aggregate used, and generalization is difficult, but the strength and modulus variation trends with temperature are of the same form.

3. Research significance

The object of this research study is to provide useful input to aid the provision of a fire resistance rating for SFRC.

The main objectives were: (1) to investigate the effects on steel fibre reinforced concrete (SFRC) of exposure to high temperatures, up to 1200 °C; (2) to add to our knowledge of the behavior of HPC, also in relation to that of NSC, at high temperatures; (3) to establish a relationship between fire exposure and mechanical properties by studying the behavior of SFRC exposed to the high temperatures that occur during a fire; (4) to determine the effects of initial saturation level on concrete subjected to high temperatures (both SFRC and non-SFRC).

To obtain an insight into the residual mechanical concrete properties, the pore size distribution after heating was determined by the mercury intrusion porosimetry (MIP) technique. The results of the microscopic investigations provided good

Table 2
Superplasticizing admixture dosage and workability of test concretes

	Dosage of superplasticizer by weight with respect to cement (%)	Slump range (mm)	Slump description
M-1	–	30 to 60	Normal
M-2	–	60 to 180	High
M-3	1.50	30 to 60	Normal
M-1F	1.00	30 to 60	Normal
M-2F	1.20	60 to 180	High
M-3F	1.57	60 to 180	High

Table 3
Concrete mix proportions by weight and their relative compressive strengths

Cement (kg/m^3)	Aggregate		Sand (kg/m^3)	Water (kg/m^3)	W/C ratio (kg/m^3)	Without steel fibre		With steel fibre (1% of concrete volume)	
	20 mm (kg/m^3)	10 mm (kg/m^3)				Compressive strength at age of 28 days (MPa)		Compressive strength at age of 28 days (MPa)	
311	780	390	665	205	0.66	M-1	39	M-1F	45
366	771	385	623	205	0.56	M-2	53	M-2F	60
458	938	469	408	147	0.32	M-3	99	M-3F	110

Values reported are average of 10 tests.

explanation of the change in macro behavior of SFRC in comparison to non-fibre concretes.

4. Experimental details

4.1. Materials

In this research study, the binder used was locally available ‘Green Island’ cement that is equivalent to ASTM Type I. It was in compliance with the limits of the British Standard BS EN 197-1:2000 and with a strength class of 52.5N. The chemical compositions and physical properties are given in Table 1.

The coarse and fine aggregates [12] used were of crushed granite and river sand of zone F grading complying with BS 882:1992. The two coarse aggregates were of nominal sizes 20 mm and 10 mm.

Dramix cold drawn stainless steel fibre of 25-mm length and 0.40 mm diameter (aspect ratio = 62.5) was used for the concrete reinforcement. This type of steel fibre has hooked ends; bright coating; a standard tensile strength (≤ 1700 N/mm^2); a melting temperature of 1538 °C; a density of 7.87 g/cm^3 and is loose in form at delivery.

The amount of superplasticizer added to achieve the specified workability was determined by slump tests complying with BS 1881: Part 102: 1983. The dosages range from 1.0% to 1.6% by weight with respect to cement and the levels of workability are given in Table 2. Slump values between 57 and 150 mm were recorded for the concrete test mixes. Daracem 100 superplasticizer was selected, which is commercially available and is in the form of an aqueous solution dark brown in appearance. This superplasticizer is Naphthalene based; it contains no added chlorides and is formulated to comply with specifications for Chemical Admixtures for Concrete, BS 5075 Part 3: 1985 and ASTM Designation: C494 as a Type F or a Type G Admixture. Its specific gravity is approximately 1.20 and the solid content is 40%.

Table 4
Scope of testing program

Program A: Control specimens (not heated)

Types of concrete specimens	Total number of mixes	Mixes	7 days strength	14 days strength	28 days strength
			Number of samples required for each mix		
Cubes	6	M-1, M-2, M-3, M-1F, M-2F, M-3F	3	3	3
Beams	4	M-1, M-3, M-1F, M-3F	3	3	3
Cylinders	4	M-1, M-3, M-1F, M-3F	–	–	3

Program B: Heated specimens

Types of concrete specimens	Total number of mixes	Mixes	Number of initial saturation levels for each mix	Number of maximum heating temperatures for each mix and saturation levels	Number of samples required for each case	Total number of specimens to be heated	Number of not heated control specimens required
Cubes	6	M-1, M-2, M-3 M-1F, M-2F, M-3F	3	9	3	486	18
Beams	4	M-1, M-3, M-1F, M-3F	1	9	3	108	12
Cylinders	4	M-1, M-3, M-1F, M-3F	1	6	3	72	12

Table 5
Some typical mass values of concrete specimens for the determination of saturation levels

Concrete mixes	Initial saturation levels (%)	SSD W_0 (g)	Fully dried concrete mass W_d (g)	R-value $(W_0-W_d)/W_0$	W_t $(W_0-W_0R)(1-M)$ (g)
M1	20	2324.3	2175.5	0.06	2138.4
	60	2333.2	2295.9	0.02	2239.9
M2	20	2336.5	2216.9	0.05	2187.0
	60	2339.4	2309.5	0.01	2264.5
M3	20	2503.7	2407.6	0.04	2383.5
	60	2502.2	2478.2	0.01	2442.1
M1F	20	2443.4	2349.6	0.04	2326.1
	60	2435.5	2412.1	0.01	2377.0
M2F	20	2494.1	2398.3	0.04	2374.4
	60	2508.4	2484.3	0.01	2448.2
M3F	20	2529.3	2464.5	0.03	2448.4
	60	2523.5	2507.3	0.01	2483.1

Values reported are average of 3 tests.

4.2. Scope of tests and mix proportions

The study has been performed on 6 mixtures: three of non-steel fibre reinforced concrete (M-1, M-2 and M-3) and three of steel fibre reinforced concrete (M-1F, M-2F and M-3F). M-1 and M-2 are normal strength concretes, whereas M-3 is a high performance concrete. The proportion of steel fibre added was 1.0% of concrete volume. The mix proportions [13] and the related 28-day concrete compressive strength results are summarized in Table 3.

All specimens were stored in the laboratory at a room temperature of 25 ± 3 °C. For each test, all reported results are the average of three measurements. A total number of 240 groups of three concrete specimens (162 groups of cubes, 54 groups of beams and 24 groups of cylinders), were exposed to each of the nine maximum temperature levels and cooled to room temperature before testing. Each concrete mix batch also included 3 cube specimens, which were cured normally to provide a reference to the ultimate compressive strength of unheated concrete. Cube specimens were subjected to a compressive test, beam specimens to a flexural test and cylinder specimens to an elastic modulus test. These mechanical properties, for the heated specimens, were compared with the unheated reference concrete that had been stored and tested at room temperature, in order to establish the effect of heating on strength and elasticity loss.

Three different saturation percentages of 20%, 60% and 100% were selected for 100 mm cubes only. For the 100 × 100 × 400 mm beam specimens and 100 dia. × 200 mm cylinder specimens, only 100% saturated specimens were prepared. The scope of the tests is shown in Table 4.

4.3. Sample preparation for strength tests

Three representative concrete cube specimens from each mix batch were chosen after their 28 days of water curing. Their weights and densities were measured and recorded under a saturated surface-dry condition (SSD). Concrete cubes were then placed in a furnace and dried at a temperature of 105 °C (221°F) until they reached constant dry weights and the weight of total internal evaporable water content was then obtained for each one. Dry weights of the concrete specimen were used as the base for the determination of the saturation levels within other concrete specimens. Some extracted typical test results from the weight measurements that were taken to control the saturation levels of concrete specimens are given in Table 5.

4.4. Saturation level determination method

For establishment of saturation levels in concrete, refer to Ref. [17].

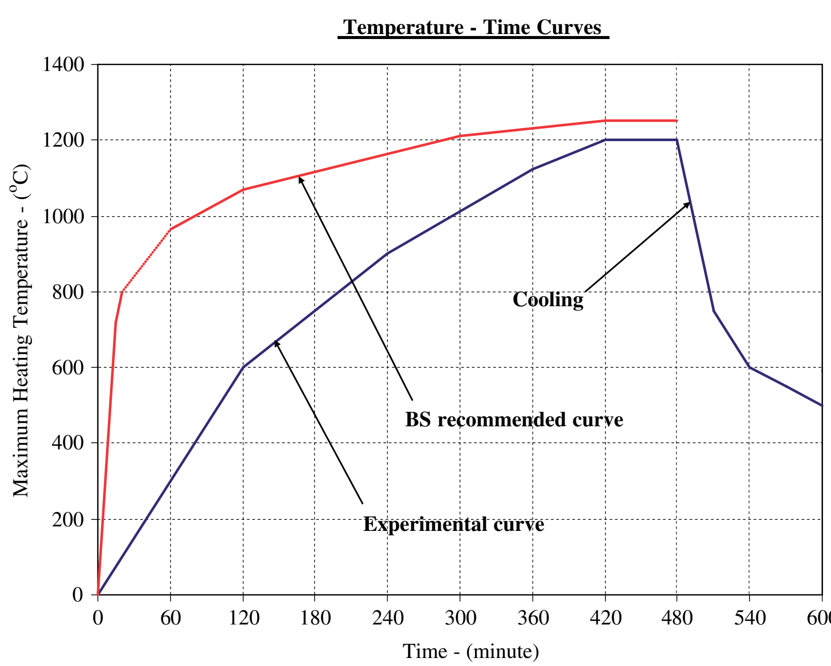

Fig. 1. Experimental and British Standard recommended temperature–time curves.

Table 6
Compressive strength after heating (MPa)

Concrete mixes	Initial saturation levels (%)	Maximum heating temperatures (°C)									
		25	105	200	300	400	600	800	1000	1100	1200
M-1	20	–	40	38	36	32	24	14	6	5	11
	60	–	37	35	34	30	21	12	6	5	10
	100	39	35	32	30	28	18	10	4	4	6
M-2	20	–	50	46	39	36	34	17	8	8	15
	60	–	47	39	38	33	29	16	8	7	15
	100	53	45	36	34	32	22	13	6	6	10
M-3	20	–	101	99	96	94	56	33	12	11	19
	60	–	98	97	93	87	56	30	12	11	18
	100	99	96	95	90	85	50	26	8	19	15
M-1F	20	–	46	42	38	35	32	16	8	7	14
	60	–	42	38	36	32	24	14	7	6	13
	100	45	41	34	32	30	20	12	5	5	8
M-2F	20	–	60	58	54	50	37	19	8	9	18
	60	–	53	50	47	44	36	18	8	8	17
	100	60	50	48	45	40	33	17	6	8	14
M-3F	20	–	112	106	102	100	69	37	14	12	19
	60	–	107	104	96	94	69	33	14	11	19
	100	110	100	97	94	90	65	28	12	10	17

Control specimens at laboratory temperature about 25 °C.
Values reported are average of 3 tests.

4.5. Saturation condition of specimens

The 100 mm cube specimens were taken from the water-curing tank at 28 days. The water curing procedure was carried out in accordance with Section 10 of CS 1:1990 at a temperature of 27 ± 3 °C. The cubes were then transferred to a furnace with a temperature of 105 °C (221°F) and weighed intermittently until their weight reached the value equivalent to the targeted saturation levels [14,15]. The specimens were then sealed immediately with polyethylene film in retaining their saturation levels until the heating test was carried out.

4.6. Specimens for mercury intrusion porosimetry test

Samples obtained from cores taken from the crushed concrete cubes were soaked in acetone to stop further hydration, in preparation for MIP tests. They were then dried at 60 °C for 24 h before the measurement. Special precautions were taken to ensure no coarse aggregates were included in the samples.

4.7. Heating regime

The simulated fire test was carried out by heating the 100 mm cube specimens with their different designated saturation percentages in an electrical furnace. The polyethylene film sealing was removed immediately before the specimens were placed in the electric furnace.

The time–temperature curve of the furnace used is compared with the standard curve recommended in BS476: Part20: 1987 shown in Fig. 1. The heating rate of the experimental curve is less than that of the BS recommendation, which is a limitation of the equipment available. However, it seems likely that the

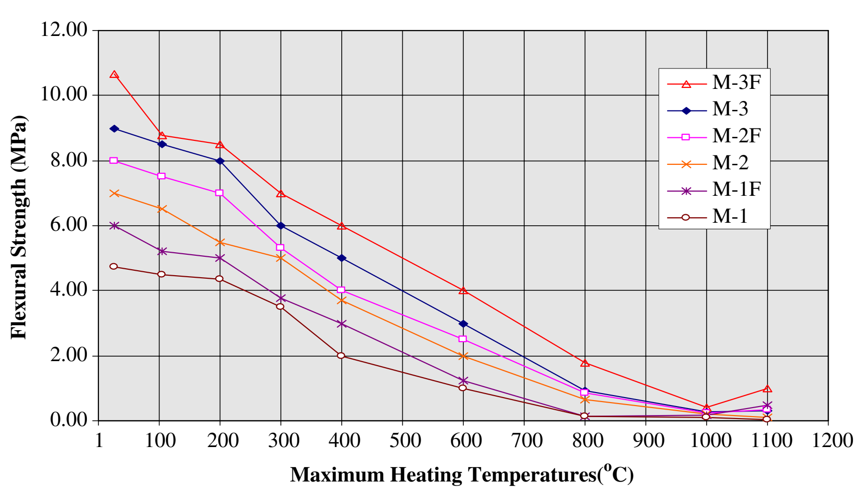

Fig. 2. Flexural strength vs. maximum heating temperature at 100% saturation.

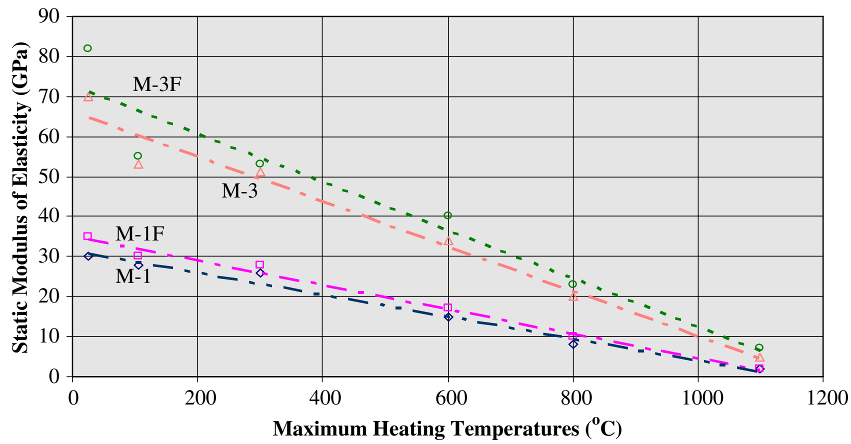

Fig. 3. Static modulus of elasticity vs. maximum heating temperatures.

effect on the ultimate results would be relatively small since the duration of exposure at the maximum temperature was maintained for as long as 1 h.

Specimens with the different saturation levels of 20%, 60% and 100% were exposed to each maximum temperature level and cooled to room temperature before mechanical properties tests were conducted.

5. Test results and discussion

5.1. Testing procedure and methods

All compression, elasticity and flexural tests were conducted according to the relevant British Standards.

5.2. Temperature effects on compressive strength

The compressive strength results for heated specimens are shown in Table 6. It can be observed that the reduction in strength is noticeable, but not disastrous, if concrete is not heated above 400 °C. However, the reduction in strength is considerable between 400 and 800 °C but even then remains useful at around the 30 MPa mark for HPC. At 1000 °C maximum temperature, all mixes have negligible strengths of between 4 MPa and 12 MPa, and at 1200 °C, between 6 MPa and 19 MPa.

For all three mixes, the addition of fibres gives small increases of about 5% to 15% regardless of mix and regardless of maximum temperature of heating. Thus, the addition of fibres to concrete is of some compressive strength benefit.

Increased saturation percentage decreases strength for all mixes and this remains the case regardless of the maximum temperature of heating. Fully saturated concretes are 5 to 12 MPa weaker than concrete 20% saturated.

5.3. Temperature effects on flexural strength

Fig. 2 shows that for all values of maximum temperature, steel fibre reinforced concretes have better flexural strength than concretes without steel fibres, although there is no significant difference in flexural strength between SFRC and the non-fibre mixes after exposure to a temperature of 1000 °C. The reduction in flexural strength occurs progressively from 105 °C up to about 1000 or 1100 °C. For concrete exposed to a maximum heating temperature of 1100 °C, it is observed that in some cases, the residual flexural strength is a little greater than that for concrete exposed to 1000 °C.

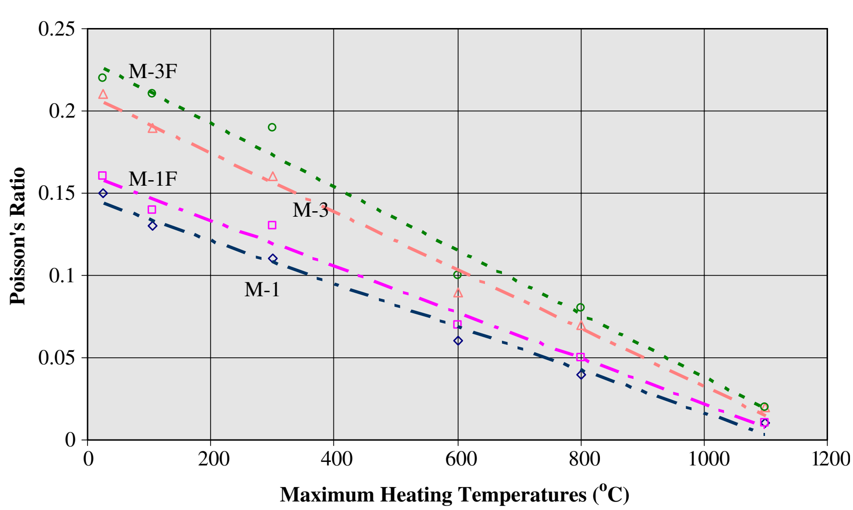

Fig. 4. Poisson's ration vs. maximum heating temperatures.

Table 7
Visual inspection on cracking

	Concrete mixes	Initial saturation levels (%)	Maximum heating temperatures (°C)									
			25	105	200	300	400	600	800	1000	1100	1200
Non-SFRC	M-1	20	N.O.	N.O.	N.O.	N.O.	N.O.	H and m	M	S	S	S
		60	N.O.	N.O.	N.O.	N.O.	N.O.	H and m	M	S	S	S
		100	N.O.	N.O.	N.O.	H	H	m	M	S	S	S
Non-SFRC	M-3	20	N.O.	N.O.	N.O.	N.O.	N.O.	H	m	S	S	S
		60	N.O.	N.O.	N.O.	N.O.	N.O.	H	m	S	S	S
		100	N.O.	N.O.	N.O.	N.O.	H	H and m	M	S	S	S
SFRC	M-1F	20	N.O.	N.O.	N.O.	N.O.	N.O.	N.O.	m	S	S	S
		60	N.O.	N.O.	N.O.	N.O.	N.O.	N.O.	m	S	S	S
		100	N.O.	N.O.	N.O.	N.O.	N.O.	H	M	S	S	S
SFRC	M-3F	20	N.O.	N.O.	N.O.	N.O.	N.O.	N.O.	H and m	S	S	S
		60	N.O.	N.O.	N.O.	N.O.	N.O.	N.O.	H and m	S	S	S
		100	N.O.	N.O.	N.O.	N.O.	N.O.	N.O.	m	S	S	S

Results reported are average of at least three specimens.
Symbols for cracking: N.O.=No obvious cracks observed, S=Serious cracks observed, m=Micro cracks observed, M=Macro cracks observed, H=Hair cracks observed.

5.4. Temperature effects on static modulus of elasticity

Fig. 3 illustrates the effects of different heating temperatures on the modulus of elasticity. It can be seen from the results that the loss in modulus of elasticity, for concrete mix M-1 exposed to between 105 °C and 1100 °C, increased from 7% to 93%. For concrete mix M-1F, the loss in elasticity ranges from 14% to 94%. For concrete mix M-3, the loss in elasticity ranges from 24% to 93%. For concrete mix M-3F, the loss in elasticity varies from 33% to 91%. Concrete mixes reinforced with steel fibres consistently show higher values of modulus of elasticity than non-fibre mixes, of between 2 and 6 GPa.

The values of modulus of elasticity given here for the higher temperatures, of course, do not reflect the true modulus of elasticity of the fired material. For this, it would be necessary to obtain a piece of uncracked, unfissured fired material and test that. In fact, our test specimens were standard cylinders and the *E* measurements given represent merely the slope of the stress–strain curve for already cracked material.

5.5. Temperature effects on Poisson's ratio

Since Poisson’s ratio is related to modulus of elasticity, the Poisson’s ratio for concrete cylinders heated at different temperatures up to 1100 °C is also determined and given in Fig. 4.

Fig. 4 indicates that for HPC incorporating steel fibres, for the M-3F mix, Poisson’s ratio starts at 0.22 and reduces to 0.02 after high temperature exposure. For HPC without steel fibres for the M-3 mix, Poisson’s ratio starts at 0.21 and ends at 0.02. For NSC with steel fibres for the M-1F mix Poisson’s ratio starts at 0.16 and ends at 0.01. For NSC without steel fibres for the M-1 mix, Poisson’s ratio starts at 0.15 and ends at 0.01.

5.6. Moisture effects on compressive strengths

Table 6 also shows the relationship of compressive strength to saturation percentage after heating. It can be seen that there is nearly always a slight reduction in compressive strength as saturation percentage increases for different maximum exposure

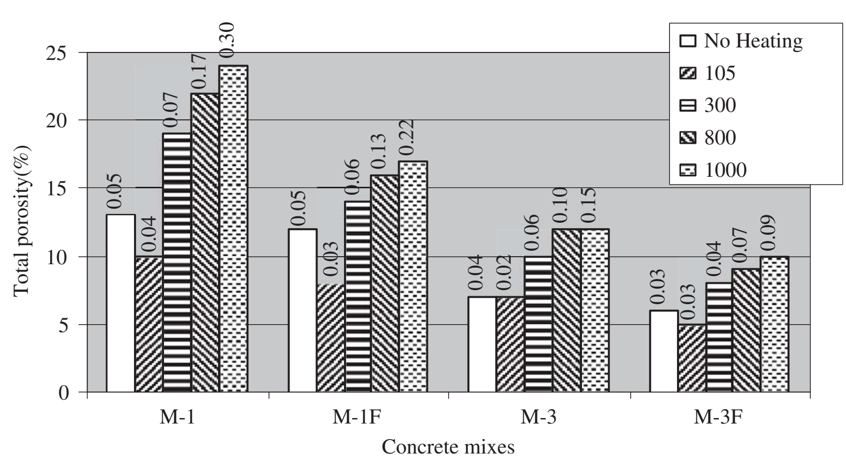

Fig. 5. Increase in porosity of concrete, with 20% saturation, after heating to various temperatures, percent. (Average pore diameters are marked on top of columns, × 10^{-6} m).

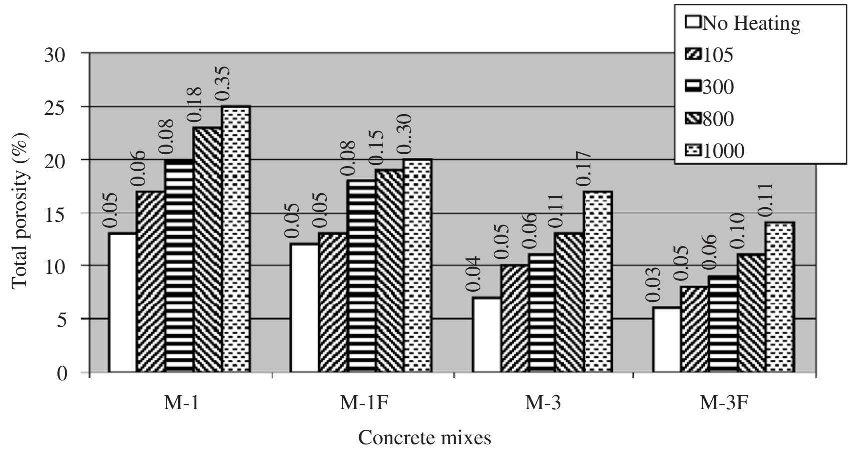

Fig. 6. Increase in porosity of concrete with 60% saturation, after heating to various temperatures, percent. (Average pore diameters are marked on top of colums, $\times 10^{-6}$ m).

temperatures. Thus, moisture of concrete specimens at the time of the firing test affects the compressive strength. Concrete specimens with higher moisture leads to a slightly lower strength as quantified in Table 6. The loss in strength may be due to internal pressure effects in the voids, which has resulted in local damage to the void structure.

5.7. Visual inspection of concrete specimens

5.7.1. Crack analysis

Cracking observations are summarized in Table 7. Networks of hairline cracks were observed on non-steel fibre reinforced concrete specimens heated to a maximum temperature of 300 °C. With further increases in maximum temperatures exceeding 400 °C, a considerable number of hairline cracks were found becoming deeper when heated to a maximum temperature of 600 °C. For maximum temperatures beyond 600 °C, severe cracking occurs on concrete specimen surfaces. It is probable that cracking is initially due to the normal thermal expansion of cement paste causing local breakdowns in bond between the cement and the aggregate. As the maximum exposure temperature rises, drying shrinkage eventually becomes much greater than thermal expansion as water is driven off. These two opposing actions progressively weaken and crack the concrete [1]. For steel fibre reinforced concrete, it is observed that hairline cracks first appeared at about 600 °C and severe cracking occurs at temperatures exceeding 800 °C. Thus, it is believed that the presence of steel fibres can delay the spread of cracking.

SFRC specimens after being subjected to very high temperatures beyond 1100 °C, suffered severe shape deformation. However, non-fibre concrete exposed to a very high temperature of 1200 °C suffered only minor shape deformation but severe cracking; concrete at these temperatures is generally very friable and porous.

5.7.2. Change of colours in Concrete with Temperature Effects

From visual inspection, it is revealed that a variation with colour, the induction of colour change in concrete is associated with maximum temperature of exposure and loss in mechanical

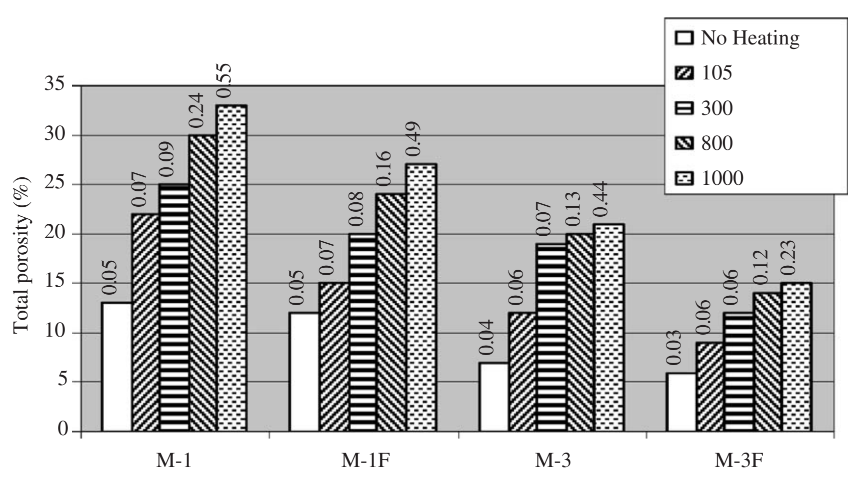

Fig. 7. Increase in porosity of fully saturated wet concrete after heating to various temperatures, per cent. (Average pore diameters are marked on top of columns, $\times 10^{-6}$ m).

properties. For concrete composed of granite as aggregate, as in our tests, after exposure to different high temperatures, a permanent colour change is induced. The colour sequence is approximately as follows: gray at 300 °C or below, yellowish gray between 400 °C and 600 °C, then pink up to 800 °C, reddish brown between 1000 °C and 1100 °C, and buff on surface with golden brown or orange brown at 1200 °C. Generally, concrete past the gray stage is friable and porous.

5.7.3. Microstructure analysis

Figs. 5–7 illustrate the porosity of the concrete mixes for each of the three initial saturation levels and the average pore diameters after heating to various maximum heating temperatures. Results show that the porosity increases as the maximum heating temperature increases. Concrete mixes containing steel fibres showed lower porosity and lower average pore diameters than non-fibre concrete. It was also observed that increases in saturation percentages at the time of heating results in higher porosity percentages in concrete. Thus, concrete specimens subjected to higher maximum temperatures were found to have higher intrusion volumes and larger pore sizes.

5.7.4. Spalling of concrete

There was no evidence of spalling for concrete specimens during the simulated fire tests even though spalling has been identified as a problem with HPC by other researchers [16–18]. Saturation level and strong dense hardened cement paste preventing moisture escape under high temperatures and internal pressures are two main factors thought to be responsible for the spalling of concrete. The absence of spalling in our tests might be one result of the slower rate of rise of temperature. Of course steel fibres are also likely to protect those particular mixes against spalling.

6. Conclusions

It is concluded that incorporating steel fibre remains beneficial to concrete which has been exposed to high temperatures up to 1200 °C confirming that at 1%, steel fibre content has no deleterious effect on heated concrete. In fact, the inclusion of steel fibre in the concrete mix leads to an improvement in mechanical properties and a better resistance to heating effects. The improved mechanical properties normally found are maintained whatever maximum temperature is experienced by the material.

After exposure to high temperatures, though properties worsened for both HPC and NSC, HPC consistently showed a higher overall residual compressive strength and flexural strength and a higher modulus of elasticity than NSC. HPC mixes started to suffer more significant compressive strength losses at a maximum exposure temperature of 600 °C, a superior performance to the 400 °C for NSC.

Generally, HPC with a higher initial saturation percentage leads to a greater decline in strength and larger pore sizes after exposure to high temperatures compared with lower saturation percentages. After heating beyond 800 °C, destruction of specimens becomes greater and mechanical strength reaches a minimum after exposure to 1000 °C.

The results of temperature on modulus of elasticity of concrete show a loss in static modulus of elasticity of concrete with the increase of heating temperature; concrete mixes reinforced with steel fibres have between 2 and 6 GPa higher values of modulus of elasticity than non-fibre mixes. Poisson's ratio is little affected by steel fibres but is marginally greater than the identical mix without fibres. The value of Poisson's ratio drops with increased exposure temperatures to negligible values at 1000 °C.

In all cases, the porosity of the concrete varies with saturation level and with maximum temperature of exposure: Strength results correlated positively with porosity as would be expected, higher porosity corresponding with lower strengths.

In addition, it can be concluded that the research study has identified a correlation that exists between the final permanent colour of heated concrete and the maximum temperature reached. The permanent fired colours produced might usefully be studied for different aggregate types as a potential forensic tool for estimating temperatures which have been reached in real fires. As temperature increases, the colour of concrete changes; by knowing that certain colours correspond with specific temperature ranges, the temperature of fire can be estimated easily. With the information of fire temperature, the residual mechanical properties of concrete elements, which had been reached in a real fire at different places in the structure, could therefore be traced from the mechanical test results. Thus, it seems possible to develop the use of colour to determine what maximum temperature a specific element of concrete has been exposed to after a real fire and to estimate the residual mechanical properties of the element.

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