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Thermal and mechanical properties of steel-fibre-reinforced concrete at elevated temperatures

T.T. Lie and V.K.R. Kodur

Abstract: For use in fire resistance calculations, the relevant thermal and mechanical properties of steel-fibre-reinforced concrete at elevated temperatures were determined. These properties included the thermal conductivity, specific heat, thermal expansion, and mass loss, as well as the strength and deformation properties of steel-fibre-reinforced siliceous and carbonate aggregate concretes. The thermal properties are presented in equations that express the values of these properties as a function of temperature in the temperature range between 0°C and 1000°C. The mechanical properties are given in the form of stress–strain relationships for the concretes at elevated temperatures. The results indicate that the steel fibres have little influence on the thermal properties of the concretes. The influence on the mechanical properties, however, is relatively greater than the influence on the thermal properties and is expected to be beneficial to the fire resistance of structural elements constructed of fibre-reinforced concrete.

Key words: steel fibre, reinforced concrete, thermal properties, mechanical properties, fire resistance.

Résumé : Les propriétés thermiques et mécaniques pertinentes du béton renforcé de fibres d'acier à haute température ont été déterminées pour utilisation dans les calculs de résistance contre le feu. Ces propriétés incluaient la conductivité thermique, la chaleur spécifique, l'expansion thermique et la perte de masse, ainsi que la résistance et les déformations du béton renforcé de fibres d'acier fait avec des granulats carbonatés ou siliceux. Les propriétés thermiques sont présentées dans des équations qui expriment les valeurs de ces propriétés en fonction de la température couvrant un domaine de 0°C à 1000°C. Les propriétés mécaniques à haute température des bétons sont données en forme de relations déformation–contrainte. Les résultats indiquent que les fibres d'acier ont une petite influence sur les propriétés thermiques du béton. L'influence sur les propriétés mécaniques est cependant relativement supérieure à l'influence sur les propriétés thermiques et devrait être bénéfique à la résistance au feu des éléments structuraux faits de béton armé de fibres d'acier.

Mots clés : fibre d'acier, béton armé, propriétés thermiques, propriétés mécaniques, résistance au feu.
[Traduit par la rédaction]

Introduction

In recent years, the construction industry has shown significant interest in the use of fibre-reinforced concrete owing to the improvements in structural performance it can provide compared to traditional plain concrete. These improvements have extended the use of fibre-reinforced concrete to applications in the area of structural fire resistance.

At present, studies are in progress to determine the performance of steel-fibre-reinforced concrete structural members in fire (Kodur and Lie 1995). In the past, the performance of these and other structural members at temperatures encountered in fire could only be determined by testing. Over the years, however, methods have been developed for the calculation of the fire resistance of various structural members (Friedman 1992; Lie 1992; Sullivan et al. 1993). These calculation methods are far less costly and time consuming than testing. However, to perform these calculations, a knowledge of the thermal and mechanical properties of the materials at elevated temperatures, used in the construction of the structural members, is required.

The present study was undertaken to establish the thermal and mechanical properties of steel-fibre-reinforced concrete at elevated temperatures for use in mathematical models to predict the fire resistance of steel hollow structural section (HSS) columns. The study was carried out as part of a joint research project involving the National Fire Laboratory (NFL) of the Institute for Research in Construction, National Research Council of Canada (NRCC), the Fire Technology Laboratory of the Technical Research Centre of Finland, and the Institut für Baustoffe, Massivbau und Brandschutz (IBMB) of the Technische Universität Braunschweig, Germany. The data obtained from the studies were used to develop thermal and mechanical relationships, as a function of temperature, for steel-fibre-reinforced concrete. These relationships can be used as input in computer programs (Friedman 1992; Sullivan et al. 1993) to determine the behaviour of fibre-reinforced concrete structural members at high temperatures.

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Written discussion of this paper is welcomed and will be received by the Editor until August 31, 1996 (address inside front cover).

Table 1. Batch quantities and properties of concrete mix.

Property	Batch (specimen type) 1 (NRC1)	2 (NRC2)	3 (NRC3)
Cement content (kg/m^3)	380	439	439
Fine aggregate (kg/m^3)	673	621	621
Coarse aggregate (kg/m^3)			
19 mm	678	788	788
9.5 mm	438	340	340
Total	1162	1128	1128
Aggregate type	Siliceous	Carbonate	Carbonate
Water (kg/m^3)	167	161	161
Water–cement ratio	0.44	0.37	0.37
Retarding admixture (mL/m^3)	745	—	—
Superplasticizer (mL/m^3)	2500	300	1200
Steel fibre (kg/m^3)	42	—	42
28-day compressive strength (MPa)	39.9	32.6	43.2
Compressive strength at test date (MPa)	40.9	37.1	43.3

Experimental details

The experiments and the test specimens used were described in detail in earlier studies (Lie and Kodur 1995*a*, 1995*b*), and will, therefore, be only briefly described in this paper.

Concrete mix proportions

The type of aggregate influences the thermal properties of concrete (Lie 1972) and hence the two most commonly used aggregates, siliceous and carbonate, were used in the concrete mix. Further, to compare the performance of fibre-reinforced concrete with that of plain concrete, three types of concrete specimens (NRC1, NRC2, and NRC3) were investigated. The NRC1 specimens were made with fibre-reinforced siliceous aggregate concrete. The NRC2 and NRC3 specimens were made with carbonate aggregate concrete with and without fibre reinforcement, respectively.

The specimens were made from three batches of concrete. The concrete was designed to produce a 28-day compressive strength of 35 MPa. In all three batches, general purpose portland cement for the construction of concrete structures was used. The concrete mix in batch 1 was made with siliceous stone aggregate, while the mix in batches 2 and 3 was made with carbonate stone aggregate. The fine aggregate for all three batches consisted of silica-based sand. In order to improve workability, a superplasticizer was added to all three batches and a retarding admixture to batch 1.

As reinforcement, corrugated steel fibres were used. The fibres had a length of 50 mm, an equivalent diameter of 0.9 mm, and an aspect ratio of 57. The weight percentage of the steel fibres in the concrete was approximately 1.77 (42 kg/m^3).

The steel fibres were added to the fresh concrete and mixed for about 2 minutes to ensure uniform dispersion. Vibrators were used to consolidate the concrete. The 28-day compressive strength of the siliceous aggregate concrete was about 40 MPa, that of the plain carbonate aggregate concrete about 33 MPa, and that of the fibre-reinforced carbonate aggregate concrete 43 MPa. The mix proportions, together with concrete and steel data for the three batches, are given in Table 1.

Test specimens

From each batch of concrete, the following specimens were made for determining the thermal properties:

- 8 cylinders of 150 mm diameter and 300 mm length;
- 3 bricks of 200 × 100 × 50 mm.

The cylinders were used for compression tests at 28 days after the pouring of the concrete. The test specimens for the determination of the thermal conductivity and the thermal expansion were prepared by cutting the bricks to appropriate sizes (Lie and Kudor 1995*a*). Specimens for the determination of the specific heat and mass loss were obtained by grinding a portion of the bricks.

For determining the mechanical properties, the following specimens were made from each batch of concrete:

- 18 cylinders with a diameter of 80 mm and a length of 300 mm;
- 6 cylinders with a diameter of 150 mm and a length of 300 mm;
- 6 prisms with a cross section of 100 × 100 mm and a length of 400 mm.

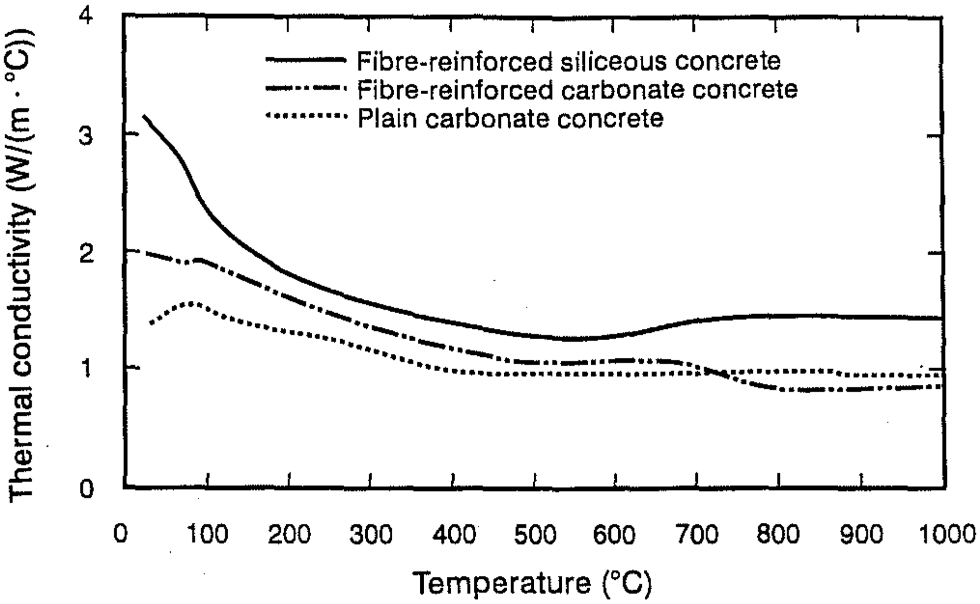
Eighteen cylinders of 80 mm diameter and six prisms of each concrete type were used for determining the mechanical properties of the concrete at elevated temperatures. Two thermocouples were installed in each of the 80 mm cylinders and in each prism. The thermocouple junctions in the cylinders were located at the central axis at a distance of 100 mm from each end of the cylinder and those in the prisms at 125 and 275 mm from one end of the prism. The six cylinders of 150 mm diameter were used for compression tests at 28 days after the pouring.

The specimens were de-moulded 1 day after coating, then soaked under water for 7 days and, subsequently, conditioned in a climate room at 50% relative humidity and 20°C.

Methods for measuring thermal properties

The measured thermal properties were the thermal conductivity, specific heat, thermal expansion, and the mass loss of the concretes at elevated temperatures. All measurements were made with commercially available instruments. Full details of the instruments and the test procedure are given in Lie and Kudor (1995*a*).

Fig. 1. Thermal conductivity of various concrete types as a function of temperature.



The thermal conductivity of the concretes was measured using a non-steady-state hot wire method. The measurements were made in the temperature range between room temperature and 1000°C.

The specific heat was measured using a differential scanning calorimeter for temperatures up to 600°C. For measuring the specific heat above 600°C, a high temperature differential thermal analyzer was used. The measurements were made, up to a temperature of 1000°C.

The thermal expansion of the concretes was measured with a dilatometric apparatus, capable of producing curves that show the expansion of the concrete with temperatures in the range between room temperature and 1000°C.

The mass loss with temperature was measured by means of a thermogravimetric analyzer in the temperature range between room temperature and 1000°C.

Methods for measuring mechanical properties

The mechanical properties that were measured were the strength and deformation properties of the concretes at elevated temperatures. To determine these properties, stress–strain and creep tests were carried out by IBMB in Germany. The tests were conducted in a special testing machine, consisting of an electrical furnace, in which the temperatures and rate of temperature rise could be controlled, and a loading device capable of producing controllable loads, strains, and strain rates. Further details of the test procedure are given in Lie and Kodur (1995*b*).

The stress–strain tests were carried out at a number of selected temperatures in the range between room temperature and 750°C under selected loads that varied from 15% to 60% of the compressive strength of the concretes at 20°C. The creep tests were carried out under the same loads in the temperature range between room temperature and 750°C.

Results and discussion

Thermal properties

The thermal conductivities of the various concretes at elevated temperatures are shown in Fig. 1. The thermal conductivity for all three concrete types decreases with increase in temperature up to approximately 400°C. Above this temperature, the thermal conductivity was nearly constant. The presence of steel fibres increases the thermal conductivity to a small extent. This increase in thermal conductivity can be attributed to the fact that the thermal conductivity of steel is about 50 times higher than that of concrete. The thermal conductivity of fibre-reinforced siliceous concrete is higher than that of the carbonate concrete because of the higher crystallinity of the siliceous aggregates as compared to that of the carbonate aggregate.

In Fig. 2, the specific heats of the concretes are shown as a function of the concrete temperature. For all three types of concrete, the specific heat shows a peak at temperatures near 100°C and 425°C. The first increase is caused by evaporation of free water and the second by removal of crystal water from the cement paste (Lie 1972). In these temperature regions, most of the heat supplied to the concrete is used for the removal of water and only a small amount is available for raising the temperature of the material. As a consequence, the specific heat increases substantially in these temperature regions.

The increase in specific heat for the fibre-reinforced siliceous aggregate concrete, at about 550°C, can be attributed to the presence of quartz, which transforms in this temperature region. The steep increase in specific heat, for both the plain and the fibre-reinforced carbonate concretes, at about 750°C is due to the presence of dolomite in the aggregate, which disassociates and absorbs heat in this temperature region (Lie and Allen 1972).

The specific heat is slightly affected by the presence of the steel fibres. For carbonate concrete, the specific heat of the fibre-reinforced concrete is slightly higher in the temperature range of 0–1000°C, except for the temperature region near 750°C, where the specific heat of the fibre-reinforced concrete slightly exceeds that of the plain concrete.

The thermal expansions for the concretes are shown as a function of the concrete temperature in Fig. 3. For the fibre-

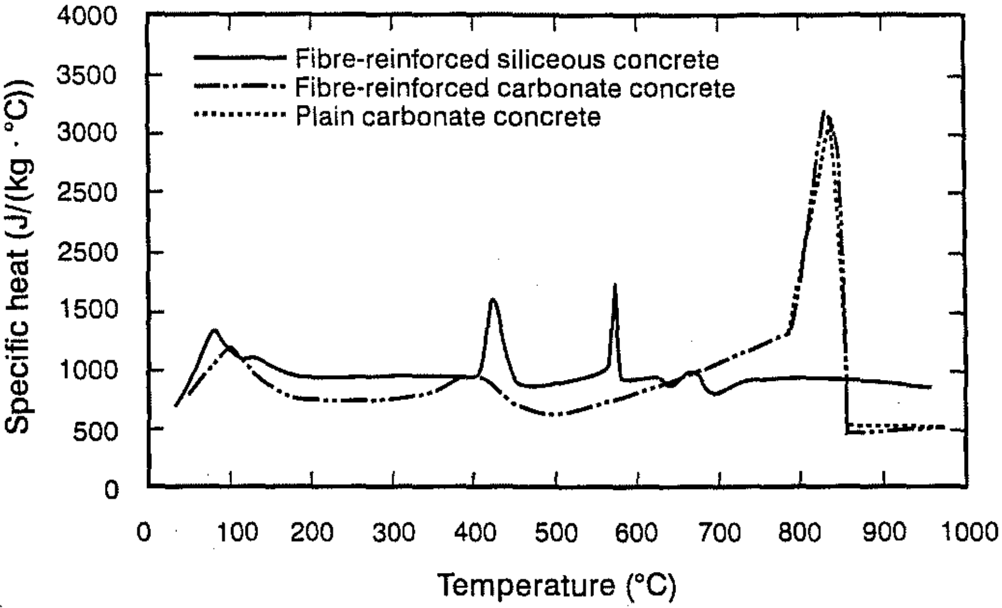


Fig. 2. Specific heat of various concrete types as a function of temperature.

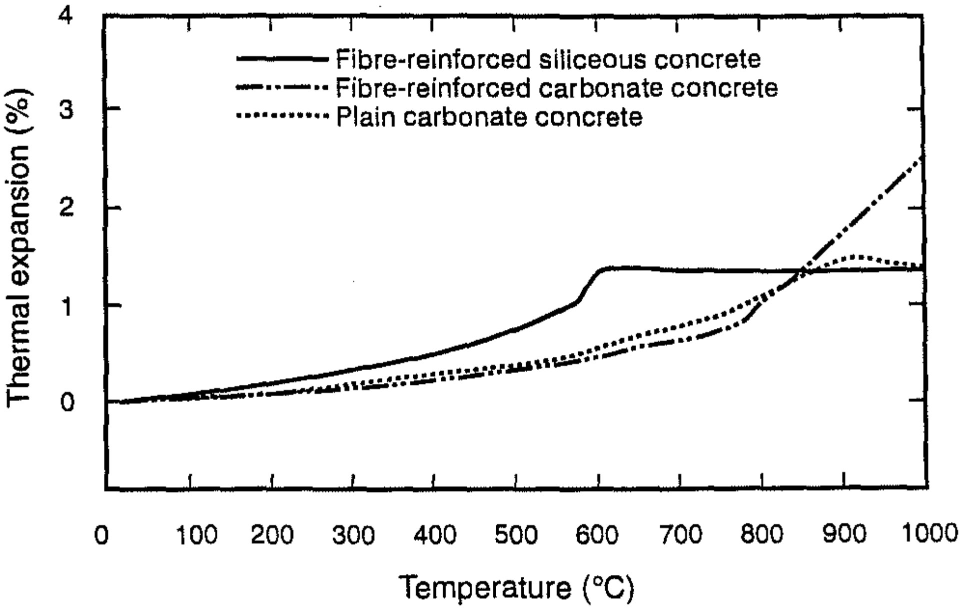


Fig. 3. Thermal expansion of various concrete types as a function of temperature.

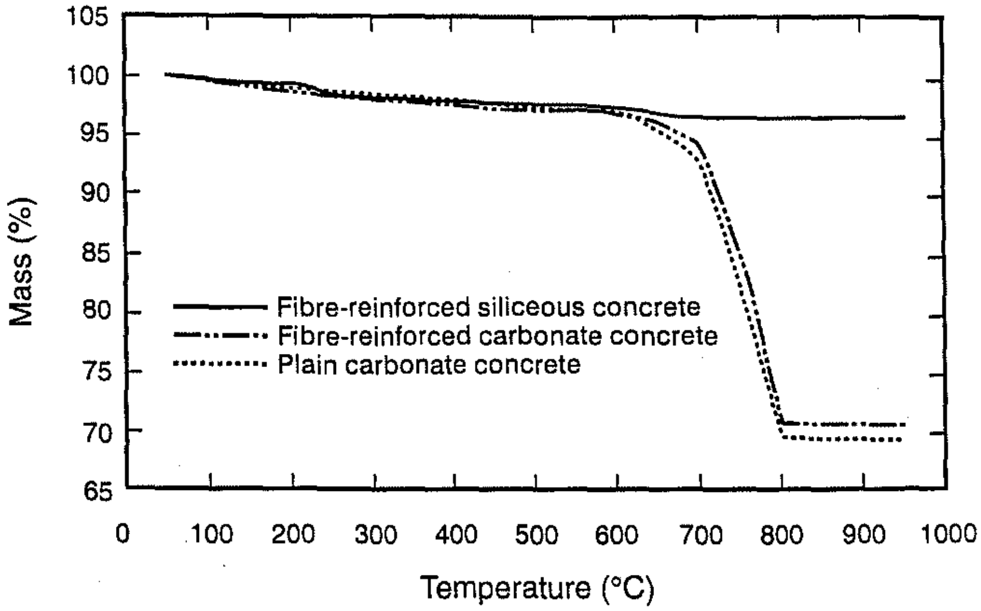
reinforced siliceous aggregate concrete, the thermal expansion increases with temperature up to about 600°C and then remains constant. The considerable enhancement of the thermal expansion near 550°C can be attributed to transformation of quartz in the siliceous aggregate. The plain and the fibre-reinforced carbonate concrete have similar thermal expansions up to a temperature of about 800°C. Above this temperature, the thermal expansion of the fibre-reinforced carbonate concrete increases considerably above that of the plain concrete. This steep increase of thermal expansion with temperature can be attributed to the presence of the steel fibres, which continue to expand at an increasing rate.

In Fig. 4, the mass losses for the three concretes are shown as a function of the concrete temperature. The mass loss for all three concrete types is very small until about 600°C, where it is about 3% of the original mass. Between 600°C and 800°C, the mass of plain and fibre-reinforced carbonate aggregate concrete drops considerably with the temperature and this can be attributed to the dissociation of the dolomite in the concrete. Above 800°C, the mass loss again decreases slowly with temperature. The mass loss of the concretes is not significantly affected by the presence of steel fibre reinforcement in the investigated temperature range of 0–1000°C.

Overall, the thermal properties, at elevated temperatures, exhibited by steel-fibre-reinforced concrete, are similar to those of plain concrete.

To facilitate the use of the thermal properties as input data for the calculation of the temperatures of steel-fibre-reinforced concrete construction exposed to heat, formulas have been derived (Lie and Kodur 1995*c*) that give these properties as a function of temperature in the temperature

Fig. 4. Mass loss of various concrete types as a function of temperature.



range of 0 – 1000°C. These formulas are given in Appendix 2.

Mechanical properties

The results of the measurements of the mechanical properties of the concretes showed that the compressive strength at elevated temperatures of fibre-reinforced concrete is higher than that of plain concrete. The presence of steel fibres increases the ultimate strain and improves the ductility of the concrete (Lie and Kodur 1995*b*). However, the effect of aggregate type on the compressive strength is not significant.

Based on the results, stress – strain curves for the concretes at elevated temperatures were derived (Lie and Kodur 1995*c*). These curves are shown in Fig. 5. They can be determined by expressions similar to those for plain concrete (Lie 1992), with the only difference that the stress maxima and their locations move to high values. The equations that give the stress – strain relations for steel-fibre-reinforced carbonate and siliceous aggregate concretes are given in Appendix 2.

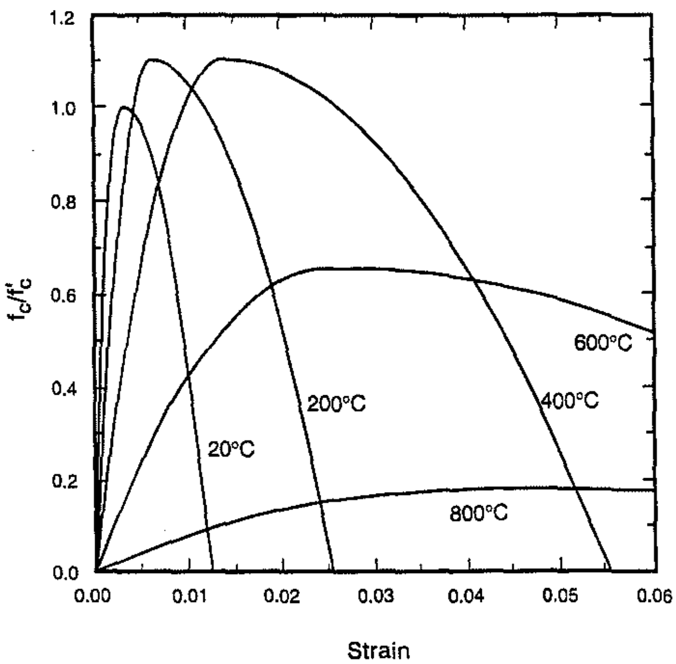
Current research

Research is now in progress at the National Research Council of Canada to develop mathematical models for the calculation of the fire resistance of HSS columns filled with fibre-reinforced concrete, using the thermal and mechanical properties, given in this paper, as input data. Simultaneously, fire tests are being carried out on full-size circular and rectangular HSS columns filled with various types of fibre-reinforced concretes. These tests are for the purpose of verifying the validity of the models for various values of the parameters that determine the fire resistance of the columns, such as load intensity, section dimensions, effective length of the column, and concrete strength.

Research impact

The development of rationale design approaches for the use of fibre-reinforced concrete will result in wider use of this material in buildings. When used in buildings, the structural

Fig. 5. Stress – strain curves for fibre-reinforced concrete at various temperatures.



members must satisfy appropriate fire resistance requirements. In the past, the performance of structural members, at temperatures encountered in fire, could only be determined by testing. In recent years, however, the use of numerical methods for the calculation of the fire resistance of various structural members is gaining acceptance (Lie 1992; Kudor and Lie 1995), since these calculation methods are far less costly and time consuming than testing.

The proposed relationships, for thermal and mechanical properties at elevated temperatures, will facilitate the use of the available mathematical models for the calculation of the fire resistance of structural members made of steel-fibre-reinforced concrete.

Summary and conclusions

Experimental and theoretical studies were carried out to investigate the influence of steel-fibre reinforcement on the behaviour of concrete at elevated temperatures. The results and conclusions can be summarized as follows:

1. The compressive strength at elevated temperatures of fibre-reinforced concrete is higher than that of plain concrete. The presence of steel fibres increases the ultimate strain and improves the ductility of a fibre-reinforced concrete member.
2. Steel-fibre-reinforced concrete exhibits, at elevated temperatures, mechanical properties that are more beneficial to fire resistance than those of plain concrete.
3. Steel-fibre-reinforced concrete exhibits, at elevated temperatures, thermal properties that are similar to those of plain concrete.
4. The proposed relationships for thermal and mechanical properties of steel-fibre-reinforced concrete, at elevated temperatures, can be used as input data in mathematical models for the calculation of the fire resistance of concrete structural members.

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Appendix 1. List of symbols

c_c specific heat $(\mathrm{J \cdot kg^{-1} \cdot {}^\circ C^{-1}})$
f_c concrete stress at temperature T (MPa)
f_c' cylinder strength of concrete at temperature T (MPa)
f_{co}' cylinder strength of concrete at room temperature (MPa)
k thermal conductivity $(\mathrm{W \cdot m^{-1} \cdot {}^\circ C^{-1}})$
M mass at temperature T (kg)
M_o mass at room temperature (kg)
T temperature (°C)
α coefficient of thermal expansion $(\mathrm{m \cdot m^{-1} \cdot {}^\circ C^{-1}})$
ε_c concrete strain at temperature T $(\mathrm{m \cdot m^{-1}})$
ε_{max} concrete strain at maximum stress of stress–strain curves for temperature T $(\mathrm{m \cdot m^{-1}})$

Appendix 2. Properties of steel-fibre-reinforced concrete

Thermal capacity

Siliceous aggregate concrete
For $0 \le T \le 200$°C,

$$\rho_c c_c = (0.005T + 1.7) \times 10^6$$

For $200 < T \le 400$°C,

$$\rho_c c_c = 2.7 \times 10^6$$

For $400 < T \le 500$°C,

$$\rho_c c_c = (0.013T - 2.5) \times 10^6$$

For $500 < T \le 600$°C,

$$\rho_c c_c = (-0.013T + 10.5) \times 10^6$$

For $T > 600$°C,

$$\rho_c c_c = 2.7 \times 10^6$$

Carbonate aggregate concrete
For $0 \le T \le 400$°C,

$$\rho_c c_c = 2.566 \times 10^6$$

For $400 < T \le 410$°C,

$$\rho_c c_c = (0.1765T - 68.034) \times 10^6$$

For $410 < T \le 445$°C,

$$\rho_c c_c = (-0.05043T + 25.00671) \times 10^6$$

For $445 < T \le 500$°C,

$$\rho_c c_c = 2.566 \times 10^6$$

For $500 < T \le 635$°C,

$$\rho_c c_c = (0.01603T - 5.44881) \times 10^6$$

For $635 < T \le 715$°C,

$$\rho_c c_c = (0.16635T - 100.90225) \times 10^6$$

For $715 < T \le 785$°C,

$$\rho_c c_c = (-0.22103T + 176.07343) \times 10^6$$

For $T > 785$°C,

$$\rho_c c_c = 2.566 \times 10^6$$

Thermal conductivity

Siliceous aggregate concrete
For $0 \leq T \leq 200°C$,

$$k = 3.22 - 0.007T$$

For $200 < T \leq 400°C$,

$$k = 2.24 - 0.0021T$$

For $400 < T \leq 1000°C$,

$$k = 1.4$$

Carbonate aggregate concrete
For $0 \leq T \leq 500°C$,

$$k = 2.000 - 0.001775T$$

For $500 < T \leq 1000°C$,

$$k = 1.402 - 0.000579T$$

Coefficient of thermal expansion

Siliceous aggregate concrete
For $0 \leq T \leq 530°C$,

$$\alpha = -0.00115 + 0.000016T$$

For $530 < T \leq 600°C$,

$$\alpha = -0.0364 + 0.000083T$$

For $600 < T \leq 1000°C$,

$$\alpha = 0.0135$$

Carbonate aggregate concrete
For $0 \leq T \leq 750°C$,

$$\alpha = -0.00115 + 0.00001T$$

For $750 < T \leq 1000°C$,

$$\alpha = -0.05187 + 0.000077T$$

Mass loss

Siliceous aggregate concrete
For $0 \leq T \leq 1000°C$,

$$M/M_o = 0.9987 - 0.00003992T$$

Carbonate aggregate concrete
For $0 \leq T \leq 700°C$,

$$M/M_o = 1 - 0.000065T$$

For $700 < T \leq 800°C$,

$$M/M_o = 2.6 - 0.00235T$$

For $800 < T \leq 1000°C$,

$$M/M_o = 0.72 - 0.000015T$$

Stress–strain relations for siliceous and carbonate aggregate concretes

For $\varepsilon_c \leq \varepsilon_{max}$,

$$f_c = f_c'\left[1 - \left(\frac{\varepsilon_{max} - \varepsilon_c}{\varepsilon_{max}}\right)^2\right]$$

For $\varepsilon_c > \varepsilon_{max}$,

$$f_c = f_c'\left[1 - \left(\frac{\varepsilon_c - \varepsilon_{max}}{3\varepsilon_{max}}\right)^2\right]$$

where

$$\varepsilon_{max} = 0.003 + (7.0T + 0.05T^2) \times 10^{-6}.$$

For $T \leq 150°C$,

$$f_c' = f_{co}'[1 + 0.000769(T - 20)]$$

For $150 < T \leq 400°C$,

$$f_c' = 1.1f_{co}'$$

For $T > 400°C$,

$$f_c' = f_{co}'\left[2.011 - 2.353\left(\frac{T - 20}{1000}\right)\right]$$