Pergamon

Cement and Concrete Research, Vol. 25, No. 8, pp. 1791-1802, 1995
1995 Elsevier Science Ltd

0008-8846/95 $9.50+.00

0008-8846(95)00175-1

STRENGTH DEVELOPMENT OF HIGH STRENGTH CONCRETES WITH AND WITHOUT SILICA FUME UNDER THE INFLUENCE OF HIGH HYDRATION TEMPERATURES

Swee Liang Mak* and Kazuyuki Torii†
*CSIRO Division of Building, Construction and Engineering
P.O. Box 56, Highett, Victoria 3190, Australia
†Department of Civil Engineering, Kanazawa University
Kodatsuno, Kanazawa, 920 Japan

(Refereed)
(Received June 8, 1995)

ABSTRACT

High performance concretes of high compressive strength are finding increasing applications in many fields of construction such as core walls and columns in tall buildings, long-span bridges and marine structures. In thick cross-sections, the high binder contents of some high strength concretes can result in the development of high *in-situ* temperatures. The combined influence of limited moist curing and high hydration temperatures may significantly influence the progress of hydration. This can affect the long-term development of *in-situ* strength and other engineering properties. Knowledge of *in-situ* strength development under these conditions is needed to ensure safe utilisation of this new generation of construction materials.

This paper presents results of an investigation on the strength development of high strength concretes with and without silica fume subjected to high *in-situ* temperature conditions. A temperature match conditioning (TMC) system was developed and used to simulate the semi-adiabatic temperature development within medium sized high strength concrete columns. The results of this investigation show that *in-situ* temperatures of up to 70°C significantly increased the 7-day strength of a high strength silica fume concrete. Although no strength regression was observed up to 1 year, the silica fume concrete subjected to high early temperatures showed significantly lower strengths when compared to concrete cured at standard temperature. For the silica fume concrete subjected to high early temperatures, non-evaporable water contents suggest little additional hydration beyond 3 days.

Introduction

High strength concretes are typically proportioned with high total binder contents, often in excess of 500 kg/m^3. Potentially, this results in the development of high *in-situ* temperatures in thick structural cross-sections. Peak *in-situ* temperatures up to 70°C are quite common (1–7).

Whilst high *in-situ* temperatures generally accelerate the early strength development of concrete, the medium- and long-term strength development may be retarded or even regressed (8–10). In concrete mixes with low water/binder ratios, self-desiccation also occurs (11–13). The relative humidity within capillary pores is reduced to levels that are normally considered too low for any significant hydration to proceed. This condition is relevant for high strength concretes since low water/binder ratios of approximately 0.3 are typically used. Self-desiccation may be further exacerbated by the rapid consumption of free water due to the accelerated hydration of cement induced by high *in-situ* temperatures. The development of high *in-situ* temperature also has other implications which include high thermal gradients which can cause thermal cracking.

With the increasing utilisation of high performance concretes, and especially those containing supplementary cementitious materials, an understanding of the effects of *in-situ* temperature conditions on strength development is important. This provides a means for estimating the real strength of concrete in structures. Ultimately, such data allows estimates of the relationship between *in-situ* and standard cube or cylinder strength, thereby enabling safe and efficient structural design.

In this paper, the strength development of two high strength concretes with and without silica fume subject to the influence of high hydration temperatures is described. The influence of temperature is elucidated from comparisons between concrete cured under standard conditions and those undergoing temperature match conditioning (TMC). To obtain some understanding of the interrelationship between strength development and the progress of hydration, results from non-evaporable water contents of concrete are also discussed. Supplementary results from relative humidity measurements within concrete blocks are also presented to indicate the effects of self-desiccation.

Experimental

Concrete mixes and materials

Two concrete mixes were used in this study, an 80 MPa plain Portland cement concrete (Mix P80) and a 100 MPa silica fume concrete (Mix S100). The Portland cement was a Type GP cement widely available in Australia, whilst the coarse aggregate used was a basalt with a maximum size of 14 mm. Physical and chemical characteristics of the binders are shown in Table 1.

TABLE 1
Physical and chemical characteristics of GP cement and silica fume

	Type GP cement	Silica fume
SiO_2 (%)	21.0	92.3
CaO (%)	64.1	0.27
Al_2O_3 (%)	5.8	0.99
Fe_2O_3 (%)	2.9	0.87
C (%)		2.7
LoI (%)	1.6	2.55
SG	3.15	2.1
SSA (m^2/kg)	300	17000–20000

One of the primary objectives of this evaluation was to determine the influence of silica fume on concrete properties. Therefore, the mix proportions of the concretes were deliberately chosen to allow a direct comparison between a plain Portland cement concrete and a silica fume concrete on the basis of equal total binder content and equal water/binder ratio. For both concretes, the total binder contents were 500 kg/m^3 and the water/binder ratio were nominally 0.3. A formaldehyde-based lignosulphonate-type superplasticiser was added to achieve similar initial slumps. Mix details are shown in Table 2.

TABLE 2
Nominal mix proportions for high strength concretes

	Cement (kg/m^3)	SF (kg/m^3)	Water (kg/m^3)	Coarse agg. (kg/m^3)	Sand (kg/m^3)	SP (l/m^3)	Slump (mm)
P80	500	0	150	1330	595	5	130
S100	460	40	150	1385	535	6	150

Concrete mixing, specimen preparation and curing

Concrete mixes were prepared in an 80 L capacity rotary pan mixer. For each mix, 80 L of concrete was prepared, from which, a total of 45 cylinders, 100 mm diameter × 200 mm high, were cast. Each batch was separated into three sets, each of which was placed under one of three curing regimes:

- standard water bath at 23°C (B23);
- sealed at 23°C (S23); or
- TMC.

Sealing was achieved using a plastic contact adhesive film and was aimed at simulating the neutral moisture condition of internal concrete relative to that near the surface.

Temperature match conditioning

To investigate the influence of temperature on concrete properties, concrete cylinders were subjected to simulated *in-situ* temperature conditions using specially developed TMC equipment. The TMC system consists of a water tank with a heater controlled by a personal computer via a solid state relay switch. The conditioning tank has a 500 L capacity and is capable of accommodating over forty 100 × 200 mm cylinders at any one time. Process control software was developed to provide accurate matching of temperature between the water in the tank and the desired temperature profile. Matching of the water bath temperature with the input temperature profile was nominally accurate to within ± 0.2°C. Figure 1 shows the schematic layout of the TMC system. In order to simulate the moisture conditions of internal concrete, TMC cylinders were also sealed after the 3-day temperature match conditioning regime.

The semi-adiabatic temperature profiles used in this experiment were obtained from an earlier investigation on the *in-situ* core strength in high strength concrete column elements (14), where a series of column elements with dimensions of 0.8 × 0.8 m in cross-section and 1.2 m high were cast under laboratory conditions. The column elements had cross-sectional dimensions similar to those of lower storey columns in the 55-storey Melbourne Central Building where an

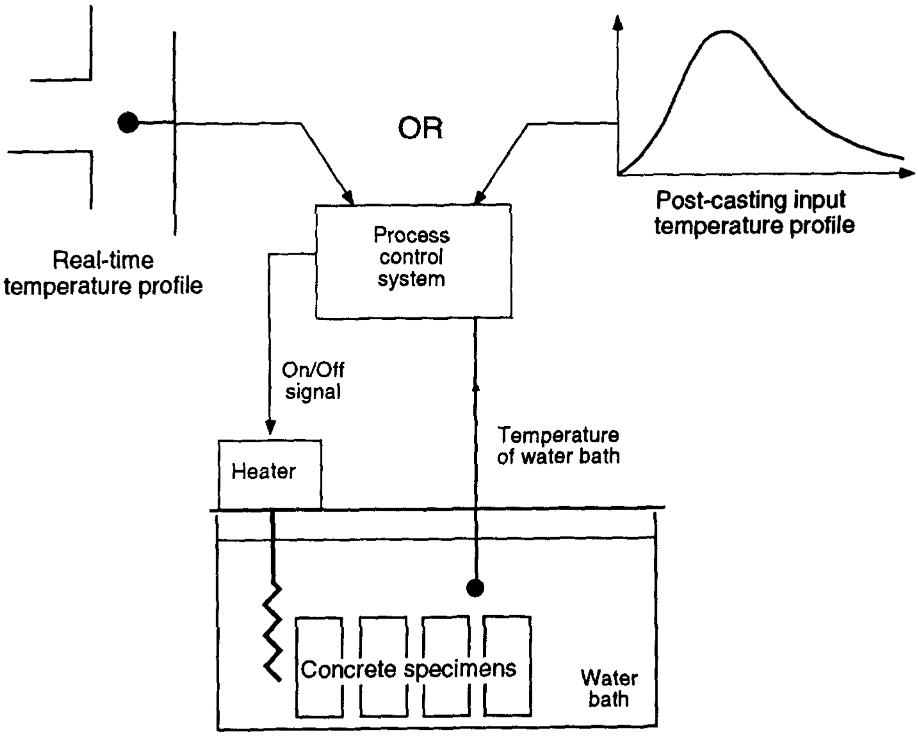

FIG. 1
Schematic lay-out of TMC system.

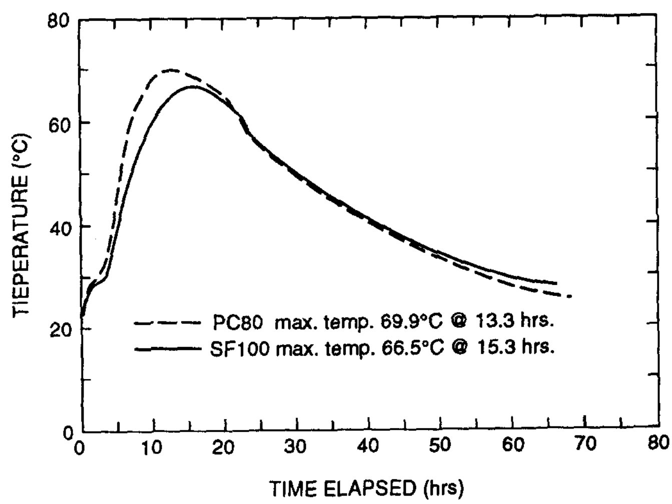

FIG. 2
Temperature profiles used in TMC tests.

80 MPa concrete was used. The temperature profiles at the centre of the 800 × 800 mm cross-sections are shown in Fig. 2.

Determination of non-evaporable water content

The non-evaporable water (w_n) content was determined from hardened mortar in concrete by drying crushed specimens for 24 hours at 105°C and then placing them in a furnace at 1000°C. The mortar specimens were sampled immediately after compressive strength tests on concrete specimens.

Compressive strength test

Cylinder compressive strengths were determined at 7, 28, 91 and 360 days. At each age, three cylinders for each condition were tested. All cylinders were capped with a high strength sulphur capping compound 24 hours prior to testing and maintained in their respective conditions until testing. For specimens with well trowelled ends, the use of a high strength sulphur capping with sufficient cap curing time has been found to be satisfactory for compressive strengths in excess of 120 MPa (15,16). The average coefficient of variation for all test results reported in this paper did not exceed 3%. Cylinders were tested in a 3000 kN compression testing machine.

Results and Discussion

Temperature development in high strength concrete columns

The maximum *in-situ* temperature in the column produced with the SF concrete was 66.5°C, which was marginally lower than that of 69.9°C obtained in the PC concrete column. The maximum temperature in the SF concrete column was achieved 15.3 hours after casting, whilst that in the PC concrete column was achieved slightly earlier at 13.3 hours after casting.

Strength development under standard temperature conditions

When cured in water under standard temperature conditions (B23), the compressive strength of the silica fume concrete, S100, was consistently higher than that of the plain Portland cement concrete, P80, as illustrated in Fig. 3. The 1-year compressive strengths of the PC and SF concretes were 100 and 111 MPa respectively.

The level of moist curing affected the strength of the PC concrete more than it did the SF concrete. As shown in Fig. 4, where the strength ratio of B23 to S23 cylinders with age is plotted, the difference in strength between fully moist cured and sealed cylinders was larger in the PC concrete when compared to the SF concrete. Therefore, when compared to the sealed situation where no net moisture gain is achieved, the provision of full moist curing benefitted the PC concrete to a larger extent when compared to the SF concrete.

Strength development of concrete under high 'in-situ' temperature conditions

The strength development of the two high strength concretes was affected markedly by the high *in-situ* temperature curing under TMC. Figure 5 shows the strength development of the PC concrete under three curing regimes, i.e. B23, S23 and TMC. For the PC concrete, the TMC cylinders showed higher early strengths when compared to those cured at standard temperature. The TMC cylinders continued to develop strength up to 1 year but at a slower rate than the water-cured cylinders. At 1 year, the TMC cylinders actually showed marginally lower strengths when compared to the B23 cylinders. However, if comparing cylinders with similar external moist curing

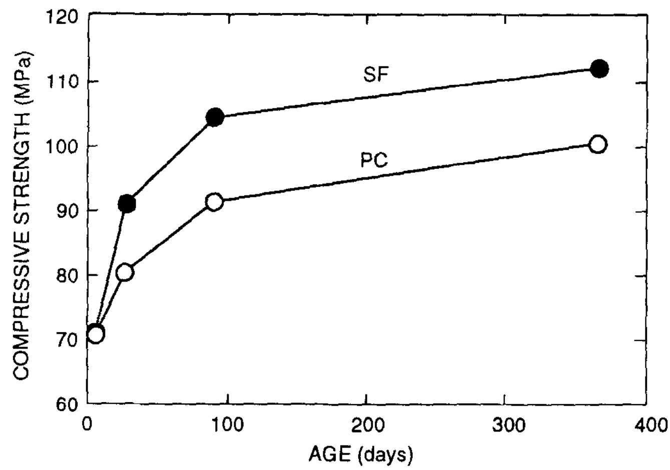

FIG. 3
Strength development of PC and SF concretes cured in water at 23°C (B23).

conditions, i.e. TMC and S23, it is clear that the high early temperatures had resulted in a significant strength increase.

The early age strength of the SF concrete due to TMC was also appreciably enhanced when compared to concrete cured at standard temperature. As illustrated in Fig. 6, the 7-day strength of the TMC cylinders was almost 20% higher than that of the S23 cylinders. However, high early age temperatures affected the later age strength development of the SF concrete in quite a different way when compared to the PC concrete. It is evident from Fig. 6 that the TMC cylinders did not show sustained strength development when compared to standard cylinders. The 28-day strengths of cylinders under all three regimes were virtually identical at approximately 90 MPa. However, the increase in compressive strength of the TMC cylinders between 28 days and 1 year was only 5 MPa, whilst that of the B23 and S23 cylinders exceeded 10 MPa. As a result, the 1-year compressive strength of TMC cylinders was significantly lower than those cured at standard temperature.

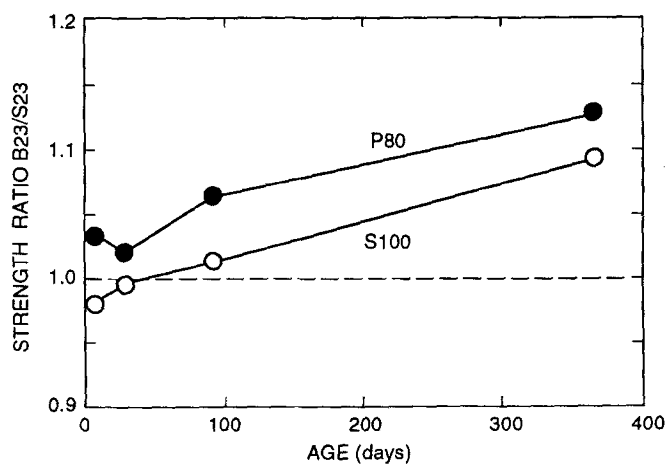

FIG. 4
Strength ratio between B23 and S23 cylinders with age for PC and SF concretes conditioned at 23°C.

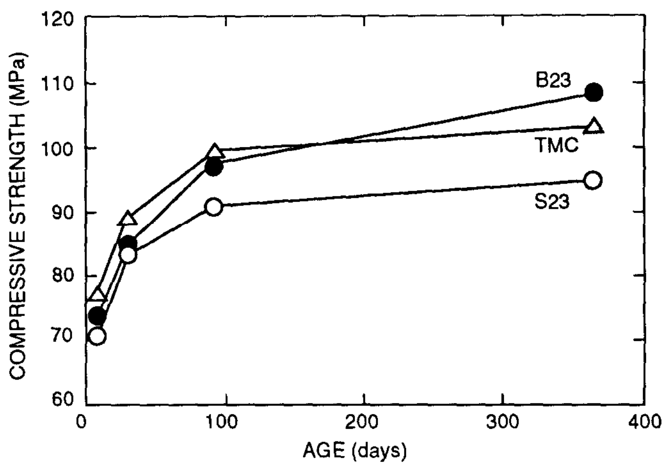

FIG. 5
Strength development of PC concrete under various curing regimes.

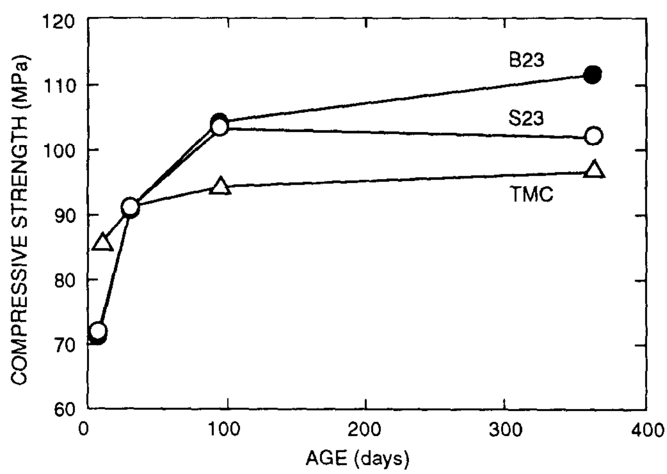

FIG. 6
Strength development of SF concrete under various curing regimes.

The influence of temperature on strength can be clearly described in terms of the strength ratio between TMC and S23 cylinders, where no extra moist curing is available under either condition. The changes in f(TMC)/f(S23) with time are shown in Fig. 7. It is evident that high early age curing temperatures resulted in a sustained increase in strength for the PC concrete when comparing cylinders under similar external moisture conditions. However, the opposite was found for the SF concrete. Whilst early strength development was significantly accelerated, up to 20% at 7 days, high early age temperatures resulted in a lower 1-year strength in the TMC concrete compared to concrete conditioned at standard temperature.

If compared to fully water-cured concrete, the difference in strength between TMC specimens and those cured at standard temperature becomes even larger. As shown in Fig. 8, f(TMC)/f(B23) for the PC concrete decreased with age as the water-cured specimens gained strength at a higher rate compared to the TMC concrete. At 1-year, the strength of TMC cylinders for the PC concrete was 5% lower than that of standard water-cured cylinders. By contrast, the compressive strength of TMC cylinders for the SF concrete was 15% lower than those of standard water-cured cylinders.

Non-evaporable water content of concrete

At standard temperature, the rate of increase in non-evaporable water content, w_n, varied significantly according to binder type. The non-evaporable water contents of mortar obtained

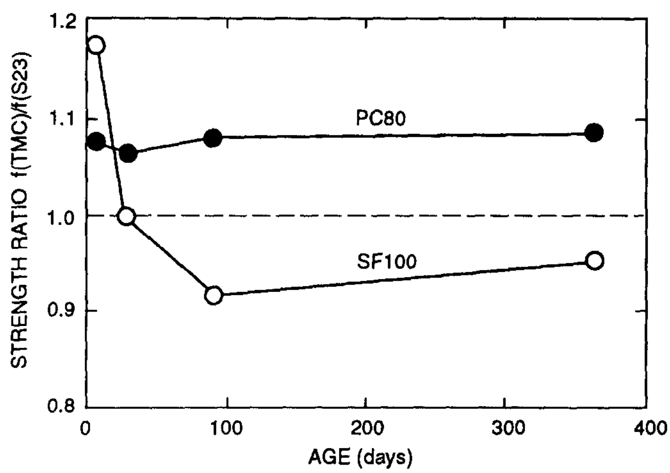

FIG. 7
Compressive strength ratio of TMC to S23 cylinders.

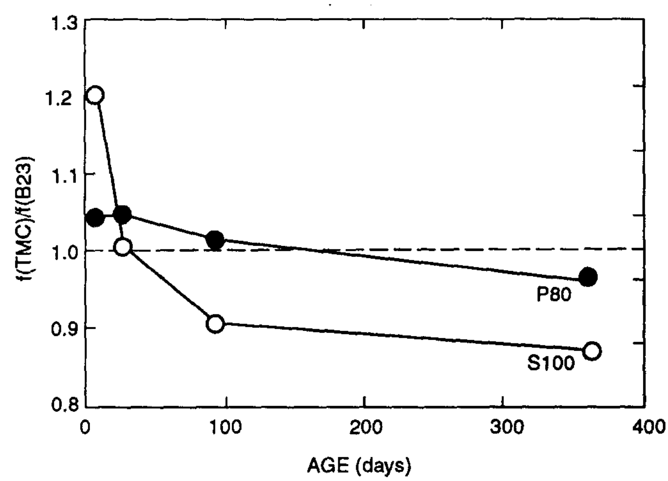

FIG. 8
Compressive strength ratio of TMC to water-cured cylinders.

from hardened concrete at various ages up to 91 days are shown in Fig. 9. Comparing concretes sealed at 23°C, w_n for mix S100 was slightly higher than that found in mix P80 at 3 and 7 days. After 28 days, w_n for the PC concrete had exceeded that of the SF concrete. Whilst the rate of increase in w_n for the SF concrete was very modest, the w_n for the PC concrete continued to increase significantly with age.

The influence of high early temperature on w_n differed markedly for the two concretes. For the PC concrete, TMC significantly increased the w_n at all ages when compared to S23 concrete. The large early age increase in w_n for the TMC concrete is particularly evident and the w_n continued to increase with age for both curing conditions. For the SF concrete, high temperatures also resulted in a higher w_n in the TMC concrete at early ages when compared to S23 concrete. However, there was no appreciable change in the w_n of the TMC concrete with age, remaining constant at approximately 6% from as early as 3 days. By 91 days, w_n of the SF concrete cured at standard temperature had exceeded that of the TMC concrete.

The changes in non-evaporable water content with age and due to curing conditions correlated quite well with compressive strength, as shown in Fig. 10 for the B23, S23 and TMC concretes. In general, an increase in compressive strength is commensurate with an increase in w_n. The linear correlation coefficients between compressive strength and w_n for the PC and SF concretes were 0.85 and 0.89 respectively.

Concrete humidity under the influence of high hydration temperature

The different rates of change in non-evaporable water content of the two different mixes due to high curing temperatures can also be related to the relative humidity of high strength concrete. Figure 11 shows the relative humidity within cavities cast into 400 mm cubes which were thermally insulated with 100 mm thick polyurethane foam all around to provide semi-adiabatic temperature development conditions (14). The temperature profiles achieved under these conditions were very similar to those obtained in the 800 × 800 mm cross-section elements described earlier.

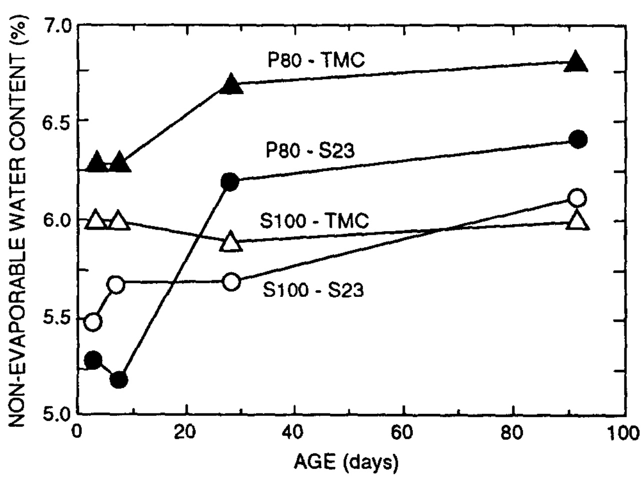

FIG. 9
Non-evaporable content in concrete for PC and SF concrete cured at 23°C and TMC.

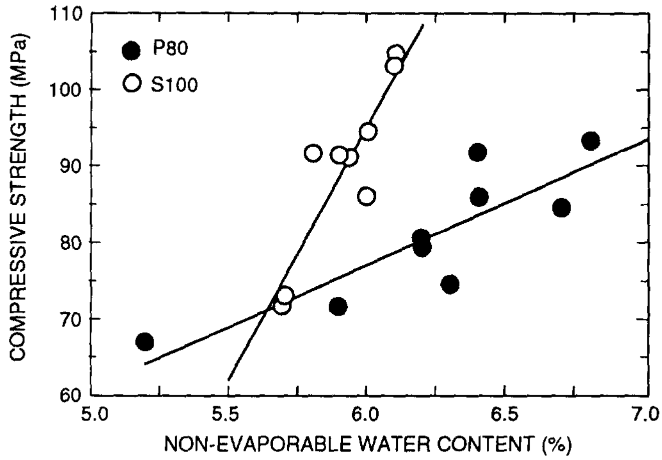

FIG. 10
Correlation between compressive strength and non-evaporable water content of concrete.

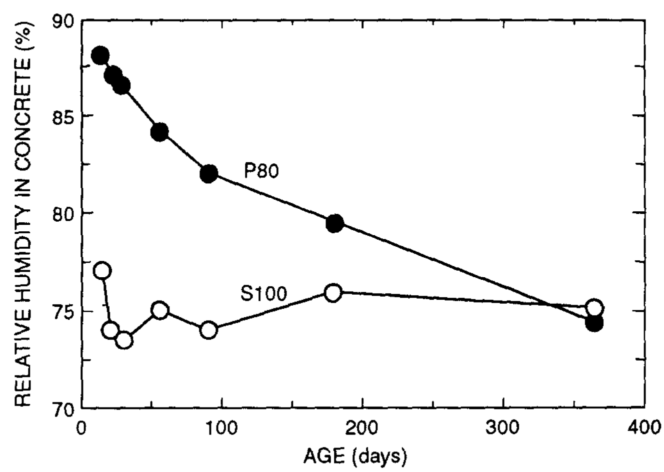

FIG. 11
Relative humidity in concrete measured in well-insulated 400 mm blocks.

The SF concrete showed a much more rapid rate of reduction in relative humidity than the PC concrete. Initial measurements taken at 14 days showed that the RH in the PC concrete was approximately 90%, whilst that in the SF concrete was already as low as 75%. The RH within the SF concrete did not change appreciably thereafter, with the 1-year value being close to 75%. However, the RH in the PC concrete showed a gradual reduction from 90% at 14 days to approximately 80% after 1 year.

These results provide additional evidence to support the findings from non-evaporable water content. In the silica fume concrete undergoing TMC, it can be inferred that hydration reactions stopped at a very early age due to self-desiccation. This is indicated by the lack of change in w_n as well as the relatively low and constant relative humidity in the concrete. By contrast, the RH in the PC concrete remained quite high in spite of the high temperatures, and the gradual drop suggested a more gradual consumption in free water. This is supported by the w_n results which show a continuous increase in non-evaporable water content that was also commensurate with the continuous strength development with age.

Although these results indicate that hydration in the silica fume concrete under TMC had significantly slowed, full hydration is neither achievable nor always a prerequisite for high strength development. This is because other phenomena such as the filler effect may also contribute to strength development. In the silica fume concrete, very high early strengths were achievable, i.e. approximately 86 MPa at 7 days due to the high temperatures under TMC. From the data obtained up to 1 year, no strength reduction has been observed.

Conclusions

High early age temperatures significantly accelerate the 7-day strength of a high strength silica fume concrete with no significant increase in strength thereafter when compared to concrete cured at standard temperatures. By contrast, a high strength PC concrete showed enhanced medium-term strength development due to high early age hydration temperatures.

The stagnated strength development of a silica fume high strength concrete is consistent with the rapid stabilisation of non-evaporable water content as well as reduction in concrete humidity at very early ages due to self-desiccation.

The influence of high early age hydration temperatures on the strength development of high performance concretes differs markedly depending on the type of binder used. The combined effects of high hydration temperature and restricted moist curing led to a larger difference between TMC and standard cylinder strengths for a high strength silica fume concrete when compared to a plain Portland cement concrete of similar mix proportions.

Acknowledgments

The authors gratefully acknowledge the contributions from Mr David Ritchie and Mr Jim Varsamis in the experimental work. This research was undertaken whilst the second author was a visiting scientist at CSIRO with the support from the Ministry of Education, Japan.

References

1. Aitcin, P. C. and Riad, N., 'Curing temperature and very high strength concrete', Concrete International, **10**(10), 69–72 (1988).
2. Bentur, A. and Goldman, A., 'Curing effects, strength and physical properties of high strength silica fume concretes', J. Materials in Civil Engineering, ASCE, **1**(1), 46–58 (1989).
3. Tachibana, D., Imai, M., Yamazaki, N., Kawai, T. and Inoda, Y., 'High strength concrete incorporating several admixtures', Proc. 2nd Int. Symp. on Utilization of High Strength Concrete, Univ. California, Berkeley (1990).
4. Yuan, R. L., Ragab, M., Hill, R. E. and Cook, J. E., 'Evaluation of core strength in high strength concrete', Concr. Int., **13**(5), 30–34 (1991).
5. Cook, W. D., Miao, B., Aitcin, P. C. and Mitchell, D., 'Thermal stresses in large high strength concrete columns', ACI Materials J., **89**(1), 61–68 (1992).

6. Kanda, T., Sakuramoto, F. and Suzuki, K., 'Compressive strength of silica fume concrete at higher temperatures', ACI SP–132, pp. 1089–1103.
7. Mak, S. L., Attard, M. M., Ho, D. W. S. and Darvall, P. LeP., 'Cross-sectional strength gradients in high strength concrete columns', Cem. Concr. Res., **24**(1), 139–149 (1992).
8. Klieger, P., 'Effect of mixing and curing temperature on concrete strength', Proc. ACI Journal, **29**(12) (1958).
9. Alexanderson, J., 'Strength losses in heat cured concrete', Handlingar (Proc.) No. 43, Swedish Cement and Concrete Institute (1972).
10. Springenschmid, R. and Breitenbucher, R., 'Technological aspects for high strength concrete in thick structural members', Proc. Symp. on Utilization of High Strength Concrete, Stavanger, Tapir Publ., pp. 487–496 (1987).
11. Powers, T. C., 'A discussion of cement hydration in relation to the curing of concrete', Proc. Highway Research Board, **27**, Washington DC, pp. 178–188 (1945).
12. Copeland, L. E. and Bragg, R. H., 'Self-desiccation in portland cement pastes', ASTM Bulletin, No. 204, 24–39 (1955).
13. Atlassi, E., 'Some moisture properties of silica fume mortar', American Concrete Institute, Special Publication SP 132, pp. 903–919 (1992).
14. Mak, S. L., 'Factors influencing the in-situ strength in high strength concrete columns', Ph.D. dissertation, Dept of Civil Engineering, Monash University, Melbourne (1993).
15. Mak, S. L. and Sanjayan, G., 'Mix proportions for very high strength concretes', Proc. 2nd National Structural Engineering Conf., Adelaide, Australia, pp. 127–130 (1990).
16. Mak, S. L. and Attard, M. M., 'Evaluation of specimen-end preparation procedures on the strength of high strength concrete cylinders', Australian Civil Engineering Transactions, **CE34**, 321–330 (1992).