Study of High Strength Concretes at raised Temperature up to 200 °C : Thermal Gradient and Mechanical Behaviour

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ABSTRACT

Data on the high strength concrete behaviour at high temperature is of concern in predicting the safety of buildings and constructions in response to certain accidents or particular service conditions. Investigations were carried out on the behaviour of four concretes (two high strength concrete with and without polypropylene fibres, one lightweight aggregate concrete and one normal strength concrete). The four groups of specimens were subjected to identical testing conditions. After a heating – cooling cycle at 200 °C, thermal gradient and thermal stability, compressive strength, modulus of elasticity and splitting tensile strength were analysed. Comparisons and interesting conclusions were drawn about the thermal stability at high temperature and the residual mechanical properties of the tested concretes.

INTRODUCTION

Concrete is recognised as an excellent thermal resistant building material. With the uses of concrete in certain building constructions and industrial facilities, in nuclear reactor containment building and in nuclear waste packages, additional information is required on the effect of high temperatures. An understanding of high temperature behaviours is necessary for designers to determine the required concrete thickness for structures and to determine if cracking or spalling is likely to occur in situation of high temperature exposure. Much has been learned about the engineering properties of high strength silica fume concrete, mainly the properties of this concrete in case of fire [1, 2, 3, 4]. There is a need of data concerning the properties of this concrete in case of low heating rate like in nuclear applications.

Research studies have been done in the field of concrete under service or accidental conditions in nuclear applications where concrete is exposed to high thermal and mechanical stresses which are unusual in conventional structural engineering. The high temperatures have an influence not only on the stress-strain behaviour of concrete but also induce heat and moisture transfers. When designing concrete structures to be subjected to high temperature, it is necessary to set the reasonable characteristic values, taking into account the temperature dependency of the mechanical properties of concrete.

Kuznetsov and Rudzinskii [5] studied high temperature heat and mass transfer in a concrete layer used for biological protection of nuclear reactors at critical heat loads. About the hygrothermal consequences following a loss of coolant accident (LOCA) on a nuclear containment vessel, the accident conditions consist of a rise from ambient to a maximum temperature of 160 °C and a pressure of 650 kPa. This rise is followed by a dwell and a cooling that last several days [6]. Kontani and Shah [7] published detailed results on the pore pressure and temperature distribution in concrete at a sustained high temperature (171 °C) following a loss of coolant accident. It is admitted that, in the case of an accident, the temperature inside the concrete containment vessel may increase but may not exceed 180 °C. Furthermore, compared with fire standard curve the concrete heating rate is very low. Moreover, in the nuclear waste management field, research works were recently performed on the thermo-hydro-mechanical behaviour at high temperatures (60 to 450°C) of concretes for interim storage structures [8, 9, 10].

The main objective of this investigation was to study the effect of elevated temperature on the mechanical properties of four concretes intended for nuclear applications : a high strength concrete incorporating polypropylene fibres, a high strength concrete without fibres, a concrete incorporating lightweight aggregates and a normal strength concrete. The applied heating curve was not the standard fire curve but a heating-cooling cycle close to RILEM recommendations [11]. In this report, results on thermal gradient and moisture escape during the heating, strength and modulus of elasticity after heating are summarised, so as to correctly estimate the characteristics of high strength concrete structures subjected to a high temperature. The study adds important data to existing information on the behaviour of high strength concrete under elevated temperatures.

RESEARCH GOALS

The following conclusions were drawn from reviewing the published literature : - the properties of high strength concrete vary with temperature differently than those of normal strength concrete [3], - lightweight aggregate concrete retains higher proportions of the original modulus of elasticity at high temperature than normal weight aggregate concrete [12], - polypropylene fibres affect the release of moisture from the fibre concrete and reduce the local internal vapour pressures caused by water vaporisation; there are concerns about the moisture escape and fibre melting during the concrete heating up [4, 13], - there seems to be a critical temperature level between 100 and 200 °C in which the effects of transient thermal and hydric phenomena reach a maximum whatever concrete is used [14, 15, 16].

Consequently, comparative tests were performed on two high strength concretes and two normal strength concretes (see Table 1) at the University of Cergy Pontoise. The basic design of three concrete mixes was the same, with the amount of cement kept at 450 kg/m^3 level. The three mixes contained the same mortar matrix (same quantities of sand, cement, silica fume, water). The water/cementitious materials ratio was 0.30 in the three mixes. A French CEM 1 - OPC cement (with a strength of 52.5 MPa), two classes of crushed silico-calcareous aggregates (4 to 10 mm and 8 to 20 mm) and 0 to 5 mm silico-calcareous sand were used. One concrete mix contained expanded clay aggregate. A superplasticizer (naphtalene-sulfonate) and a condensed silica fume also were used in three mixes. Polypropylene fibres were 13 mm long.

Notations : CC = Control High Strength Concrete, FC = High Strength Concrete incorporating Polypropylene Fibres, LC = Lightweight aggregate concrete, OC = Ordinary Concrete.

For the OC concrete, the amount of cement was smaller and water cement ratio was 0.43. This concrete incorporated 8/20 coarse silico-calcareous gravel, 4/12 fine silico calcareous gravel and 0/4 silico-calcareous Seine sand. The superplasticizer was Glenium 27. Physical and mechanical residual properties after high temperature exposures of a similar concrete were previously studied by the French Atomic Energy Commission (CEA) [9].

Table 1. Composition of concrete mixes CC, FC, LC and OC (kg/m^3)

Concrete type	CC	FC	LC	OC
Coarse gravel 8/20	815	815		780
Fine gravel 4/10	318	318		420
Sand 0/5	782	782	782	750
Lightweight Aggregate			494	
Polypropylene Fibre		2		
CPA CEM I 52.5 Cement	450	450	450	350
Silica Fume	45	45	45	
Water	150	150	150	150
Superplasticizer	12	12	12	1.75
Water/binder	0.30	0.3	0.30	0.43
Weight	2569	2571	1930	2452

TEST SCHEDULE

Lightweight aggregate was premoistened (with a part of the water of the mix proportions) in order to prevent segregation in the concrete due to its low density. The aggregates, cement and silica fume were first mixed for two or three minutes. Then water and superplasticizer agent mixed therewith were added to the mix. The mixing was then continued for an additional three minutes. All cylinders were cast in two layers. The specimens were cast in cardboard moulds and were compacted by using a vibrating table. K type thermocouples were positioned at the centre of the freshly mixed concrete specimens. The specimens were capped with plastic sheet. Plastic sheet in the interior part of the cardboard mould and plastic cap sealed the specimens to ensure mass curing. Then the specimens were transferred to the moist-curing room until required for testing. After 30 days of curing, the specimens were tested. Mechanical tests were performed in order to determine residual compressive strength, modulus of elasticity and splitting tensile strength.

In accordance with the RILEM specifications for mechanical testing of concrete at high temperatures, the four groups of specimens were subjected to identical testing conditions. The test specimens were subjected to a temperature of 200 °C, and the behaviour compared to that observed at 20 °C. During the heating period moisture in the test specimens was allowed to escape freely. The tests were carried out on 11x22 cm and 16x32 cm concrete normalized cylinders. The heating equipment was an electrically-heated kiln. Temperatures at the centre and at the surface of the specimens were monitored by type K thermocouples connected to a data acquisition unit. Cylinders from each mixture were placed in the kiln and the kiln was heated to the desired temperature of 200 °C at a rate of 1 °C/min. After 7 hours at that temperature, the kiln was turned off. It was allowed to cool before the specimens were removed to prevent thermal shock to the specimens. The rate of cooling was not controlled. The compressive strength tests were performed according to NF P 18-406 French specifications. The data were obtained for an age of 30 days up to 40 days. At least three specimens were tested for each parameter.

RESULTS AND DISCUSSION

1. Thermal stability

The aggregates were supposed to be thermally stable within the temperature range of exposure. The unstable component of the concretes under investigation was the cement paste. No spalling was observed during the heating-cooling cycles. It seems that the water vapour pressure and the thermal stresses were lower than the material strength for the four tested concretes. Neither the aggregates nor the cement mortar did spall during heating up to 200 °C.

2. Temperature curves

Heat-test specimens were exposed in the kiln from room temperature to 200 °C. The duration of a full cycle was about fifteen hours. Surface temperature measurements were carried out on three points at the surface of the specimens (see Fig. 1). Then the surface average temperature was calculated in respect to RILEM recommendations. Thermocouples inserted in the concrete specimens allowed to measure temperature at the centre of the specimens. The typical heating–cooling cycles are shown in Figure 2.

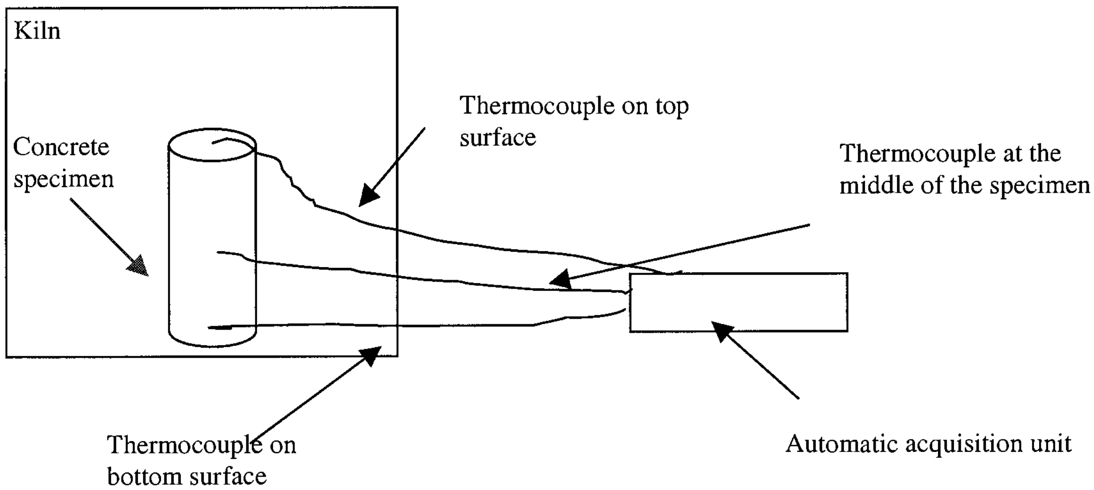

Fig. 1 Location of surface temperature measuring points

During heating the temperature differentials values indicated that heat transfer through the lightweight aggregate concrete (LC) was lower than that through the high strength concrete used as reference (CC). The temperature differentials through the concrete specimen thickness depended on the aggregate type. The temperature differentials could be as high as 92 °C (more than 11 °C/cm of concrete) for LC concrete. In the temperature range 120 – 200 °C heat transfer through FC specimens was greater than that through CC specimens. These experimental results showed clearly that the adding of polypropylene fibres to the high strength concrete mix lead to less thermal gradient in the concrete element at elevated temperature. Figure 3 shows that during heating the temperature differentials in FC and OC specimens increased, reached a maximum ($\Delta\theta$ = 72 to 76 °C) then decreased. A lower thermal gradient resulted in lower risk of concrete spalling. Furthermore, in the LC and CC specimens water dehydration lead to high thermal gradient.

During heating up to 200 °C there was no decrease of thermal gradient. The increase of thermal gradient in LC and CC specimens (in consequence an increase of thermal stresses) could contribute to concrete spalling. Ordinary concrete specimens presented lower thermal gradients than high strength concretes specimens. This may be due to the fact that free water escaped more easily from ordinary concrete than from high strength concretes.

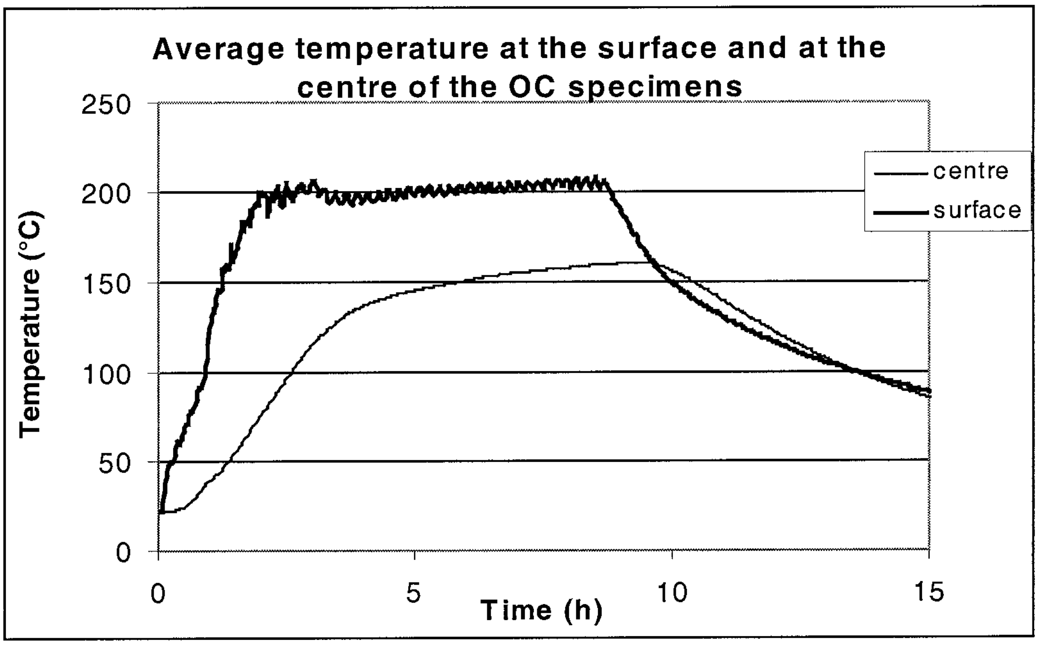

Fig. 2 Measured temperatures during a heating – cooling cycle

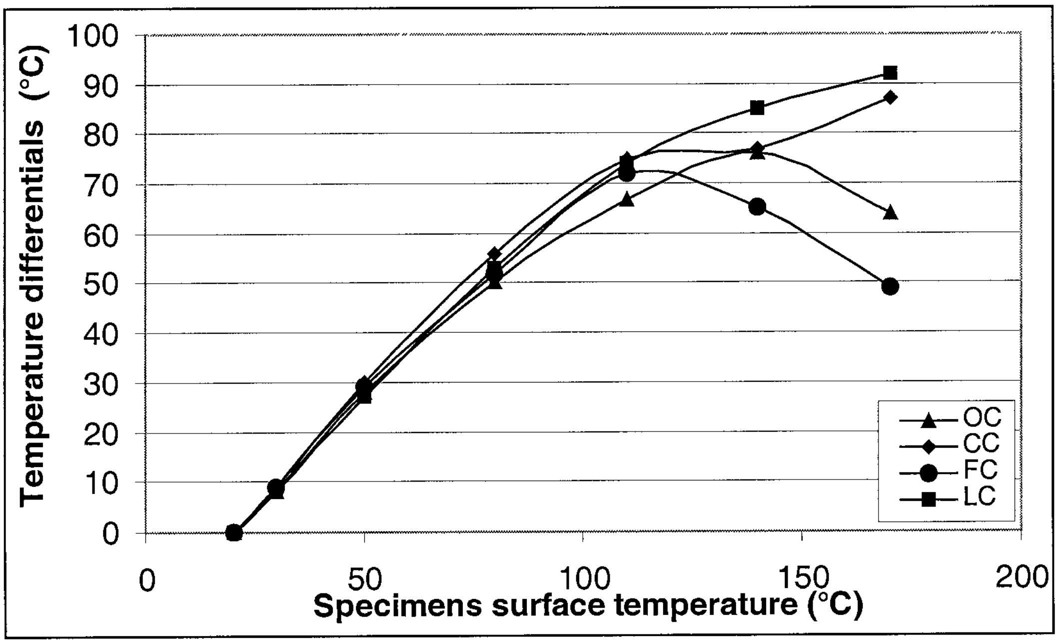

Fig. 3 Temperature differentials between the surface and the centre of the 16x32 cm concrete specimens

3. Mechanical properties

3.1 Initial compressive strength

In order to asses the effect of elevated temperatures on concrete mixes under investigation, measurements of properties of test specimens were performed shortly before and after heating when specimens were cooled down to room temperature. The initial strength of heat-test specimens was determined on a reference specimens set for each type of concrete. Reference test specimens were crushed at the beginning of the heating tests. The results of the measurements above are compiled in Figure 4.

The behaviour of polypropylene high strength concrete was very close to that of the reference high strength concrete. By adding 2 kg of polypropylene fibres to high strength concrete, the compressive strength and modulus of elasticity varied little. The mechanical properties (compressive strength and modulus of elasticity) of the lightweight aggregate concretes were less than that of the normal aggregate high strength concrete. As can be seen the replacement of the normal weight aggregate with a lightweight aggregate had an important effect on the compressive strength and the modulus of elasticity (a decrease of up to 36 %). This result is in line with those published by Ramakrishnan et al. [17] and Zhang et al. [18].

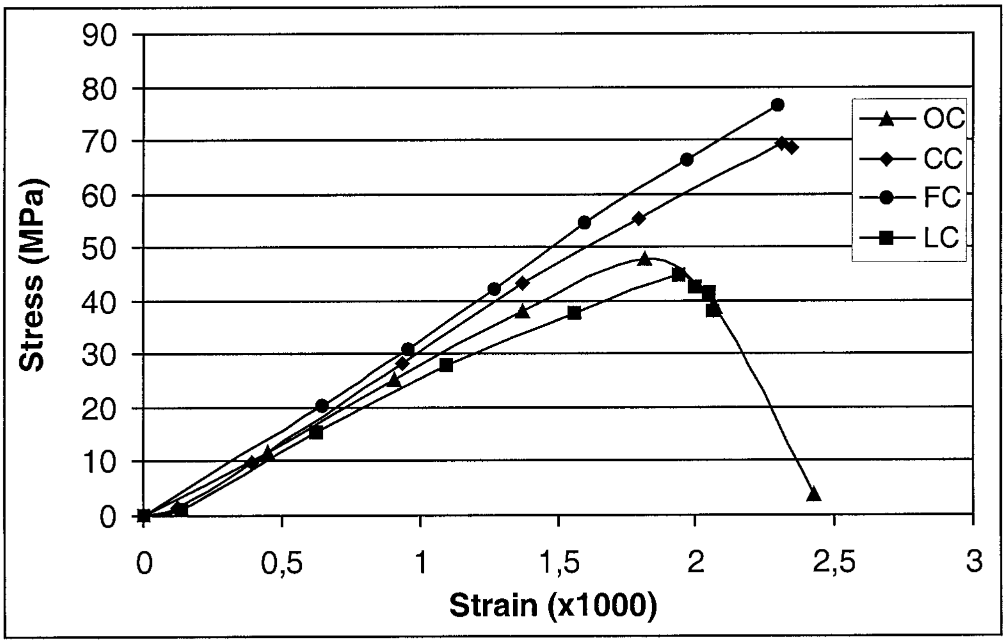

Fig. 4 Stress-strain relationships of the tested concretes at room temperature

3.2 Residual compressive strength

The changes in mechanical properties in the series of concretes were studied after exposure to 200 °C. The behaviour of the tested specimens is presented in Figure 5.

After initial heating up to 200 °C, both the compressive strength and modulus of elasticity were reduced (to about 9-38 % of the non-heated strength and about 14-33 % of the non-heated modulus of elasticity). The results indicated that in the tested temperature range lightweight aggregates (expanded clay aggregates) has improved the heat resistance of the concrete. The adding of polypropylene fibres modified the high strength concrete thermal behaviour but not the residual mechanical behaviour. Polypropylene fibres did not improve neither the initial compressive strength nor the residual compressive strength. The results showed also that ordinary concrete endured the effect of elevated temperature better than high strength concrete and better than lightweight aggregate concrete.

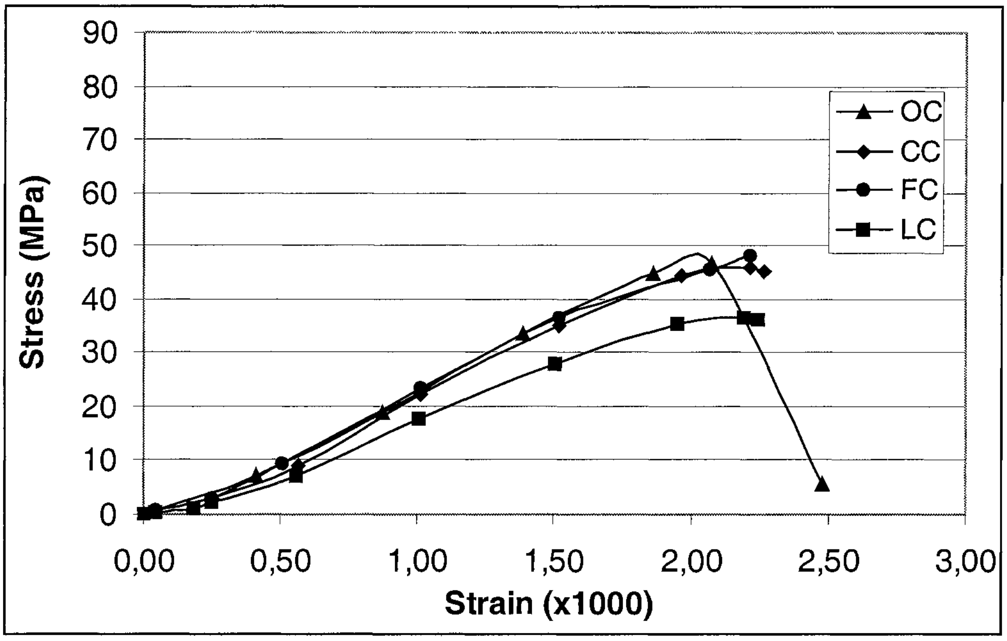

Fig. 5 Stress-strain relationships of the tested concretes after exposure at 200 °C and cooled down.

3.3 Modulus of elasticity

The results of modulus of elasticity and compressive strength are summarised in Table 2. Residual modulus of elasticity of the tested concretes specimens subjected to 200 °C can be expressed as a percentage of the modulus of elasticity of the corresponding reference specimens. The polypropylene fibres did not modify neither the initial modulus of elasticity nor the residual modulus of elasticity. By replacing normal weight aggregate with lightweight aggregate the initial modulus of elasticity decreased but the heat resistance was improved.

Table 2. Compressive strength and modulus of elasticity of the tested concretes

	CC	FC	LC	OC
Initial compressive strength (MPa)	70 (100 %)	72 (100 %)	45 (100 %)	48.5 (100 %)
Residual compressive strength (MPa)	46 (66 %)	45 (62 %)	37 (82 %)	44 (91 %)
Initial modulus of elasticity (GPa)	32 (100 %)	33 (100 %)	23 (100 %)	25.8 (100 %)
Residual modulus of elasticity (GPa)	23 (72 %)	22 (67 %)	18 (78 %)	22.3 (86 %)

3.4 Residual splitting tensile strength

The specimens which were used for splitting tests were 11x22 cm normalized cylinders. The results are shown in Table 3. The heat-resistance of the splitting tensile strength appeared to improve when lightweight aggregates were used. This is probably the result of an improved transition zone between the cement paste and the more porous lightweight aggregates which leads to reduced microcracking at the paste/aggregate interface. Polypropylene fibres did not improve the residual splitting tensile strength. In addition, a slight tensile strength increase was observed for the ordinary concrete.

Table 3. Splitting tensile strength of the tested concretes.

	CC	FC	LC	OC
Initial splitting tensile strength(MPa)	4.8 (100 %)	4.9 (100 %)	3.0 (100 %)	3.5 (100 %)
Residual splitting tensile strength (MPa)	3.0 (63 %)	2.9 (59 %)	2.5 (83 %)	3.6

CONCLUSION

This paper provides a systematic comparison of results of high temperature tests (200 °C) on two high strength concretes and two normal strength concretes subjected to identical testing conditions. Three mixes that had the same water/binder ratio of 0.30 and one ordinary concrete mix were tested. This research adds important data to existing information on the behaviour of lightweight aggregate and fibre high strength concretes under elevated temperatures. The following conclusions may be drawn :

There was a significant discrepancy in heat effects on high strength concretes with and without polypropylene fibres. Thermal gradients were significantly lowered by adding polypropylene fibres to concrete (2 kg/m^3). This could result in low risk of concrete spalling. In this way polypropylene fibres improved the thermal behaviour of the tested concrete.

The mineral composition of the coarse aggregates had a great influence on the temperature resistance properties. The temperature differentials through the concrete specimen thickness depended on the aggregate type and the results indicated that they could be as high as 92 °C (more than 11 °C/cm of concrete). Thermal gradients were greater in lightweight aggregate concrete than in normal weight aggregate high strength concrete due to high free water content.

Ordinary concrete presented lower thermal gradients than high strength concretes. This may be due to the fact that free water escaped more easily from ordinary concrete than from high strength concretes.

Mechanical properties of concrete were studied at room temperature and after exposure to elevated temperature. Polypropylene fibres did not modify the residual mechanical properties of the tested high strength concrete. Neither the compressive behaviour nor the tensile behaviour was significantly modified by the adding of polypropylene fibres.

The substitution of lightweight aggregate for the normal weight aggregate in high strength concrete can provide benefits from reduced density but the concrete compressive strength is reduced. Results indicated that lightweight aggregate concrete endured the effect of elevated temperature better than normal aggregate concrete. The heat-resistance of the splitting tensile strength appeared to improve when lightweight aggregates were used.

Furthermore the residual mechanical properties of ordinary concrete were better than that of the other tested high strength concretes.

For other accidental conditions like fire, there is need for further work on the temperature resistance of these tested concretes. Experimental studies are going on for test temperature varying from 600 to 700 °C. Thermal stability and residual mechanical properties are analysed in reference to chemical and physical reactions that occur in concrete at temperatures greater than 200 °C.

REFERENCES

1. Jahren, P.A., "Fire resistance of high strength/Dense concrete with particular reference to the use of condensed silica fume". SP 114-50, ACI, Detroit, 1989, pp. 1013-1049.
2. Hertz, K.D., "Danish Investigations on Silica Fume Concretes at Elevated Temperatures". ACI Materials Journal. Vol. 89. N° 4, 1992, pp. 345-347.
3. Phan, L.T., Carino, N.J. "Review of mechanical properties of HSC at elevated temperature", Journal of Materials in Civil Engineering, Vol. 10, N° 1, 1998, pp. 58-64.
4. Nishida, A., Yamazaki, N., Inoue, H., Schneider, U., Diederichs, U., "Study on the properties of High Strength Concrete with Short Polypropylene Fibre for Spalling Resistance", International Conf. on Concrete under Severe Conditions – Environment and Loading. 1995, Sapporo, Japan.
5. Kuznetsov, G.V. and Rudzinskii, V.P., "High temperature heat and mass transfer in a concrete layer used for biological protection of nuclear reactors at critical heat loads"; Teplofizika vysokih temperatur, Vol. 37, N°5, 1999, pp. 809-813. (in Russian).

6. Shekarchi, M., Debicki, G., Granger, L., Clastres, P., "High Performance Concrete Behaviour under Accident Conditions"; 5th International Workshop on Materials Properties and Design, Durable Reinforced Concrete Structures, Weimar, October 1998, pp. 283-300.
7. Kontani, O. and Shah, S.P., "Pore pressure in sealed concrete at sustained high temperatures"; Concrete Under Severe Conditions: Environment and Loading, Vol. 2, Edited by K. Sakai, N. Banthia and O.E. Gjorv, 1995, pp. 1151-1162.
8. Sercombe, J., Gallé, C., Durand, S., Bouniol, P., "On the importance of thermal gradients in the spalling of high-strength concrete", 14th Engineering Mechanics Conference, ASCE, Austin, Texas, USA, 21-24 May, 2000.
9. Gallé, C., Sercombe, J., Pin, M., Arcier, G., Bouniol, P., "Behaviour of high performance concrete under high temperature (60-450°C) for surface long-term storage: thermo-hydro-mechanical residual properties", MRS Conference, Sydney, Australia, 27-31 August, 2000.
10. Ranc, G., Sercombe, J., Rodriguez, S., Gatabin, C., "Structural and local behaviour of reinforced high strength concrete structures subjected to high temperatures", FraMCos-4 International Conference, Cachan, France, 28 May – 2 June, 2001.
11. RILEM TC 129-MHT, "Test methods for mechanical properties of concrete at high temperatures"; Part 1: Introduction, Part 2: Stress-strain relation, Part 3: Compressive strength for service and accident conditions, Materials and Structures, Vol. 28, N° 181, 1995, pp. 410-414.
12. Zoldners, N.G. "Effect of high temperatures on concretes incorporating different aggregates", Philadelphia, ASTM, 1960, Vol. 60, pp. 1087-1108.
13. Chéné, G., Kalifa, P., Menneteau, F.D., Pimienta, P., "Behaviour of high performance concrete incorporating organic fibres exposed to fire"; Rapport du Projet National BHP2000, CSTB, France, 2000, (in French).
14. Khoury, G.A., Grainger, B.N., Sullivan, P.J.E. "Transient Thermal Strain of Concrete : Literature Review, Conditions within specimen and behaviour of individual constituents", Magazine of Concrete Research, Vol. 37, N° 132, 1985, pp. 131-144.
15. Noumowe, N.A., Clastres, P. Debicki, G., Costaz, J-L., "Transient Heating Effect on High Strength Concrete", Nuclear Engineering and Design, N° 235, 1996, Elsevier Science. Pp. 99-108.
16. Noumowe, N.A., Clastres, P. Shekarchi, Z.M. Debicki, G., "Thermal Stability of Concrete under Accidental Situation", 14th International Conference on Structural Mechanics in Reactor Technology, 1997, Lyon, France.
17. Ramakrishnan, V., Bremner, T.W., Malhotra, V.M., "Underwater Fatigue Performance of Structural Lightweight Concrete", Third CANMET/ACI International Conference on Durability of Concrete, 1994, Nice, France.
18. Zhang, M.-H., Gjorv, O., "Mechanical properties of High-Strength Lightweight Concrete", ACI Materials Journal, V. 88, N°3, May-June 1991, Pp. 240-247