The Performance of Concrete at Elevated Temperatures (as measured by the reduction in compressive strength)

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Abstract

The paper describes experimental work carried out at Imperial College by the second author under the supervision of the first. The aim was to select a concrete mix which could perform as well at high temperatures as at ambient temperature. The testing was carried out on cement matrix and also on cementitious materials with different percentage replacements of the cement. In order to optimize the performance of concrete, various thermally stable aggregates were used in the mixes tested.

The type of concrete described would be suitable for buildings which are required to have an enhanced fire endurance. Other structures which would benefit from concrete with a high performance at elevated temperatures are chimneys, nuclear and conventional reactors, and launching pads and pavements for vertical take-off aircraft.

Introduction

The mechanical performance of concrete at any temperature depends on the properties of the cement, the aggregates, and the bond between them. A series of tests was carried out (1) to investigate the behavior of pastes containing Type 1 Ordinary Portland Cement (OPC), OPC + various replacement cementitious materials, and (2) to investigate concretes using thermally stable aggregates in conjunction with these cements and cementitious materials.

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Previous tests[2,3,4,5] aimed at determining the performance of different types of natural and manufactured aggregates indicated that concrete containing certain aggregates begins to break down at temperatures as low as 350°C, whereas the cement paste samples appeared to retain their integrity up to temperatures in excess of 550°C.[6] The objective of the present series of testing was, therefore, to examine whether it was possible to increase the base temperature limit of the binder and find a compatible aggregate for optimum performance at high temperature. Performance was defined by measuring compressive strength of the samples after heating them to temperatures up to 600°C.

Tests Undertaken

The research program included the six tests listed below, but in this paper only selected results from the first and second series of tests are described.

1. Residual strength after heating and natural cooling to ambient temperature.
2. Hot compressive strength after heating to different temperatures.
3. Residual strength after cooling at different rates.
4. Residual strength after heating and cooling to ambient temperature under different environments.
5. Residual strength after maintaining the samples for different periods of time at high temperature.
6. Residual strength after maintaining the samples under precompression for different periods of time at high temperature.

Samples Used and Preparation

The samples were 63.0 mm (2.5 in.) diameter and 63.0 mm (2.5 in.) long. The cement paste samples were mixed as prescribed in ASTM C305[7] and campacted as described in ASTM C192.[8] For the concrete samples, the ingredients were mixed dry for one minute, before adding the water and mixing for a further two minutes. The samples were then allowed to cure at 20°C and 100% RH for at least 12 months, until they were required for testing. The increase in strength for all samples between 12 and 18 months, during which period the testing was carried out, was negligible. The ends of the cylinders had been ground flat and perpendicular to their axes prior to testing.

Description of Materials

Table 1 gives the 28-day cylinder strength and proportions of binders tested which were OPC paste (C), OPC + slag (C+S), OPC + fly ash (C+FA), OPC + silica fume (C+SF). To make concrete mixes in the proportions shown in Table 2 the aggregates were Lytag, a propriety lightweight

Table 1. Proportions and strength of cement pastes

CONSTITUTENTS	PROPORTION – DRY WEIGHT			
	C	C+S	C+FA	C+SF
Cement (C)	1	0.35	0.70	0.90
Slag (S)	—	0.65	—	—
Silica fume (SF)	—	—	—	0.10
Fly ash (FA)	—	—	0.30	—
Water	0.36	0.34	0.34	0.43
Strength (N/mm^2)	79.5	68.7	71.8	66.3
(psi)	11,528	9,962	10,411	9,614

Table 2. Proportions and strength of concrete

MIX	PROPORTION– DRY WEIGHT				
	C+LA	C+SF+LA	C+FB	C+SF+FB	C+S+FB
C	1	0.90	1	0.90	0.35
S	—	—	—	—	0.65
SF	—	0.10	—	0.10	—
LA	—	—	—	—	—
coarse	1.26	1.26	—	—	—
fine	1.08	1.08	—	—	—
FB	—	—	—	—	—
	coarse	—	—	1.46	1.46
1.46					
fine	—	—	1.89	1.89	1.89
Water	0.67	0.73	0.63	0.77	0.60
N/mm^2	44.9	65.0	57.5	37.8	50.0
(psi)	6,511	9,425	8,338	5,481	7,250

aggregate which is an expanded pulverized fuel ash (LA) and crushed firebrick (FB), and these were used as aggregates for the cement pastes described in Table 1.

The maximum size of the coarse aggregates was 12.7 mm (0.5 in.) and conformed to the grading limits in BS 3797.9 The maximum size of the coarse aggregates was 9.5 mm (0.375 in.) and also conformed to the grading limits in BX 3797. The percentage of firebrick fines passing through the 2.4 mm (No. 7) sieve was 82.1% and the percentage off Lytag fines was 58.9%.

Previous testing on different types of concrete with a constant volume aggregate fraction (0.67) indicated that the load induced thermal strains for a given imposed stress were independent of the type of aggregate.[4,5] For this reason, the aggregate volume fraction for all the types of concretes tested was kept nearly constant (between 0.65 and 0.67). In Table 2, only the shorthand nomenclature has been used for the constituents.

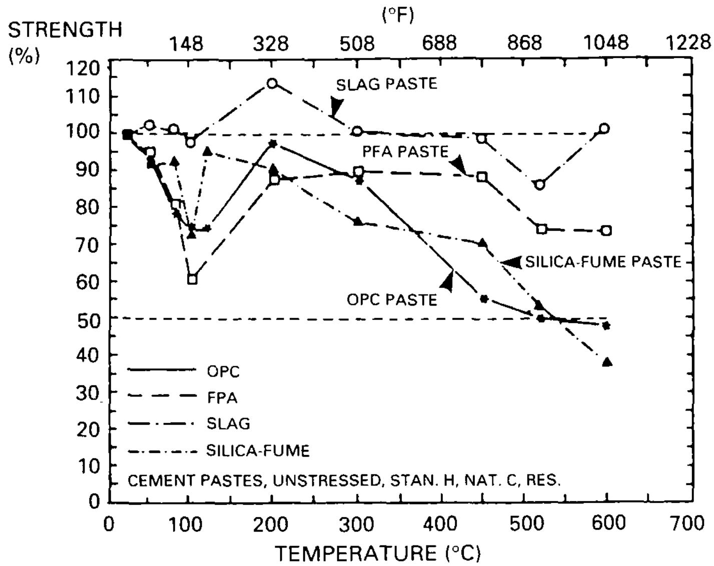

Figure 1. Relationship of residual strength of different types of cement pastes with temperature.

Apparatus

Since the program covered a large range of testing, a number of furnaces were used including three cylindrical furnaces,[9] each capable of testing three samples at the same time,[1,10] and a horizontal furnace with a chamber 275 mm (11 in.) deep, 200 mm (8 in.) wide and 925 mm (36 in.) long capable of heating a number of samples simultaneously.[2] A muffle furnace was also used and placed around a compression machine for testing single specimens at high temperature.

The rate of heating of the furnaces could be controlled, and the temperature distributions within the furnaces and the samples had been previously calibrated. The longitudinal and lateral temperature distributions of the samples at all the rates of heating were maintained at a level which ensured that the stresses due to the temperature gradients were insignificant,[10] thus ensuring that the authentic material property was being measured.

Test Procedure

The residual strength tests in series 1 were performed on all the mixes after heating at a rate of 1oC per minute to temperature levels of 50°C, 80°C, 100°C, 120°C, 200°C, 300°C, 450°C, 520°C and 600°C. The samples were held at test temperature for a period of 9 to 22 hours and then allowed to cool naturally within the furnace.

The hot compressive strength tests in series 2 were conducted on the concrete after heating at approximately 1.5°C per minute, and maintained for a period of 2 to 6 hours at a temperature level of 80°C, 100°C, 120°C 200°C, 300°C, 450°C, 520°C and 600°C.

Results

Residual Strength

The variation of residual strength with temperature is given in Figures 1 to 5.

The residual strength of the cement pastes in Figure 1 shows a depression in strength around 100°C, the depression being largest for the FA/ cement paste reaching 60% of the cold strength. The slag paste did not exhibit any loss in strength. The residual strengths of the pastes recovered at 200°C to 90% for the FA paste. The OPC paste recovered its residual strength nearly completely at 200°C, but thereafter the strength for the cement paste dropped to 50% and the silica fume paste dropped to 40% at 600°C. The FApaste retained its residual strength from 200oC to 500oC and only dropped to 70% at 600°C.

There was no significant reduction in strength for the slag cement up to 600°C.

The residual strength for firebrick concrete and Lytag concrete in Figure 2 shows little loss in strength up to 200°C. Thereafter the strength dropped

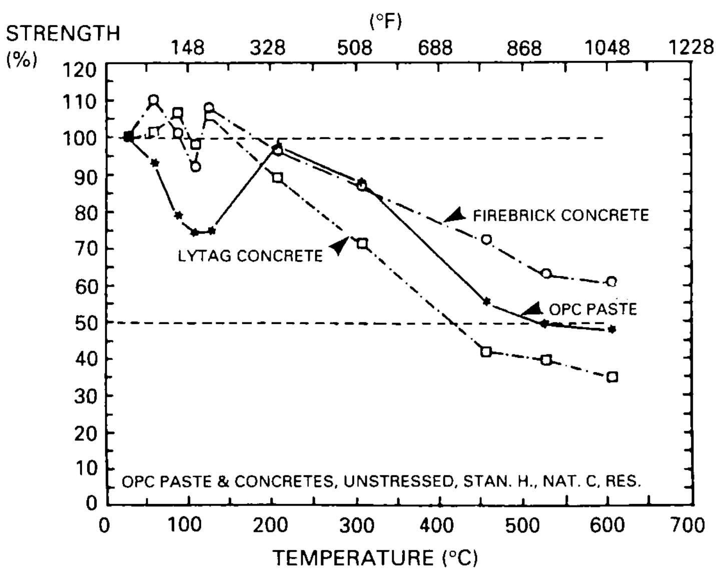

Figure 2. Relationship of residual strength of OPC paste, Lytag OPC concrete, and firebrick OPC concrete with temperature.

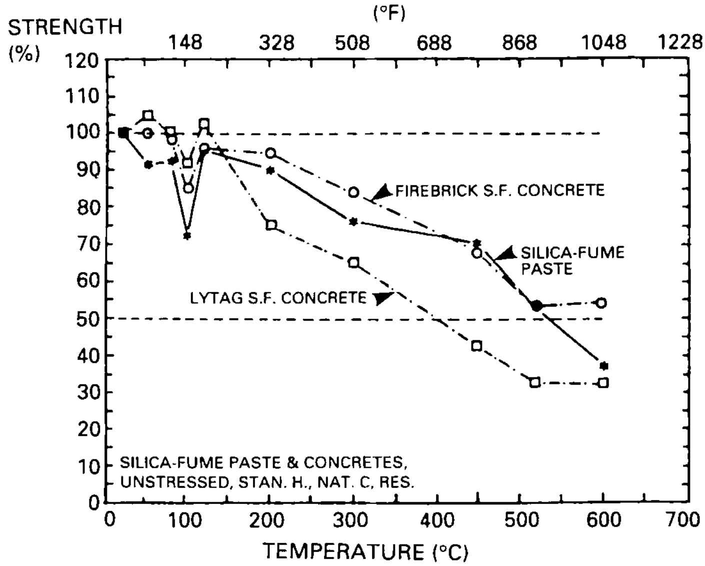

Figure 3. Relationship of residual strength of silica-fume paste, Lytag concrete containing silica-fume, and firebrick concrete containing silica-fume with temperature.

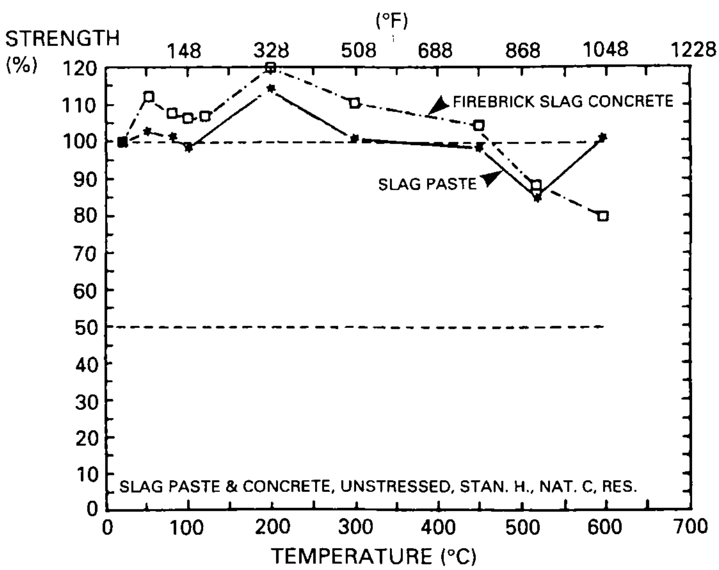

Figure 4. Relationship of residual strength of slag paste and firebrick concrete containing slag with temperature.

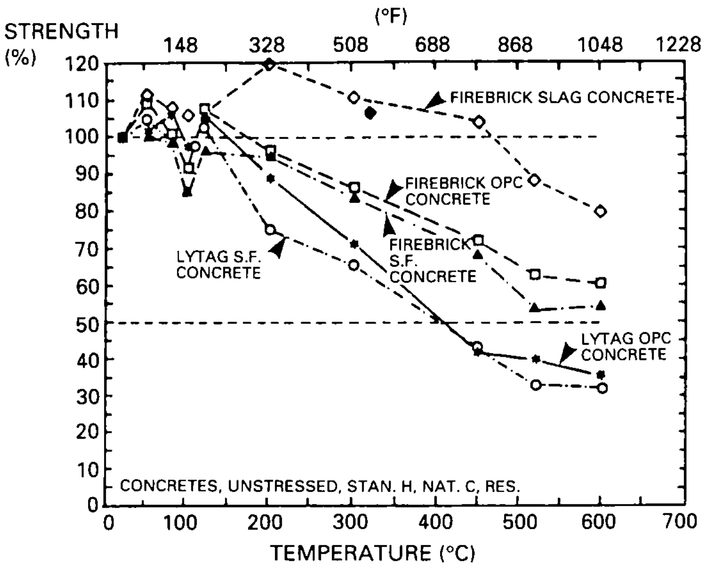

Figure 5. Relationship of residual strength of different types of concrete with temperature.

to 60% for the firebrick concrete and 50% for the Lytag concrete at 600°C.

The residual strength for the silica fume firebrick concrete and Lytag concrete in Figure 3 exhibited similar behavior, with the silica fume firebrick concrete dropping to 50% at 600°C and the silica fume Lytag concrete dropping to 30% at the same temperature.

As indicated in Figure 4, the firebrick slag concrete behaved similarly to the slag paste showing a slight increase in strength up to 120% at 200°C. The residual strength was higher than the cold strength up to a temperature of about 500°C but thereafter it decreased until at 600°C it had dropped to 80%.

Figure 5 shows the residual strengths of all the concretes tested on the same plot for comparison.

Hot strength

The variation of hot compressive strength with temperature of the concrete tested is given in Figures 6 to 10.

Figure 6 shows that the hot strength of Lytag concrete drops to just over 60% at 80oC, recovers to about 90% at 100°C, and gradually drops to 60% at 600oC. Figure 7 shows that the hot strength of the firebrick concrete decreases in strength to just over 70% at 100°C, completely recovers gradually at 300°C, and thereafter decreases in strength to just over 50% at 600°C.

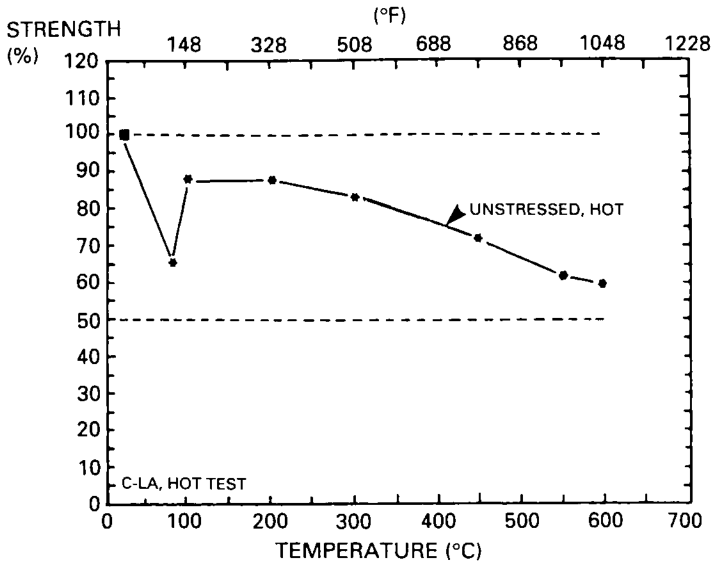

Figure 6. Relationship of hot strength of Lytag concrete with temperature.

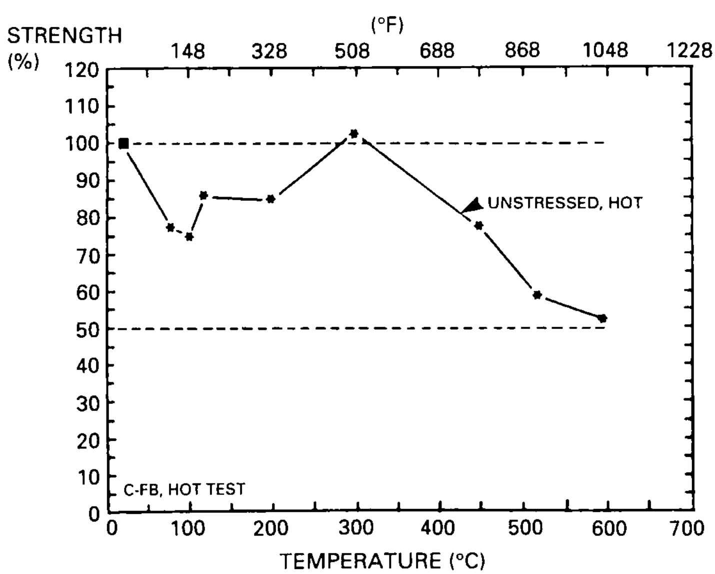

Figure 7. Relationship of hot strength of firebrick concrete with temperature.

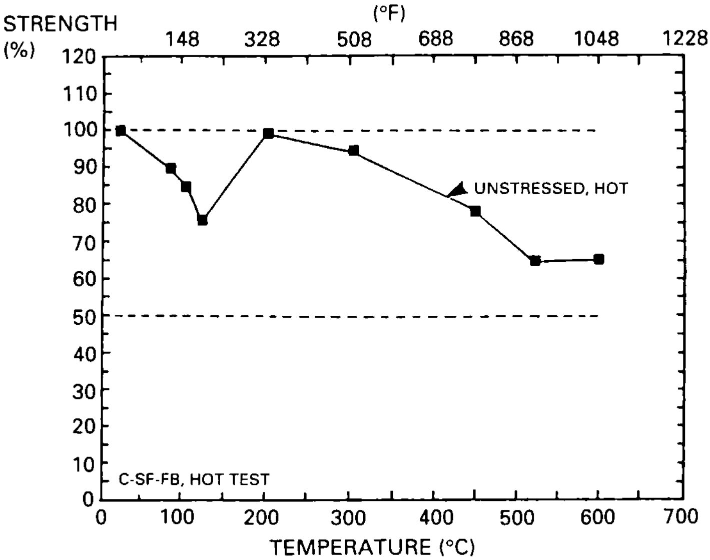

Figure 8. Relationship of hot strength of firebrick concrete containing silica-fume with temperature.

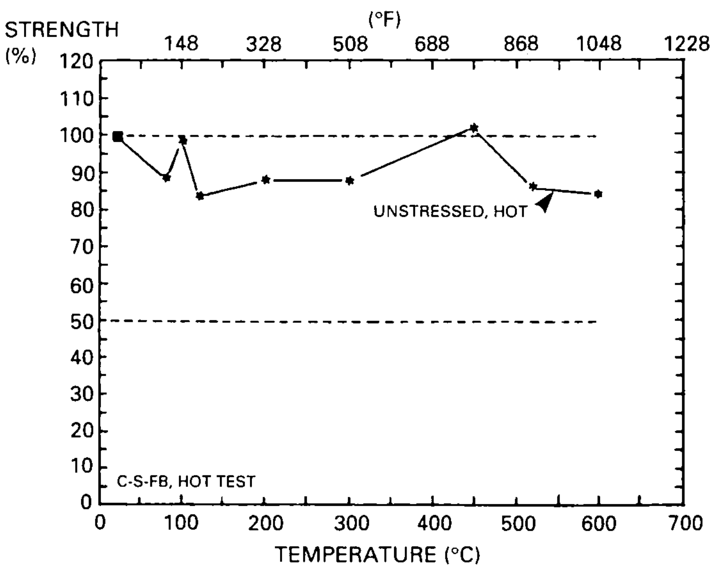

Figure 9. Relationship of hot strength of firebrick concrete containing slag with temperature.

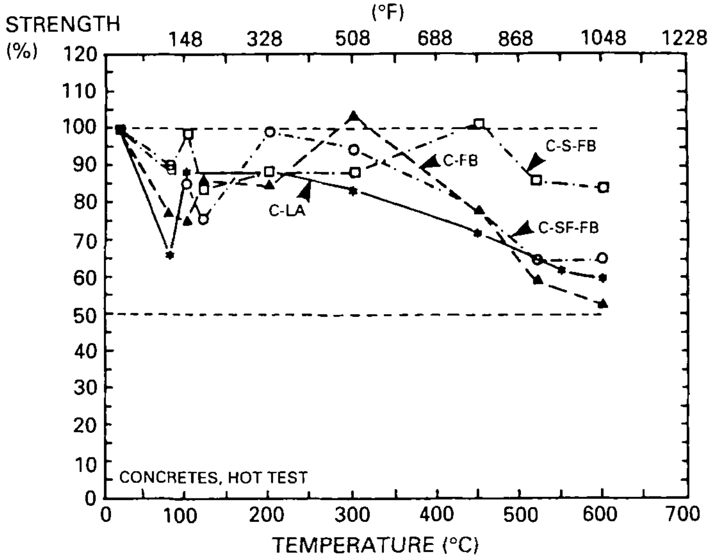

Figure 10. The variation in the hot strength of the different concrete specimens with temperature.

Conclusions

It is clear from the above that replacing 10% of the weight of the cement with silica fume in the paste does not improve the performance of concrete at high temperature but that replacing 30% of the weight of the cement with fly ash exhibits an improvement in performance in the paste. However, the optimum performance of the paste appears to occur when 65% of the cement is replaced by ground, granulated blast furnace slag.

When inert aggregate in the form of lightweight aggregate is introduced into the cement paste, firebrick slag concrete performs best up to temperatures of 600°C, especially when used in conjunction with a slag cement paste.

References

1. Sharshar, Roozbeh, "Effect of Elevated Temperatures on the Strength of Different Cement Pastes and Concretes," Ph.D. Thesis, University of London, London, England, 1989.
2. Sullivan, P.J.E., "The Structural Behavior of Concrete at Elevated Temperature," Ph.D. Thesis, University of London, London, England, 1970.

3. Sullivan, P.J.E. and Labani, J.M., "Flexural Behavior of Plain and Reinforced Lightweight Aggregate Concrete Beams up to 600°C," *Cement and Concrete Research*, 1974, pp 231-237.
4. Khoury, G. A., "The Effect of Elevated Temperature on Concrete," Ph.D. Thesis, University of London, London, England, 1983.
5. Khoury, G.A., Grainger B., and Sullivan, P.J.E., "Strain of Concrete During First Time Heating," *Magazine of Concrete Research*, Sept. 1985, Dec. 1985, and March 1986.
6. Sullivan, P.J.E. and Khoury, G.A., "Transient and Steady State Temperature Creep Strains for Typical Reactor Pressure Vessels," Federation Internationale de la Precontrainte Congress, London, England, 1978.
7. "Mechanical Mixing of Hydraulic Cement Pastes and Mortars of Plastic Consistency," ASTM C305-65, American Society of Testing and Materials, Philadelphia, PA, 1965.
8. "Making and Curing Concrete Test Specimens in the Laboratory," ASTM C192-81, American Society of Testing and Materials, Philadelphia, PA, 1981.
9. Sullivan, P.J.E., Khoury, G.A., and Grainger, B.," Apparatus for Measurement of the Transient Thermal Strain Behavior of Unsealed Concrete Under Constant Load for Temperatures up to 700°C," *Magazine of Concrete Research*, Vol. 35, No. 125, December 1983, pp 229-235.
10. Khoury, G.A., Sullivan, P.J.E., and Grainger, B.,"Radial Temperature Distributions Within Solid Concrete Cylinders Under Transient Thermal States," *Magazine of Concrete Research* Vol. 36, No. 128, Sept. 1984, pp 145-156.