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MICROSILICA AND GROUND GRANULATED BLAST FURNACE SLAG EFFECTS ON HYDRATION TEMPERATURE

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ABSTRACT

The heat of hydration of cement mixes is of great importance to civil engineers. A testing setup was developed to provide a continuous recording of temperature inside cement mixes by means of a computer, digital voltmeter, and thermo-couples. Four mixes were tested by the suggested testing setup. A plain normal Portland cement (NPC), 90% NPC/10% microsilica, 40% NPC/10% microsilica/50% ground granulated blast furnace slag (ggbs), and 50% NPC/50% sand mixes were used. Microsilica reduced the temperature rise in paste and ggbs reduced it even further. Cement content was seen, as expected, to have significant effect on the rise in hydration temperature. Cement replacement materials had also clear effect on the time needed to reach the peak temperature. Microsilica slightly accelerated the arrival time at peak temperature, whereas ggbs significantly delayed it. Moreover, ggbs clearly reduced the differential change in temperature as a function of time compared to the other mixes. © *1997 Elsevier Science Ltd*

Introduction

In many concrete and civil engineering applications, there is a need to measure temperature in and around a structure or material (1,2). The hydration of Portland cement is an exothermic reaction from which heat is evolved (3). The determination of temperature during hydration is of great importance to civil engineers. It is essential for the estimation of in situ compressive strength using maturity equation (4). Such a method can serve as an early warning to the lack of strength associated with cold weather concreting. It can also be used as a good indication of strength development in hot weather for the purpose of formwork removal. In addition to this, the control of the undesirable direct and indirect effects of high early heat of hydration is paramount for the production of concrete with specific properties.

Heat of hydration is significantly affected by different cement-replacement materials such as microsilica, fly ash, and ground granulated blast furnace slag (ggbs) (5,6). The effects of these materials on heat of hydration is significant. Ggbs and fly ash lower early heat of

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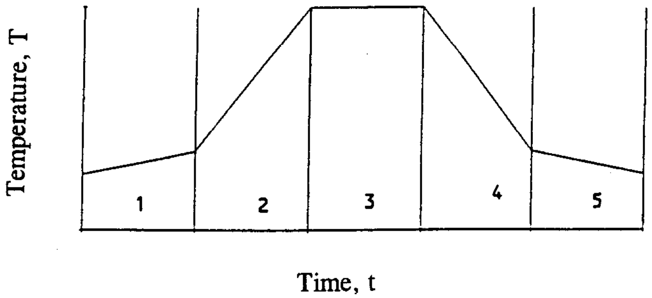

FIG. 1.
Temperature-time curve showing the different stages.

hydration compared to plain NPC (7,8). The greater the replacement level, the lower the early liberation of heat.

As to the effect of ggbs on the heat of hydration, the physical and chemical characteristics of ggbs particles play an important factor. According to Sersale (9), cementitious properties of ggbs are positively influenced by an increase in lime and alumina contents, and negatively by an increase in silica content.

There is however some disagreement among researchers on the effect of microsilica on the heat of hydration. Microsilica is considered to be highly reactive pozzolan as a result of the very high specific surface area of the particles (10). While in some studies, the replacement of NPC by 10% and 20% microsilica slightly reduced early heat of hydration (11), other studies showed otherwise (12).

Heat of hydration of cement mixes is a function of time and thus it affects the temperature of hydration of mixes. A typical graphical representation of the temperature-time (*T*-*t*) curve is shown in Figure 1 (13). Such a curve is common of testing setups where some heat loss is expected. The figure illustrates also the stages of the development of heat of hydration. The border line defining each stage is based on the sudden change in the slope of *T*-*t* curves. These are defined as follows: Induction: initial reactions, slight heat gain; Acceleratory: heat gain exceeds heat loss significantly; Steady-State: heat gain and heat loss are more or less similar; Deceleratory: heat gain is less than heat loss; and Slow Down: heat gain is much less than heat loss.

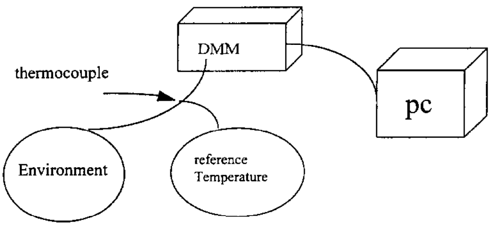

FIG. 2.
The testing setup for continuous recording of temperature during hydration.

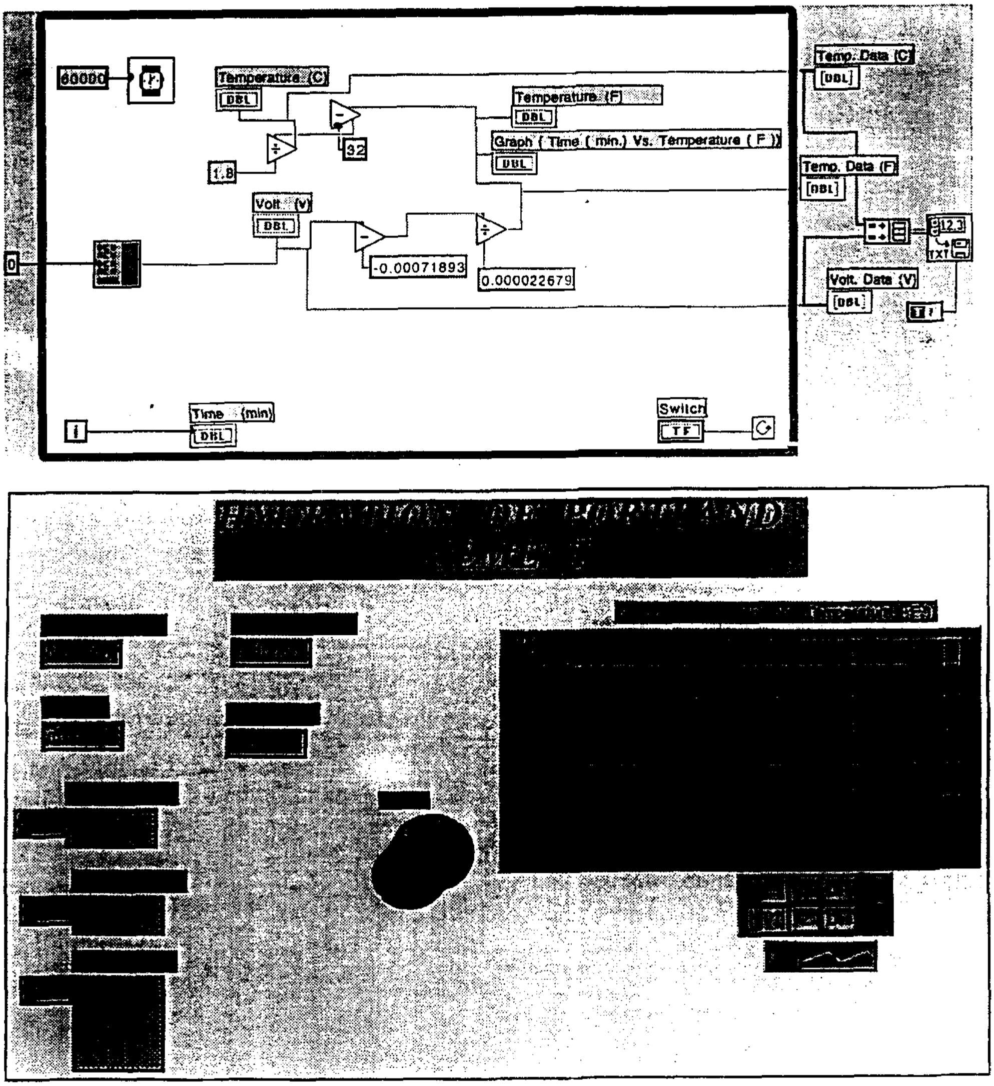

FIG. 3.
(*a*) Lab computer program. (*b*) Computer screen configuration used to run the computer program.

Experimental Details

Testing Setup

Equipment. For continuous recording of temperature during hydration in cement mixes, a computerized testing setup was developed. It is composed of the following: a personal computer equipped with a Labveiw compiler and adequate spread sheet package; a DMM (digital volt meter); a thermocouple with known thermal emf in absolute millivolts; a

TABLE 1
Chemical Composition of the Different Cementitious Materials Used

Oxide	Sio$_2$	Al$_2$0$_3$	Fe$_2$0$_3$	CaO	MgO	Na$_2$O	K$_2$O	TiO$_2$	SO$_3$
NPC	20.9	5.5	2.7	64.3	2.5	0.3	0.8	—	2.8
Microsilica	89.7	0.605	0.82	0.425	1.005	0.3	1.585	—	0.38
ggbs	36.8	10.0	1.2	41.9	7.2	0.3	0.5	0.6	0.1

reference temperature (0°C using water and ice); and a testing environmment, which was chosen to simulate actual concrete in site. Containers that were insulated against heat loss were used for such thing. Some heat loss was allowed. To be consistent, however, identical containers were used for all mixes.

The above equipment were connected in the way shown in Figure 2.

Computer Program. A Labview compiler was used in the construction of the computer program needed to record temperature. Figure 3a shows the Labview computer program and Fig. 3b shows the computer screen configuration used to control and run the program. The DMM receives the signals from the thermocouple and transmits them to the computer. The computer then converts these readings to temperature using a linear interpolation equation relating millivolts to temperature, which is obtained by the methods of least squares using the data given in the literature (14). For more accurate interpolations, the temperature range in obtaining the equation was limited to 0–150 °C. The temperature results obtained by the computer were analyzed using a spread sheet package (EXCEL was used in this study).

Materials

For this study we used the following materials. NPC conforming to British Standards BS12:1995 was used, the chemical composition of which is shown in Table 1. The microsilica used was Norwegian in origin and contained about 90% amorphous silica (see Table 1). The chemical composition of ggbs is also shown in Table 1. Sand conforming to BS882 was used in the mortar mix.

Mix Proportions

Details of the mix proportions are shown in Table 2. Water content was kept constant and was chosen to give a paste and mortar of an acceptable consistency.

TABLE 2
Mix Proportions by Weight (grams)

Mix	NPC	Microsilica	Slag	Sand	Water
1	1000	0	0	0	350
2	900	100	0	0	350
3	400	100	500	0	350
4	500	0	0	500	350

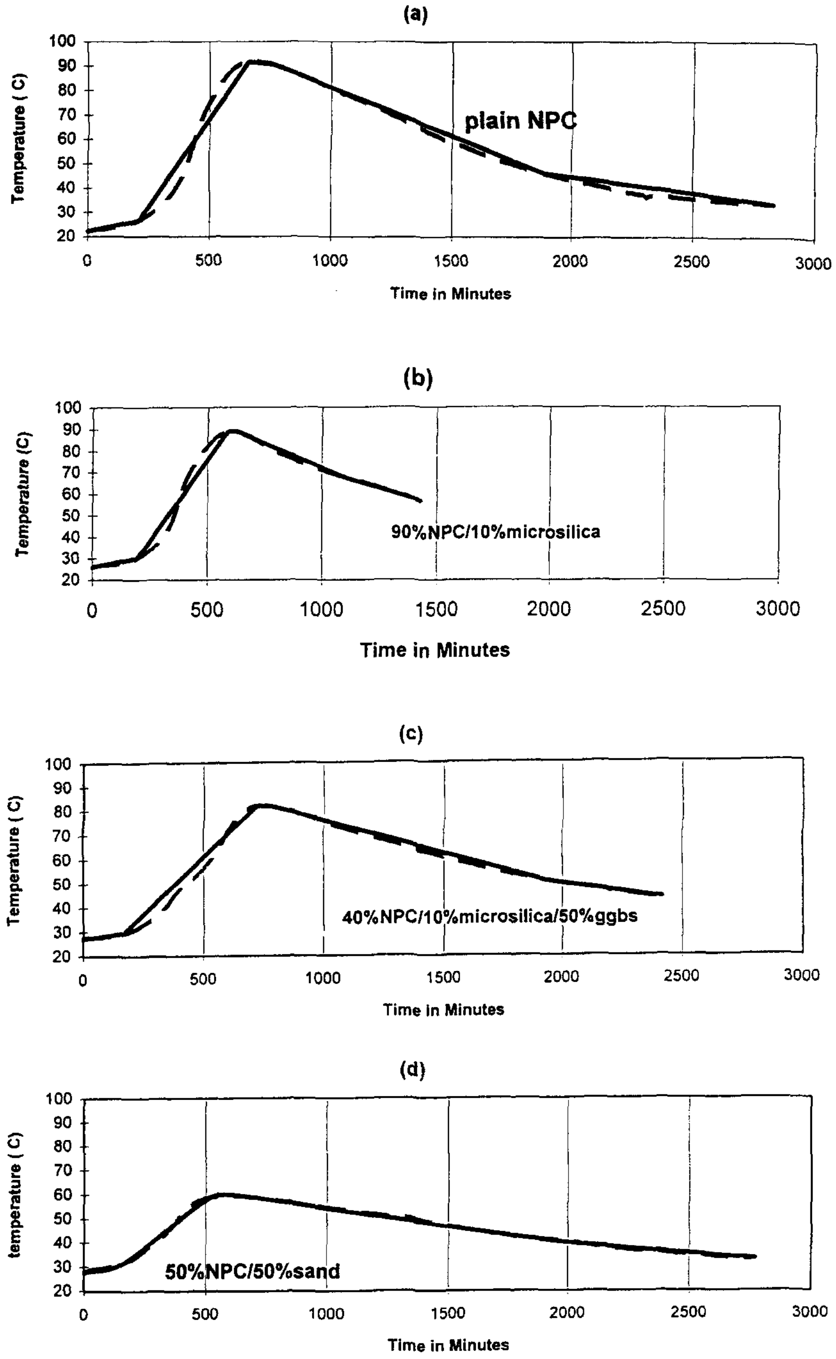

FIG. 4.

Temperature-time (*T*-*t*) curves and the linear graphical interpolation for the four mixes: (*a*) plain NPC; (*b*) 90% NPC/10% microsilica; (*c*) 40% NPC/10% microsilica/50% ggbs; and (*d*) 50% NPC/50% sand.

TABLE 3
Summary Details of Temperature-Time (*T-t*) Curves

	Plain NPC	NPC/ microsilica	NPC/ microsilica/ggbs	Mortar mix
Time to reach peak temperature (minutes)	660	589	721	525
Peak temperature (°C)	91.7	89.2	81.9	59.1
Max. temperature rise (°C)*	69.6	63.2	54.9	31.4

*This is the difference between peak temperature and initial mix temperature

Mixing and Testing

The materials were thoroughly mixed and placed in a fairly well insulated container. Some heat loss was allowed to simulate actual concrete in site. To be consistent, however, identical containers were used for all mixes. One end of the thermocouple was inserted at the center of the paste and the second end was placed in another container in which temperature was kept at 0°C (reference temperature). The third end was attached to the DMM. One-minute readings were recorded.

A Type K thermocouple was used. For this kind of thermocouple, the linear equation relating millivolts to temperature was found (using the data in ref. 14) to be:

$$V = 0.000022679 \times T - 0.00071893$$

thus:

$$T = (V + 0.00071893)/0.000022679$$

where V is the voltage reading in volts and T is the temperature in °F.

The correlation coefficient of the above equation was found to be 0.9999. Temperature was then mathematically converted to °C; °C = (°F - 32)/1.8.

Results and Discussion

Four different mixes were used to investigate the effect of microsilica, ggbs, and cement content by means of the testing setup. As documented in the literature, cement content, ggbs, and microsilica affect heat of hydration (3,5,6). The results obtained from the current testing setup seems to confirm such a trend.

Figure 4 shows the time-temperature (*T-t*) curves and the linear interpolation of each curve for the different mixes. The results seem to be in line with previous works by others (9,10). The *T-t* curves are typical to what is expected in cement mixes (13) when using the testing setup that allows loss of heat. The stages of the *T-t* curves shown in Figure 1 can also be identified for each mix.

The effects of cement content on temperature peak is illustrated by the result of the mortar mix (500 g of NPC as compared to 1000 g of plain NPC mix). The rise in temperature was little less than half that of plain NPC mix and the time needed to reach the peak temperature

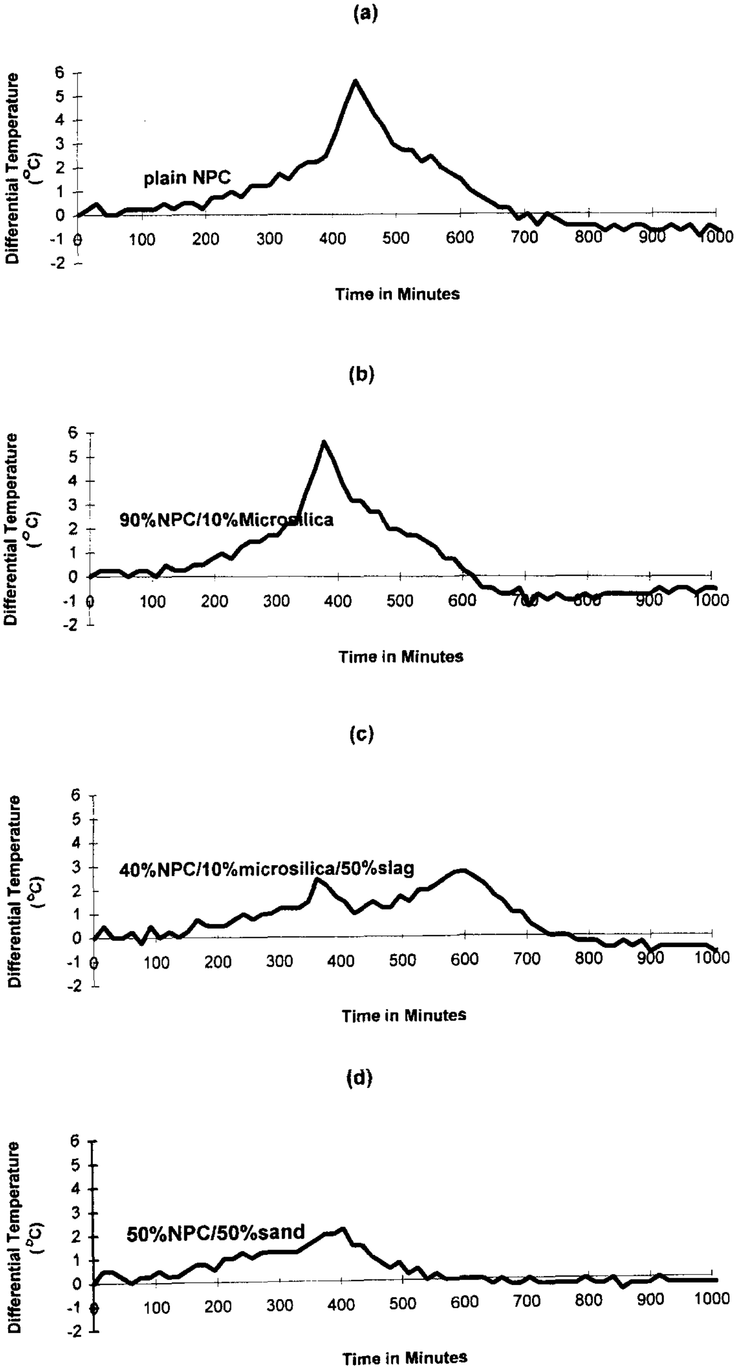

FIG. 5.

The differential increment of temperature as a function of time for 15-min intervals: (*a*) plain NPC; (*b*) 90% NPC/10% microsilica; (*c*) 40% NPC/10% microsilica/50% ggbs; and (*d*) 50% NPC/50% sand.

was about 2 h shorter due to the fact that heat of hydration is directly proportional to cement content (see Table 3).

As far as microsilica is concerned, there is still (as indicated in the Introduction) some disagreement amoung researchers on its effect on the development rate of the heat of hydration. In the current work, the replacement of 10% of NPC by microsilica accelerated the time to reach peak temperature as compared to plain NPC (see Table 3). This accelerated hydration is partially attributed to the lower cement content (see the results of the mortar mix) and to the high surface area of the particles of microsilica, which are classified as highly reactive pozzolan.

Pozzolanic reactions are also accompanied by the liberation of some heat. This liberated heat is less than that produced by the hydration of NPC (15). The rise of temperature (difference between peak temperature and initial mix temperature) for the microsilica mix is expected to be lower than that of plain NPC mainly due to the lower NPC content. A difference of about 6°C was observed between NPC and NPC/microsilica mixes (see Table 3).

As to the hydration of ggbs, activators are essential for the beginning of the reaction of ggbs particles with water. The initial reaction of ggbs particles with water forms a layer that inhibits further reaction (3). Activators (mainly the alkalis, $Ca(OH)_2$, NaOH, and KOH) are released from the reaction of NPC with water. Because of this, it would be expected that there will be some delay in the release of heat of hydration. The amount of delay in the hydration of ggbs depends on the physical and chemical composition of ggbs. Some types delay hydration significantly, whereas other delays it only slightly.

Table 3 shows that the peak temperature was delayed for the ggbs mix by over 2 h compared to NPC/microsilica/ggbs mix. The drop in the deceleration part of the curve is slower than those of plain NPC or NPC/microsilica mixes. The rise of temperature for the ggbs mix was also about 15°C and 11°C lower than plain NPC and NPC/microsilica mixes, respectively.

Another important parameter is the differential change in temperature as a function of time (dT/dt). This gives an indication of the intensity of hydration reactions taking place at any specific time. The maximum change in temperature corresponded to the greatest amount of hydration reactions taking place. The results (Fig. 5) for 15-min intervals indicate that (dT/dt) is also affected by cement content and cement type.

The differential contribution, dT/dt, (for 15-min intervals) to total rise in temperature for plain NPC and microsilica mixes was seen to peak at 440 and 375 min, respectively, by 5–6°C (see Figs. 5a and b). Similar observation can be seen for the mortar mix (at 410 min) but with much lower contribution (about 2°C) due to the lower cement content. Ggbs, on the other hand, showed a different behavior. The maximum intensity of the reaction spanned over a relatively long period of time. The dT/dt for 15-min intervals was less than half that of the NPC mix, 2–3°C only.

A further analysis of these results indicates that there is a specific period of time for maximum contribution to total temperature rise. A relatively sudden sharp contribution is seen for plain NPC and NPC/microsilica mixes extending over a period of about 100 min. Ggbs showed a different behavior. As far as ggbs mix is concerned, there is no sudden contribution similar to that found in the case of the other mixes. In fact the differential contribution extended over a period of about 300 min (three times more than NPC mix).

Conclusions

Based on the above results and discussion, the following conclusions can be drawn:

1) the testing setup was successful in recording temperature rise inside cement mixes continuously;
2) lower cement contents result in lower rises in hydration temperatures of cement mixes and in faster arrivals at peak temperatures;
3) microsilica seems to slightly accelerate hydration but with lower peak temperatures;
4) ggbs lowers peak temperature and extends the time needed to arrive at it; and
5) the results indicate that the incremental change in temperature as a function of time was significantly lower in the case of ggbs than in the case of plain NPC or NPC/microsilica.

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