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EFFECT OF TEMPERATURE ON THERMAL PROPERTIES OF HIGH STRENGTH CONCRETE

by

V.K.R. Kodur[1] and M.A. Sultan[2]

ABSTRACT

For use in fire resistance calculations, the relevant thermal properties of high strength concrete were determined as a function of temperature. These properties included the thermal conductivity, specific heat, thermal expansion and mass loss, of plain and steel fibre-reinforced concrete made of siliceous and carbonate aggregate. 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 effect of temperature on thermal conductivity, thermal expansion, specific heat and mass loss of HSC is discussed. Test data indicate that the type of aggregate has significant influence on the thermal properties of HSC, while the presence of steel fibre-reinforcement has very little influence on the thermal properties of HSC.

Keywords: high strength concrete, high temperature behaviour, reinforced concrete columns, thermal properties, steel fibre-reinforced concrete

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INTRODUCTION

In recent years, the construction industry has shown significant interest in the use of high strength concrete (HSC). This is due to the improvements in structural performance, such as high strength and durability that it can provide compared to traditional normal strength concrete (NSC). HSC is being used in many applications such as bridges, offshore structures and infrastructure projects. In recent years, its use has been extended to high rise buildings.

In buildings, HSC structural members are designed to satisfy the requirements of serviceability and safety limit states. One of the major safety requirements in building design is the provision of appropriate fire safety measures for structural members. The basis for this requirement can be attributed to the fact that, when other measures for containing the fire fail, structural integrity is the last line of defence.

The results of fire tests (Diederichs et al. 1995, Kodur 1998, Phan 1996) have shown that there are well-defined differences between the properties of HSC and NSC at high temperatures. Further, concern has developed regarding the occurrence of explosive spalling when HSC is subjected to rapid heating, as in the case of a fire (Diederichs et al. 1995, Phan 1996).

Studies are in progress at the National Research Council of Canada (NRC) to develop fire resistance design guidelines for the use of HSC for possible incorporation in codes and standards. The main objective of this research, being undertaken in partnership with industry, is to study the behaviour of HSC at elevated temperatures and to develop calculation methods for predicting the fire resistance for columns. For the development of such calculation methods, the properties of HSC at elevated temperatures are required.

The present study was undertaken to establish the thermal properties of high strength concrete at elevated temperatures. The data can be used to develop mathematical models to predict the fire resistance of high strength concrete structural members.

RESEARCH SIGNIFICANCE

In order to understand and eventually predict the performance of HSC structural members, the material properties that determine the behaviour of the member at elevated temperatures must be known. The behaviour of a structural member exposed to fire is dependent, in part, on the thermal, mechanical and deformation properties of the material of which the member is composed.

To be able to predict the fire resistance of a structure, the temperatures in the structure must be determined. For such calculations, knowledge of the thermal properties, at elevated temperatures, of the materials that comprise the structure is required. Whereas these properties have been established for various normal strength concrete (Lie 1992, Lie and Kodur 1996), this is not the case with high strength concrete. In this study, the relevant thermal properties of various high strength concrete at elevated temperatures were measured. These properties included thermal conductivity, specific heat, thermal expansion and mass loss of the various high strength concrete at elevated temperatures.

Data obtained from the experimental studies is used to develop simple relationships expressing thermal properties as a function of temperatures for various types of HSC. These relationships can be used as input to computer programs (Kodur and Lie 1996, Sullivan et al. 1993) to determine the behaviour of HSC structural members at high temperatures.

THERMAL PROPERTIES OF HIGH STRENGTH CONCRETE

Data from various studies show (Phan 1996, Kodur 1997a, 2000), that for HSC, the spalling of concrete under fire conditions is a major concern. The spalling is due to the low water-cement ratio in HSC (Kodur 1997b) and has been observed in HSC structural members under laboratory and real fire conditions (Phan 1996, Kodur 2000). Spalling, which results in the loss of concrete during a fire, exposes deeper layers of concrete to fire temperatures, thereby increasing the rate of transmission of heat to the inner layers of the structure, including the reinforcement.

In order to predict the spalling behaviour of HSC under fire conditions, the thermal properties are required. Also, data from various studies (Diederichs et al. 1995, Kodur 1997, Kodur and Lie 1998) show that the presence of fibre-reinforcement and the use of carbonate aggregate can be used to minimize spalling in HSC. There is very little information on the thermal and mechanical properties of HSC. Hence, in this study, the thermal properties of both plain HSC and steel fibre-reinforced HSC of two aggregate types were investigated.

The thermal properties that influence the temperature rise and distribution in a concrete structural section are thermal conductivity, specific heat, thermal expansion and mass loss. These properties depend on the type of aggregate and composition of the concrete mix. In this section, the thermal properties of HSC with the two most commonly used aggregates (siliceous and carbonate aggregate), as well as HSC with and without fibres, are presented.

TEST SPECIMENS

Four types of concrete specimens, namely, NRC1, NRC2, NRC3 and NRC4 were fabricated from 4 batches of concrete for studying the thermal properties. For all four batches, general purpose portland cement was used. The NRC3 and NRC4 specimens was made of HSC reinforced with steel fibres, while the other 2 batches were made with HSC without steel fibres. The concrete mix in Batches 1 and 3 (NRC1 and NRC3) was made with siliceous stone aggregate, while the mix in Batches 2, and 4 (NRC3 and NRC4) was made with carbonate stone aggregate. The fine aggregate for all four batches consisted of silica-based sand. The mass (volume) percentage of steel-fibres in Batches 3 and 4 was 1.77 (0.597). The mix proportions for the concrete were:

- cement (normal Type 1): 500 kg/m^3
- silica fume: 50 kg/m^3
- coarse aggregate (size 9.5 mm): 1100 kg/m^3
- fine aggregate: 700 kg/m^3
- water: 140 kg/m^3
- steel fibres: 45 kg/m^3

RIBTEC steel-fibers of the XOREX type were used as reinforcement in NRC3 and NRC4 batches. XOREX is a mild carbon steel with tensile strength of approximately 960 MPa. The corrugated shape of these fibers provided a strong mechanical bond to the concrete. The fibers, which were 50 mm in length with a 0.9 mm equivalent diameter, had an aspect ratio of 57.

The steel-fibres were added to the fresh concrete and mixed for about 5 minutes to ensure uniform dispersion. Both superplasticizer (about 8 l/m^3) and retarding admixture (about 1.2 l/m^3) were used to improve workability of concrete mix. Vibrators were used to consolidate the concrete.

For each concrete mix, 152 mm x 304 mm cylinders and bricks of size 200 mm x 100 mm x 80 mm were fabricated. The specimens were de-moulded one day after casting, then soaked under water for seven days and, subsequently, cured in a climate room at 50% relative humidity and 20°C temperature. Compression tests were conducted using the cylinder samples at 28 days after the pouring of the concrete. The 28-day cylinder compressive strength for Batch 1 and Batch 2 was approximately 80 MPa, while the corresponding strength for Batches 3 and 4 was approximately 90 MPa. The bricks were used to determine the thermal properties of the concrete at elevated temperatures.

METHODS FOR MEASURING THERMAL PROPERTIES

The measured thermal properties were the thermal conductivity, specific heat, thermal expansion and the mass loss of the concrete at elevated temperatures. All measurements were made with commercially available instruments on atleast three specimens and the average of these values is reported here. The experiments and the test specimens used are presented in detail in earlier studies (Lie and Kodur 1995,1996), and are, therefore, only briefly described in this paper.

The test specimens for the determination of the thermal conductivity and the thermal expansion were prepared by cutting the concrete bricks to the appropriate size. Specimens for the determination of the specific heat and mass loss were obtained by grinding a portion of the bricks. The relative humidity of the specimens at the time of testing was approximately 50%.

The thermal conductivity of the concrete was measured using a non-steady state hot wire method. The measurements were made in the temperature range between 20°C and 800°C.

The specific heat was measured using a Differential Scanning Calorimeter (DSC) for temperatures up to 600°C. Above 600°C, a high temperature Differential Thermal Analyzer (DTA) was used. The specific heat was measured up to 1000°C.

The thermal expansion of the concrete was measured with a dilatometric apparatus, capable of producing curves that show the expansion of the concrete with temperature in the range from 20°C to 1000°C.

The mass loss with temperature was measured by means of a Thermogravimetric Analyzer (TGA) in the temperature range from 20°C to 1000°C.

RESULTS AND DISCUSSION

In this section, the thermal properties are compared for NRC1 with NRC2 specimens to show the influence of aggregate type (siliceous and carbonate) and for

NRC3 with NRC4 specimens to show the influence of fibre-reinforcement on the various properties.

Thermal Conductivity -- The thermal conductivity of plain HSC, with siliceous and carbonate aggregates, is shown in Fig. 1a as a function of temperature. The thermal conductivity for both siliceous and carbonate aggregate concrete types decreases with an increase in temperature. The thermal conductivity of siliceous aggregate concrete is higher than that of the carbonate concrete in the temperature range of 200°C to 800°C. This is due to the higher crystallinity of the siliceous aggregates as compared to that of the carbonate aggregate. The higher the crystallinity, the higher the thermal conductivity and its rate of decrease with temperature (Lie 1993). The effect of aggregate type on the thermal conductivity of HSC is similar to that of NSC (Harmathy 1970).

The thermal conductivity of steel fibre-reinforced HSC for two aggregate types is shown in Fig. 1 as a function of temperature. The thermal conductivity of steel fibre-reinforced HSC is almost constant in the temperature range of 400-1000°C. This can be attributed to the presence of steel fibre-reinforcement in concrete, which helps in limiting the crack growth and propagation, and thus decreases the rate of heat transfer in the specimen. Also, as in the case plain HSC, the thermal conductivity of siliceous aggregate steel fibre-reinforced HSC is higher than that of the carbonate concrete in the entire temperature range of 20°C to 1000°C.

Specific Heat – The specific heat is generally expressed in terms of thermal capacity which is a product of specific heat and density. The thermal capacity of plain HSC for the two types of aggregate is shown in Fig. 2a, as a function of temperature. For carbonate aggregate concrete, the specific heat (thermal capacity) shows a peak at temperatures near 150°C and 400°C, while for siliceous aggregate concrete, there is a small peak at 500°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 siliceous aggregate concrete, at about 500°C, can be attributed to the presence of quartz, which transforms in this temperature region.

The specific heat of HSC, similar to that of NSC, is also affected by other physicochemical processes that occur in the cement paste and the aggregates at temperatures above 600°C. The specific heat of carbonate aggregate concrete above this temperature is generally higher than that of siliceous aggregate concrete. Above 600°C, an enormous amount of heat is needed to raise the temperature of the carbonate aggregate concrete. This heat is approximately ten times the heat needed to produce the same temperature rise in siliceous aggregate concrete. The increase in specific heat is likely caused by the dissociation of the dolomite in the carbonate concrete and is beneficial in preventing spalling of the concrete (Harmathy 1970). The test data for carbonate aggregate are plotted up to 700°C since problems were encountered in measuring heat capacity with the DTA apparatus above 700°C.

The thermal capacity of steel fibre-reinforced HSC is shown in Fig. 2b as a function of temperature. The presence of steel fibres slightly increases the specific heat of the fibre-reinforced concrete in the temperature range of 0-600°C. This can be attributed to the fact that the presence of steel fibres in HSC controls cracking and the progression of cracks at lower temperatures. This in turn translates into high heat capacity. However, the influence of the steel on the specific heat of the concrete is very small in the temperature range examined.

<u>Thermal Expansion</u> -- In Fig. 3, the variation of thermal expansion with concrete temperature for siliceous and carbonate aggregate plain HSC is compared. The type of aggregate has a significant influence on the thermal expansion. For the siliceous aggregate HSC, the thermal expansion increases with temperature up to about 700°C and then remains constant. The increase in thermal expansion near 550°C can be attributed to the transformation of quartz in the siliceous aggregate. This could contribute to spalling (Harmathy 1970). For the carbonate aggregate HSC, the thermal expansion increases

steeply with temperatures above 500°C. This can be partly attributed to the dissociation of dolomite, which is present in the carbonate aggregate. . Above 800°C, the thermal expansion of the plain HSC declines somewhat, due to further dehydration and shrinkage of the concrete (Lie 1972).

The thermal expansion of steel fibre-reinforced HSC is shown in Fig. 3b for HSC with siliceous and carbonate aggregate. It can be seen that the steel fibre-reinforced concrete has similar thermal expansion as that of plain concrete up to a temperature of about 800°C. Above 800°C, the thermal expansion of steel fibre-reinforced concrete increases slightly, as compared to plain HSC, with temperature. This slight increase with temperature can be attributed to the presence of the steel fibres, which continue to expand at elevated temperatures. The yielding temperature for steel fibres is higher than for ordinary reinforcement.

<u>Mass Loss</u> -- The test data from the TGA are presented in Fig. 4a in the form of thermogravimetric curves for the siliceous and carbonate aggregate plain HSC examined in this study. Previous studies (Lie and Kodur 1995, 1996) have indicated that the type of aggregate has a strong influence on the mass loss and, therefore, on the density of the concrete at elevated temperatures. The mass loss for both concrete types is very small until about 600°C, where it is about 3% of the original mass. Between 600°C and 700°C, the mass of carbonate aggregate concrete drops considerably with the temperature. Above 750°C, the mass loss again decreases slowly with temperature. The substantial mass loss and decrease in density for carbonate aggregate concrete is caused by the dissociation of the dolomite in the concrete. This endothermic chemical reaction is expected to be beneficial in preventing spalling of concrete (Lie 1993). In the case of siliceous aggregate concrete, the mass loss remains insignificant even above 600°C.

In Fig. 4b, the mass loss for the steel fibre-reinforced HSC is shown for siliceous and carbonate aggregate types. The mass loss for steel fibre-reinforced HSC is similar to plain HSC up to about 800°C. Above 800°C, in the case of carbonate aggregate mix the mass loss in steel fibre-reinforced HSC is slightly lower than that of plain HSC. This can be attributed to the higher density of steel fibres (Purkiss 1984). Overall, the mass loss of the concrete in the temperature range of 0°C to 1000°C is not significantly affected by the presence of steel fibre-reinforcement.

SUMMARY

Based on the above experimental data, the following points can be summarized:

- The thermal conductivity of siliceous aggregate HSC is generally higher than that of carbonate aggregate HSC. The effect of steel fibre-reinforcement on the thermal conductivity of HSC is very small.
- The type of aggregate has significant influence on the specific heat of HSC at elevated temperatures. Generally, the carbonate aggregate concrete has higher specific heat in the 600°C to 850°C range. The influence of steel-fibre reinforcement on the specific heat of the concrete is very small in the temperature range investigated.
- The thermal expansion of siliceous aggregate HSC is higher than that of carbonate aggregate concrete in the 20°C to 800°C temperature range. The thermal expansion of HSC is not significantly affected by the presence of steel-fibre reinforcement at temperatures up to approximately 800°C.
- The type of aggregate has significant influence on the mass loss of HSC, with carbonate aggregate having much higher mass loss, up to 30%, at temperatures above 600°C. The mass loss of HSC is not significantly affected by the presence of steel-fibre reinforcement.

RELATIONSHIPS FOR THERMAL PROPERTIES

In recent years a number of numerical models have been developed for predicting the response of structures under fire conditions (Kodur and Lie 1996, Sullivan et al. 1993). These calculation methods for evaluating fire resistance are far less costly and time consuming. However, for the use of these calculation methods, the material properties at elevated temperatures are required.

To facilitate the use of the thermal properties as input data for the calculation of the temperatures of HSC constructions exposed to heat, simplified formulae have been derived which give these properties as a function of temperature in the temperature range of 0-1000°C. In the current study the thermal relationships for plain and steel fibre-reinforced HSC are developed for two commonly used aggregates. Furthermore, in the development of the formulae for the thermal properties, care was taken to keep the formulae simple and in a form similar to that for normal strength concrete ((Lie and Kodur 1996). These formulae are given in the Appendix. The thermal plots evaluated using the proposed formulas are plotted in Figures 1-4. It can be seen that the proposed formulae closely fit the test data through out the temperature range.

These relationships, presented in the Appendix, can be used as input to numerical models, which can then be used to determine the behaviour of HSC structural members at high temperatures ((Kodur and Lie 1996).

CONCLUDING REMARKS

Based on the studies presented in this paper, the following conclusions can be drawn:

1. The type of aggregate has significant influence on the thermal properties of HSC at elevated temperatures. The presence of carbonate aggregate in HSC increases fire resistance.
2. The thermal properties, at elevated temperatures, exhibited by steel fibre-reinforced HSC, are similar to those of plain HSC.
3. The proposed relationships for thermal properties can be used as input data for modelling the behaviour of structural members exposed to fire.

REFERENCES

1. Diederichs, U., Jumppanen, U.M. and Schneider, U., 1995. "High Temperature Properties and Spalling Behaviour of High Strength Concrete"; Proceedings of Fourth Weimar Workshop on High Performance Concrete, HAB Weimar, Germany, pp. 219-235.
2. Harmathy, T.Z., 1970. "Thermal Properties of Concrete at Elevated Temperatures"; ASTM Journal of Materials, Vol. 5, No. 1, pp. 47-74.
3. Kodur, V.K.R., 1997a. "Studies on the fire resistance of high strength concrete at the National Research Council of Canada", Proceedings: Fire Performance of High Strength Concrete, NIST Special Publication vol. 919, pp. 75-86, Gaithersburg, MD., U.S.A.
4. Kodur, V.K.R., 1997b. "Fibre-Reinforced Concrete for Enhancing the Structural Fire Resistance of Columns", Proceedings, ACI Spring Convention, Seattle, WA, U.S.A, (in press).
5. Kodur, V.R., 2000. "Spalling in high strength concrete exposed to fire - concerns, causes, critical parameters and cures", Proceedings: ASCE Structures Congress, 1-8, Philadelphia, U.S.A.
6. Kodur, V.K.R. and Lie, T.T., 1996, "A Computer Program to Calculate the Fire Resistance of Rectangular Reinforced Concrete Columns"; Third Canadian Conference on Computing in Civil and Building Engineering, Montreal, Canada, pp. 11-20.
7. Kodur, V.K.R. and Lie, T.T., 1998. "Fire Resistance of Fibre-Reinforced Concrete"; Fibre Reinforced Concrete: Present and the Future, Canadian Society of Civil Engineers, pp. 189-213.
8. Kodur, V.R.; Sultan, M.A., 1998. "Structural behaviour of high strength concrete columns exposed to fire" Proceedings: International Symposium on High Performance and Reactive Powder Concrete, Vol. 4, 217-232, Sherbrooke, Quebec.
9. Lie, T.T., 1972. "Fire and Buildings"; Applied Science Publishers Ltd., London.
10. Lie, T.T., Editor, 1993. "Structural Fire Protection: Manual of Practice"; ASCE Manual and Reports on Engineering Practice, No. 78, pp. 241, American Society of Civil Engineers, New York, NY.

11. Lie, T.T. and Kodur, V.K.R., 1995. "Thermal Properties of Fibre-Reinforced Concrete at Elevated Temperatures"; Internal Report No. 683, pp. 14, Institute for Research in Construction, National Research Council of Canada, Ottawa, Canada.
12. Lie, T.T. and Kodur, V.K.R., 1996. "Thermal and Mechanical Properties of Steel Fibre-Reinforced Concrete at Elevated Temperatures"; Canadian Journal of Civil Engineering, Vol. 23, No. 4, pp. 511-517.
13. Phan, L.T., 1996. "Fire Performance of High-Strength Concrete: A Report of the State-of-the-Art"; Report, NISTIR 5934, pp. 105, National Institute of Standards and Technology, Gaithersburg, MD.
14. Purkiss, J.A., 1984. "Steel Fibre-Reinforced Concrete at Elevated Temperatures"; International Journal of Cement Composites and Light Weight Concrete, Vol. 6, No. 3, pp. 179-184.
15. Sullivan, P.J.E., Terro, M.J., and Morris, W.A., 1993. "Critical Review of Fire-Dedicated Thermal and Structural Computer Programs"; Journal of Applied Fire Science, Vol. 3, No. 2, pp. 113-135.

LIST OF NOTATIONS

c_c	specific heat (J kg^{-1}°C^{-1})
k	thermal conductivity (W m^{-1}°C^{-1})
M	mass at temperature T (kg)
M_o	mass at room temperature (kg)
T	temperature (°C)
α	coefficient of thermal expansion (m m^{-1}°C^{-1})
ρ_c	density of the concrete (kg m^{-3})

APPENDIX
HIGH STRENGTH CONCRETE

Thermal capacity

Siliceous aggregate concrete

for $0 \leq T \leq 200°C$

$$\rho_c c_c = (0.005T + 1.70) \times 10^6$$

for $200 < T \leq 400°C$

$$\rho_c c_c = 2.70 \times 10^6$$

for $400 < T \leq 500°C$

$$\rho_c c_c = (0.013T - 2.50) \times 10^6$$

for $500 < T \leq 600°C$

$$\rho_c c_c = (-0.013T + 10.50) \times 10^6$$

for $T > 600°C \leq 1000°C$

$$\rho_c c_c = 2.70 \times 10^6$$

Carbonate aggregate concrete

for $0 \leq T \leq 400°C$

$$\rho_c c_c = 2.45 \times 10^6$$

for $400 < T \leq 475°C$

$$\rho_c c_c = (0.0260T - 12.850) \times 10^6$$

for $475 < T \leq 650°C$

$$\rho_c c_c = (0.0143T - 6.295) \times 10^6$$

for $650 < T \leq 735°C$

$$\rho_c c_c = (0.1894T - 120.11) \times 10^6$$

for $735 < T \leq 800°C$

$$\rho_c c_c = (-0.2630T + 212.40) \times 10^6$$

for $800 < T \leq 1000°C$

$$\rho_c c_c = 2.00 \times 10^6$$

Thermal conductivity

Siliceous aggregate concrete

for $0 \leq T \leq 1000$°C

$$k = 2.00 - 0.0011T$$

Carbonate aggregate concrete

for $0 \leq T \leq 300$°C

$$k = 2.00 - 0.0013T$$

for $300 < T \leq 1000$°C

$$k = 2.21 - 0.0020T$$

Coefficient of thermal expansion

Siliceous aggregate concrete

for $0 \leq T \leq 450$°C

$$\alpha = -0.0002 + 0.000011T$$

for $450 < T \leq 650$°C

$$\alpha = -0.0115 + 0.000036T$$

for $650 < T \leq 1000$°C

$$\alpha = 0.0119$$

Carbonate aggregate concrete

for $0 \leq T \leq 450$°C

$$\alpha = -0.0002 + 0.000008T$$

for $450 < T \leq 920$°C

$$\alpha = -0.0061 + 0.000021T$$

for $920 < T \leq 1000$°C

$$\alpha = 0.0242 - 0.000012T$$

Mass loss

Siliceous aggregate concrete

for $0 \leq T \leq 1000°C$

$$M/Mo = 1.000 - 0.00005T$$

Carbonate aggregate concrete

for $0 \leq T \leq 600°C$

$$M/Mo = 1.003 - 0.00006T$$

for $600 < T \leq 700°C$

$$M/Mo = 2.551 - 0.00264T$$

for $700 < T \leq 1000°C$

$$M/Mo = 0.710 - 0.00001T$$

STEEL FIBRE-REINFORCED HIGH STRENGTH CONCRETE

Thermal capacity

Siliceous aggregate concrete

for $0 \leq T \leq 100°C$

$$\rho_c c_c = (0.006T + 1.60) \times 10^6$$

for $100 < T \leq 400°C$

$$\rho_c c_c = 2.20 \times 10^6$$

for $400 < T \leq 500°C$

$$\rho_c c_c = (0.011T - 2.20) \times 10^6$$

for $500 < T \leq 600°C$

$$\rho_c c_c = (-0.011T + 8.80) \times 10^6$$

for $T > 600°C \leq 1000°C$

$$\rho_c c_c = 2.20 \times 10^6$$

Carbonate aggregate concrete

for $0 \leq T \leq 400°C$

$$\rho_c c_c = 3.81 \times 10^6$$

for $400 < T \leq 475°C$

$$\rho_c c_c = (-0.0165T + 10.41) \times 10^6$$

for $475 < T \leq 625°C$

$$\rho_c c_c = (0.0079T - 1.182) \times 10^6$$

for $625 < T \leq 700°C$

$$\rho_c c_c = (0.2333T - 142.06) \times 10^6$$

for $700 < T \leq 800°C$

$$\rho_c c_c = (-0.1800T + 147.25) \times 10^6$$

for $800 < T \leq 1000°C$

$$\rho_c c_c = 3.25 \times 10^6$$

Thermal conductivity

Siliceous aggregate concrete

for $0 \le T \le 200°C$

$$k = 2.50 - 0.0034T$$

for $200 < T \le 400°C$

$$k = 2.24 - 0.0021T$$

for $400 < T \le 1000°C$

$$k = 1.40$$

Carbonate aggregate concrete

for $0 \le T \le 500°C$

$$k = 1.80 - 0.0016T$$

for $500 < T \le 1000°C$

$$k = 1.20 - 0.0004T$$

Coefficient of thermal expansion

Siliceous aggregate concrete

for $0 \le T \le 530°C$

$$\alpha = -0.0010 + 0.000016T$$

for $530 < T \le 600°C$

$$\alpha = -0.0386 + 0.000087T$$

for $600 < T \le 1000°C$

$$\alpha = 0.0136$$

Carbonate aggregate concrete

for $0 \leq T \leq 700°C$

$$\alpha = -0.0002 + 0.000009T$$

for $700 < T \leq 870°C$

$$\alpha = -0.0345 + 0.000058T$$

for $870 < T \leq 1000°C$

$$\alpha = 0.0160$$

Mass loss

Siliceous aggregate concrete

for $0 \leq T \leq 1000°C$

$$M/Mo = 1.000 - 0.00004T$$

Carbonate aggregate concrete

for $0 \leq T \leq 700°C$

$$M/Mo = 1.003 - 0.00006T$$

for $700 < T \leq 785°C$

$$M/Mo = 2.214 - 0.00179T$$

for $785 < T \leq 1000°C$

$$M/Mo = 0.817 - 0.00001T$$

FIGURE CAPTIONS

Figure 1 Thermal Conductivity of High Strength Concrete

- a) Effect of Aggregate Type
- b) Effect of Fibre Reinforcement

Figure 2 Specific Heat Capacity of High Strength Concrete

- a) Effect of Aggregate Type
- b) Effect of Fibre Reinforcement

Figure 3 Thermal Expansion of High Strength Concrete

- a) Effect of Aggregate Type
- b) Effect of Fibre Reinforcement

Figure 4 Mass Loss of High Strength Concrete

- a) Effect of Aggregate Type
- b) Effect of Fibre Reinforcement

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