Effect of Formwork, Wall Thickness, and Addition of Fly Ash on Concrete Hydration

Rishi Gupta and Katie Kuder

August 2014

http://dx.doi.org/10.1520/ACEM20140015

Citation for this paper:

Gupta, R. & Kuder, K. (2014). Effect of formwork, wall thickness, and addition of fly ash on concrete hydration. *Advances in Civil Engineering Materials*, 3(1), 479-494.

ASTM INTERNATIONAL

Advances in Civil Engineering Materials

Rishi Gupta[1] and Katie Kuder[2]

DOI: 10.1520/ACEM20140015

Effect of Formwork, Wall Thickness, and Addition of Fly Ash on Concrete Hydration

VOL. 3 / NO. 1 / 2014

Advances in Civil Engineering Materials

doi:10.1520/ACEM20140015 / Vol. 3 / No. 1 / 2014 / available online at www.astm.org

Rishi Gupta[1] and Katie Kuder[2]

Effect of Formwork, Wall Thickness, and Addition of Fly Ash on Concrete Hydration

Reference

Gupta, Rishi and Kuder, Katie, "Effect of Formwork, Wall Thickness, and Addition of Fly Ash on Concrete Hydration," *Advances in Civil Engineering Materials*, Vol. 3, No. 1, 2014, pp. 479–494, doi:10.1520/ACEM20140015. ISSN 2165-3984

ABSTRACT

The use of different forming materials, insulating materials, and stripping times can significantly affect the maturity and hence the strength gain of concrete within forming systems. This information can be vital in determining the stripping time of scaffolding and formwork. In this project, maturity and compression tests were performed on specimens (simulating scaled-down walls) formed using a polyvinyl chloride stay-in-place (SIP) forming system with and without insulation. The findings were then compared to data obtained from walls formed by wood formwork, which is the material typically used in the field. The various parameters studied in this project were wall thickness, type of forming material, insulation, and addition of fly ash. The results indicate that with an increase in wall thickness, the peak temperature and the temperature development index (TDI) increased proportionally. TDI is defined as the area under the temperature-versus-time curve measured from the dormant temperature to the peak temperature. The data show that the proposed TDI was a good indicator of the extent of the hydration reaction, and with further research the relationship between temperature development and strength gain of concrete could be clearly identified. Increases in the peak temperature and TDI were noted in wood forming systems relative to SIP systems and in insulated systems relative to un-insulated systems. The use of fly ash in concrete resulted in a lower temperature peak and TDI and a delay in reaching peak temperature. However, the use of concrete containing fly ash in

Manuscript received March 31, 2014; accepted for publication July 28, 2014; published online August 27, 2014.

[1] Assistant Professor, Civil Engineering Program, Dept. of Mechanical Engineering, Univ. of Victoria, Victoria, BC, V8W 2Y2, Canada (Corresponding author), e-mail: guptar@uvic.ca

[2] Associate Professor and Chair, Dept. of Civil and Environmental Engineering, Seattle Univ., 901 12th Ave., P.O. Box 222000, Seattle, WA 98122-1090, United States of America.

insulated SIP systems led to a higher TDI than a conventional concrete mix formed in wood forms, indicating better concrete maturity at the same age.

Keywords

PVC SIP formwork, concrete with fly ash, insulation, maturity

Introduction

Concrete is the most widely used construction material, and its formability is one very important property. Several different types of formwork are available in the market. One way of classifying them is based on whether they are stripped or not, as (1) conventional formwork or (2) stay-in-place (SIP) formwork made using different materials such as steel, polyvinyl chloride (PVC), fiber-reinforced polymers, expanded polystyrene (EPS), etc. Typically, wood formwork is used to form concrete. However, the amount of wood that can be harvested has been reduced, increasing the cost and reducing the availability of wood. In addition, it is environmentally advantageous to decrease the amount of wood needed in construction.

New concrete forming technologies designed to reduce wood consumption include reusable and SIP formwork. After being used, reusable metal and wood forms must be removed, cleaned, transported, and stored. These systems limit design versatility because they generally come in large, flat panels. Unlike traditional formwork that is stripped after concrete has gained enough maturity, the SIP forms remain an integral part of the structure; some provide structural strength and ductility [1], some provide a higher R value, and some just provide a finished surface. Some forming systems such as insulated concrete forms increase the insulative properties and R value of the concrete walls, and some SIP systems also integrate insulation in the forming system. However, the effect of such highly insulated walls on concrete hydration at early ages is not fully understood. One such category of SIP forms are plastic forming systems, which are also more versatile than wood and metal because various shapes can be easily manufactured given plastic’s flexibility.

Because the SIP forms are not stripped and thus, never expose the surface of the concrete, it is very important to ascertain whether the concrete in the forms has met or exceeded the project specifications. One such type of forming system is a SIP system that utilizes PVC panels and connectors as formwork [2]. This forming system can be used with and without insulation, and its effect on the maturity of concrete is not fully understood.

On the material side, fly ash is a commonly used supplementary cementing material that enhances the fresh properties of concrete, including its workability [3–5]. High-volume fly ash contents are now replacing cement because (1) this results in reduced consumption of cement, thereby reducing the energy required to produce cement and the associated greenhouse gas emissions; (2) the production of many self-consolidating mixes requires high contents of fly ash; and (3) this results in cost savings and is a more sustainable process because an industrial by-product (fly ash) that otherwise would end up in a landfill is now being utilized. However, the addition of fly ash can decrease the rate of the hydration reaction, negatively affecting the construction process, as the stripping of forms may be delayed. The effect of using fly ash in concrete on the maturity of concrete was studied in this project. During the hydration reaction, heat is generated and released to the surroundings; the rate of the reaction is proportional to the heat generated. The dissipation of this heat of hydration to the environment will depend on the type of forming material used, the thickness of the concrete mass, and the use of insulation [6,7]. The effect of using insulation, wood, or a PVC SIP system on the maturity of concrete was studied in this project. The maturity of concrete was evaluated by calculating a temperature development index (TDI), which is described later.

The TDI is a close function of the hydration process, and thus it is important to note the different stages of the hydration process. The first stage is rapid heat evolution, which occurs very quickly. The concrete then moves into the dormant stage, in which the concrete is workable. The dormant stage ends with the initial set, and the concrete moves into the acceleration stage as the reaction begins to accelerate. The concrete remains workable until the final set, when the highest temperature is achieved. During the deceleration stage, the reaction slows down and the temperature is reduced, bringing the concrete to a steady state. A practical and effective way to evaluate this hydration process is to monitor the heat released by the hydration reaction over time. The temperature data also serve as an indicator of the rate of reaction, as the temperature increase is proportional to the heat generated.

Materials and Forming Systems

Concrete was prepared in a rotary drum mixer using Type I cement (Lafarge), river sand, coarse aggregate with a maximum size of 10 mm, Class F fly ash (Centralia), and admixtures including superplasticizer (Glenium 3000 NS) and air entrainer (MB VR Standard). For constructing the wood forms, lumber meeting the following specifications was used: 23/32-in. DF-DF plywood, 48/24 span rated. The forms were oiled using a release agent (WD-40) before the concrete was poured.

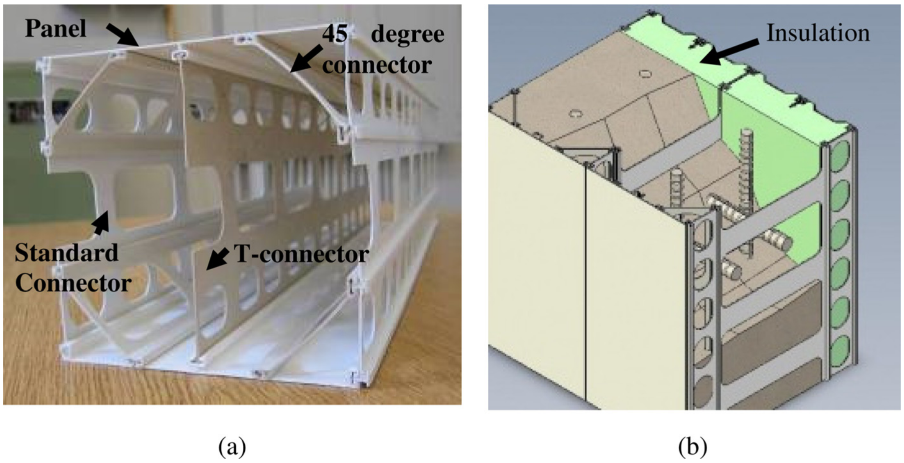
A concrete mix design typical of what is used in field construction with the PVC SIP system was used. The control concrete mix had a water–cement ratio of 0.49 with 350 kg/m^3 of cement, 1160 kg/m^3 coarse aggregate, 700 kg/m^3 sand, a dosage of 600 ml/m^3 superplasticizer, and 200 ml/m^3 air entrainer. Another mix was prepared by replacing 40 % of the cement with fly ash by weight.

POLYVINYL CHLORIDE STAY-IN-PLACE FORMING SYSTEM

The SIP forming system used in this study is briefly described below. This forming system was composed of PVC panels, connectors, and braces that formed cells. The panels were typically 150 mm wide and of variable height. The connectors, which are available in various widths, were placed perpendicular to the panels and had openings for the placement of rebar and to allow the concrete to flow through the wall. **Figure 1(*a*)** shows one such cell of the forming system braced with standard connectors, T-connectors, and the 45° braces to the panels. Insulation is also available [**Fig. 1(*b*)**] for an increased thermal mass, leading to greater energy efficiency.

The panels that make up the interior and exterior of the formwork can be curved to conform to the shape needed for the specific application, such as the aquaculture tank shown in **Fig. 2(*a*)**. Once the vertical formwork has been assembled and

FIG. 1 Components of SIP formwork cell: (*a*) top view of cell containing all components; (*b*) schematic of cell with insulation [2].



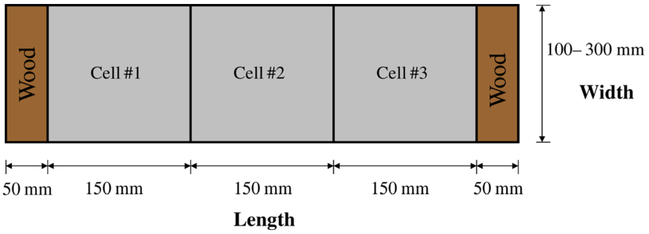
raised, wood bracing is used, as shown in **Fig. 2(*b*)**. This bracing is similar to the bracing required when the wood formwork is used and is removed once concrete within the forms has gained sufficient strength.

Specimen Preparation

To determine the influence of the PVC SIP formwork on the heat of hydration (maturity/temperature release), the results from the PVC SIP system were compared to data from a wood formwork. The SIP test wall configuration, shown in **Figs. 3** and **4**, was designed to have three rectangular cells. This configuration was chosen so that the two extra cells on either side of the middle cell would eliminate the temperature effects of closeness to the end of the wall (boundary effects). The sides of the end cells were filled with wood pieces to prevent concrete from flowing out of the wall. The final interior dimensions of the wall were 460 mm (18 in.) in length, 300 mm in height, and variable width (ranging from 100 to 300 mm). For the wood formed walls, plywood was assembled to match the interior dimensions of the SIP system.

FIG. 2 SIP systems: (*a*) aquaculture tank; (*b*) wall during construction [2].

FIG. 3
Schematic (plan view) showing dimensions of the formed specimens.



To evaluate the effect of the PVC formwork on heat dissipation and moisture conditions during concrete hydration, concrete was cast inside the PVC formwork and was compared with concrete cast inside traditional wood formwork. It was initially hypothesized that the PVC SIP formwork would contain heat and moisture during the hydration process, thereby increasing the rate of the reaction and the ultimate strength. Three variables were introduced to simulate the varying field conditions to which concrete is typically exposed: concrete composition, wall thickness, and insulation. The matrix of variables tested is shown in **Table 1**.

Test Setup

During casting, the concrete was mixed according to ASTM C192 [8] and placed into a small wall-shaped formwork 300 mm in height supported by a bracing system (previously described). A tamping rod was used to ensure the concrete was well compacted within the formwork.

Thermocouples (Type K) were embedded into the central cell at five locations, which are shown in **Fig. 5**. All thermocouples were calibrated prior to testing. One thermocouple was placed in the center of the test specimen to evaluate temperatures in the middle. Four thermocouples were placed around the central thermocouple to provide a more accurate depiction of temperatures throughout the test specimen, particularly locations closer to the formwork. It was hypothesized that if thermocouple location were critical, the thermocouples located closer to the faces of the wall

FIG. 4
Bracing of specimen constructed using PVC SIP.

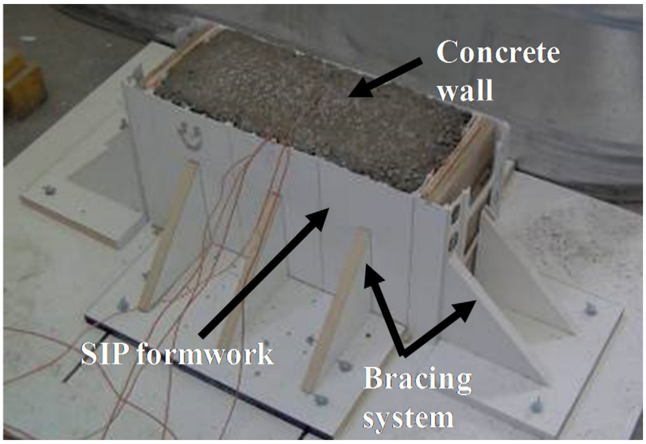


TABLE 1

Test matrix for the variables investigated.

		Specimen Width, mm		
Concrete Type	Formwork Type (R Value in ft^2-h-°F/BTU)	100	200	300
Normal	SIP (0.6)	✓	✓	✓
	Wood, 20 mm thick (0.9)	✓	✓	✓
Fly ash	SIP (0.6)	✓	✓	✓
	Wood, 20 mm thick (0.9)	✓	✓	✓
Normal	SIP with 50 mm insulation (∼8.6)	—	—	✓
	Wood with 50 mm insulation (∼8.9)	—	—	✓
Fly ash	SIP with 50 mm insulation (∼8.6)	—	—	✓
	Wood with 50 mm insulation (∼8.9)	—	—	✓

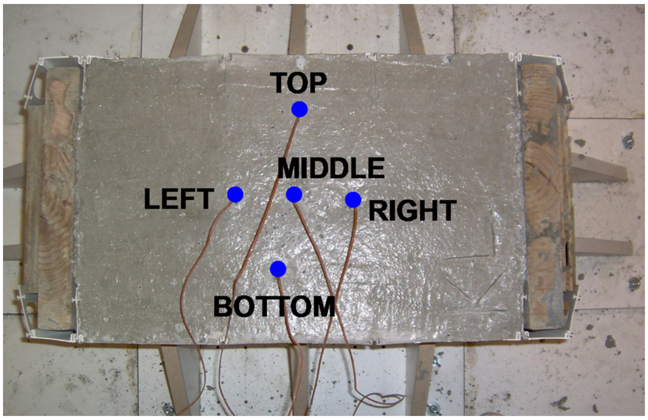
would be more affected by the ambient temperature than those in the middle, and the centrally located thermocouple would reach the highest peak temperature, as it would be surrounded by the greatest thermal mass during curing. In addition, a sixth thermocouple measured the ambient temperature in the lab. The thermocouples were attached to a data acquisition system, and the temperature was recorded for the duration of the test.

TEMPERATURE MEASUREMENTS

Before the concrete was mixed and poured into the formwork, the data acquisition system was started to obtain the initial ambient temperature. The thermocouple wires were then placed in the concrete as described earlier. Temperature readings were collected at a rate of three readings per minute, each reading being an average of 100 scans. Once the test had run for an amount of time determined by previously conducted preliminary tests indicating complete hydration, the data acquisition system was stopped and the data were saved for analysis.

FIG. 5

Thermocouple locations in the middle SIP formwork cell.



COMPRESSION TESTING

Cast Cylinders

To determine the compressive strength, cylinders (100 mm by 200 mm) were cast according to ASTM C31 [9]. Cylinders were de-molded after 24 h and moist-cured for 56 days. Testing was done using a hydraulic testing machine with a 300-kip load cell. Specimens were loaded by displacement control at a rate of 0.085 mm/min. The data acquisition system was set up to measure the applied load at a rate of 25 readings per second, each reading being an average of 1000 scans. Four cylinders were tested for each mix type (NC and FA). Neoprene caps were used in lieu of capping or grinding of cylinders.

Cores

To study the effect of the PVC SIP system and insulation on the concrete's compressive strength, we extracted drilled cores after monitoring the temperature for 36 h. This was also done to determine whether there was any correlation between temperature and strength development. Cores were taken from various 200-mm walls and subjected to compressive testing equipment as described above. The various configurations from which cores were extracted are shown in **Table 2**.

Each wall was cored with a concrete coring machine as shown in **Fig. 6**, with a 100-mm-diameter drill. Three cores were taken from each wall: one from the middle cell, and one from each of the two side cells. Each 100-mm-diameter core was then cut down to a height of 200 mm and tested for compressive strength.

Results and Discussion

DATA AVERAGING

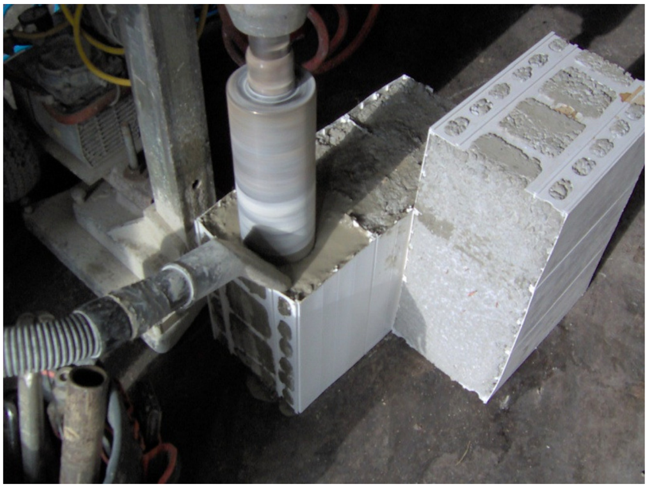
The temperature data were recorded from all six thermocouples over time. After analyzing the data, we noted that the temperature readings from the five embedded thermocouples did not vary significantly with the location of the thermocouples; therefore the average curves were deemed suitable for analysis. This finding is illustrated in **Fig. 7**. The initial readings recorded from the various thermocouples are approximately within ±1°C from the mean. These initial temperature values were not exact, as the thermocouples came in contact with the concrete at slightly different times. Note that the bottom and the top thermocouples reached the second

TABLE 2

Various specimen types used for extracting core samples.

Formwork Type	Concrete Type	Insulation
SIP	Normal	Present
		Absent
	Fly ash	Present
		Absent
Wood	Normal	Present
		Absent
	Fly ash	Present
		Absent

FIG. 6 Coring 100-mm-diameter sections for compression testing from SIP formed specimens.



lowest and highest temperatures, respectively, even though these were located approximately the same distance from the center of the wall. All thermocouples were calibrated prior to testing.

TEMPERATURE DEVELOPMENT INDEX

From the averaged data, the peak temperature (T_p) was determined, along with the time at which the peak occurred (t_p). **Figure 8** presents a typical plot of average temperature versus time, indicating the T_p and t_p. Throughout the testing program, the

FIG. 7 Typical plot of temperature versus time as a function of thermocouple location for a 200-mm-thick wall formed with wood.

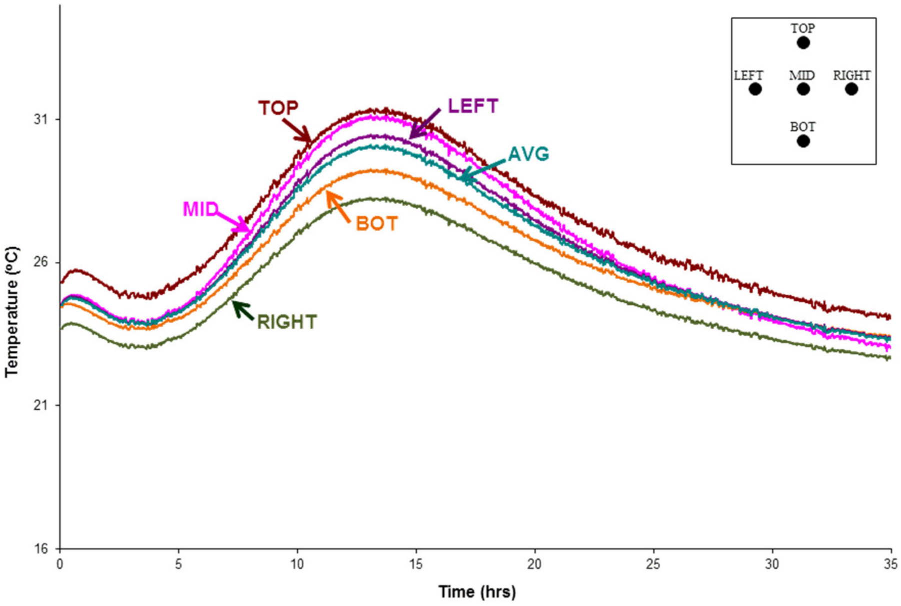
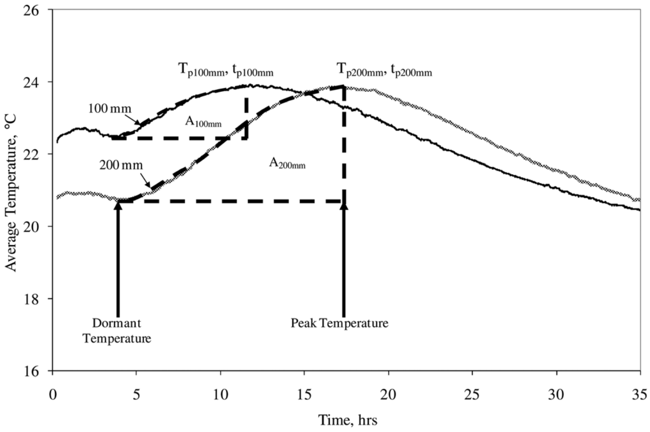


FIG. 8 Average temperature-versus-time curve for 100-mm-thick and 200-mm-thick walls.



ambient temperature in the lab fluctuated, resulting in varying initial temperatures from specimen to specimen. This situation would also be typical of a construction site where the ambient conditions were different from day to day. **Figure 8** presents the average temperature versus time for two tests performed during primary testing. The ambient temperature recorded during each test is not presented in the plot for clarity. The variation in ambient temperature was less than ±1°C in each test, and thus the effect was considered negligible. Although it was expected that the 100-mm fly ash (FA) specimen would achieve a lower peak temperature than the 200-mm FA specimen because it contained a smaller volume of concrete, the results show just the opposite. As research has shown, ambient temperatures affect the rate of the hydration process [7]: warmer temperatures speed up the hydration process and contribute to higher peak temperatures, whereas colder temperatures slow down the hydration process and contribute to lower peak temperatures. Because of the effect of ambient temperatures on the hydration process, and because ambient temperatures were not controlled during testing, there was no linear relationship between hydration and ambient temperature. Therefore, this experimental project cannot directly account for this effect.

To minimize the effect of the ambient temperature during the analysis, it was proposed that the area under the hydration curve be calculated and analyzed. This area was split into two smaller areas: A1, the region bound by the initial minimum temperature (indicating the dormant period) and the peak temperature, and A2, the region bound by the peak temperature and the final temperature at 30 h. Preliminary tests (not reported here for the sake of brevity) had indicated that the internal temperature in specimens more or less dropped to ambient temperature after 30 h [10]. In certain specimens the peak temperature was very similar to the ambient temperature and sometimes lower than that recorded at 30 h. In such cases, the value of A2 would be negative, as in the case of the 100-mm specimen with FA (**Table 3**). Refer to **Fig. 8** for identification of critical points for the temperature analysis and an illustration of the areas calculated. After analysis it was seen that the 100-mm FA specimen (shown in **Fig. 8**) achieved a smaller A1 calculation in comparison to the larger 200-mm FA specimen. The area calculation was conducted for each test, and the

TABLE 3

Temperature at peak, A1 (temperature development index [TDI]), and A2 for the SIP system.

Wall Type		Peak Temperature, °C	Time at Peak, h	A1 (TDI), °C-h	A2, °C-h
Normal concrete	100 mm	24.08	11.9	13.91	22.36
	200 mm	27.79	13.3	25.93	30.38
	300 mm	29.69	15.0	40.75	60.80
Fly ash	100 mm	22.07	13.0	5.72	−0.19
	200 mm	25.81	15.5	24.04	28.95
	300 mm	27.39	16.4	30.08	36.79

areas were compared. These values were used as an indication of temperature development during hydration. The A1 value representing temperature increase and maturity immediately after the dormant stage was found to be more relevant than that of A2 and is used extensively throughout this report. We call this value the TDI (or simply A1). The results from these comparisons are discussed later.

FORMING SYSTEMS

A record of temperature versus time for the SIP system for varying composition and wall thickness is summarized in **Fig. 9** and **Table 3**. Overall temperature test results for concrete formed using the wood forms are summarized in **Fig. 10** and **Table 4**.

EFFECT OF FLY ASH

For the walls formed using the SIP system, with the addition of FA, the peak temperature and TDI decreased for all wall thicknesses; however, the time to peak when comparing the same wall thickness increased, indicating that the extent of the reaction was reduced with the addition of FA. Similar trends were observed for the specimens formed using wood.

EFFECT OF WALL THICKNESS

Figure 11 presents the average TDI for the two mixes tested when wall thickness was varied for the SIP system. Regarding the wall thickness among the SIP specimens

FIG. 9

Average temperature versus time for walls 100, 200, and 300 mm thick formed with SIP formwork with normal concrete (NC) and 40 % fly ash replacement (FA).

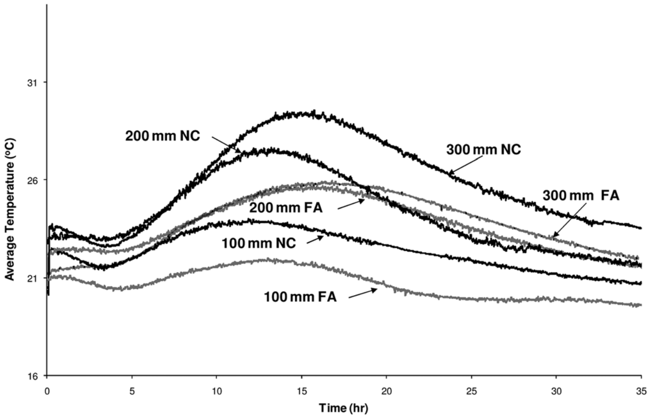
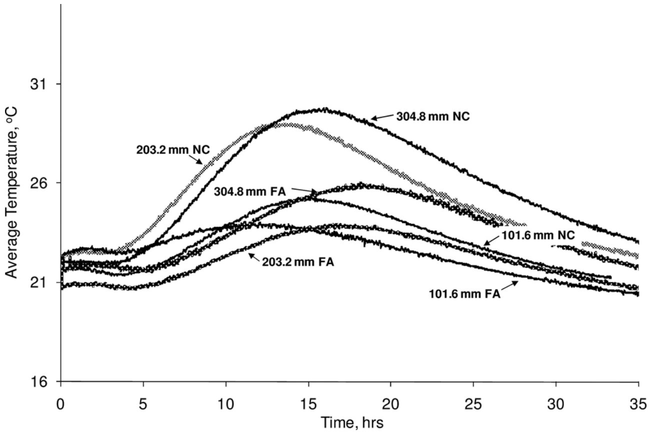


FIG. 10 Average thermocouple temperature versus time for walls 100, 200, and 300 mm thick formed with wood with normal concrete (NC) and 40 % fly ash replacement (FA).



(**Fig. 9**), the data show an increase in temperature, time to peak temperature, and TDI as the thickness increased for both mixes tested. The increase in wall thickness from 100 to 300 mm increased the TDI by more than 192 % for normal concrete (NC) SIP specimens and 210 % for FA SIP specimens. The data show that larger walls reached a higher peak temperature at a later time and achieved a greater TDI than smaller walls. In general, an increase in wall thickness was correlated with an increase in peak temperature, time to peak temperature, and total temperature development in the hydration reaction. Similar results were observed for wood formed specimens, and the results are presented in **Fig. 11**. For wood formed specimens, the increase in wall thickness from 100 mm to 300 mm increased the TDI by 120 % for NC specimens and 280 % for FA specimens. This result implies that the TDI, and hence the strength gain, in thin walls is significantly less than that in thicker walls. Thus, there is a need to closely monitor and consider the strength gain of such walls before stripping the forms, especially when high volumes of FA are used.

EFFECT OF INSULATION

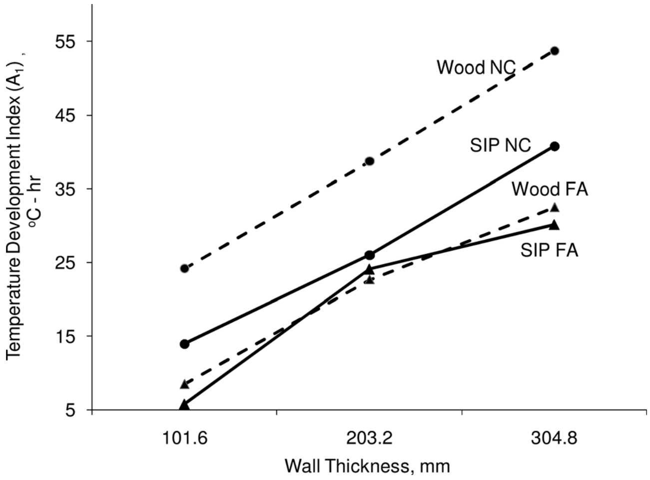
Figure 12 presents temperature versus time for walls formed with SIP formwork with and without insulation and with and without FA. Incorporating 50-mm-thick insulation with the SIP system resulted in greater TDIs and higher peak temperatures (**Fig. 12**). The use of insulation increased the peak temperature and TDI by 10 % and

TABLE 4

Temperature at peak, A1 (temperature development index [TDI]), and A2 for the wood formwork.

Wall Type		Peak Temperature, °C	Time at Peak, h	A_1 (TDI), °C-h	A_2, °C-h
Normal concrete	100 mm	25.31	15.0	24.12	34.07
	200 mm	29.12	13.5	38.71	60.93
	300 mm	29.85	15.7	53.71	76.99
Fly ash	100 mm	24.09	12.1	8.44	3.99
	200 mm	24.02	16.7	22.65	29.67
	300 mm	26.11	18.1	32.47	37.85

FIG. 11 TDI (A1) as a function of wall thickness for walls formed with PVC SIP and wood formwork for NC and FA.



52 %, respectively, for the NC mix and by 13 % and 83 %, respectively, with the use of FA.

Figure 13 presents average temperature versus time for wood formed specimens with and without insulation. Similar to the results for the SIP specimens, the data indicate that when insulation was used, the peak temperature was greater than in walls without insulation. The NC specimen with insulation also achieved a greater temperature development than the NC specimen without insulation; however, this trend was not visible in the FA specimens. When insulation was used with the NC

FIG. 12 Average thermocouple temperature versus time for walls formed with SIP formwork with NC and FA with and without insulation (Insul).

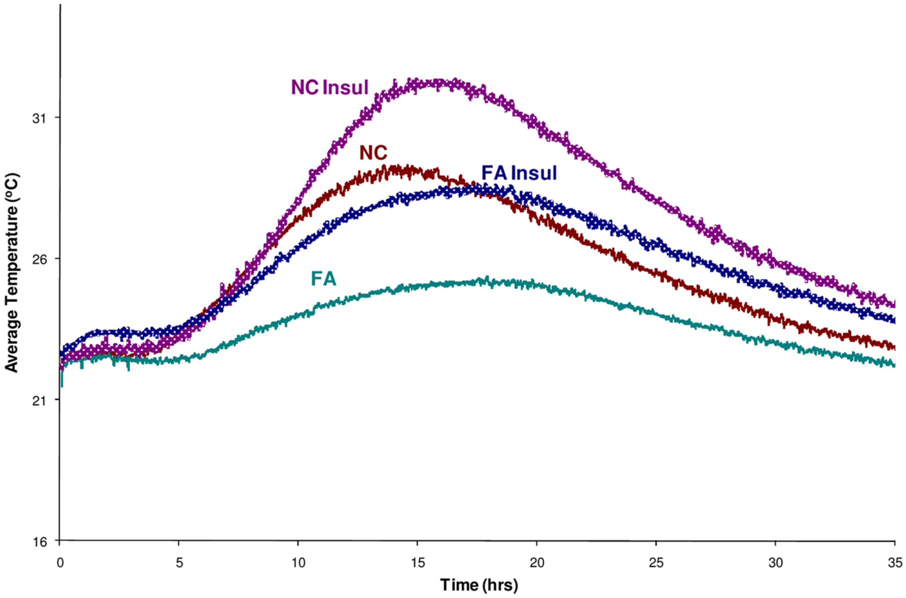
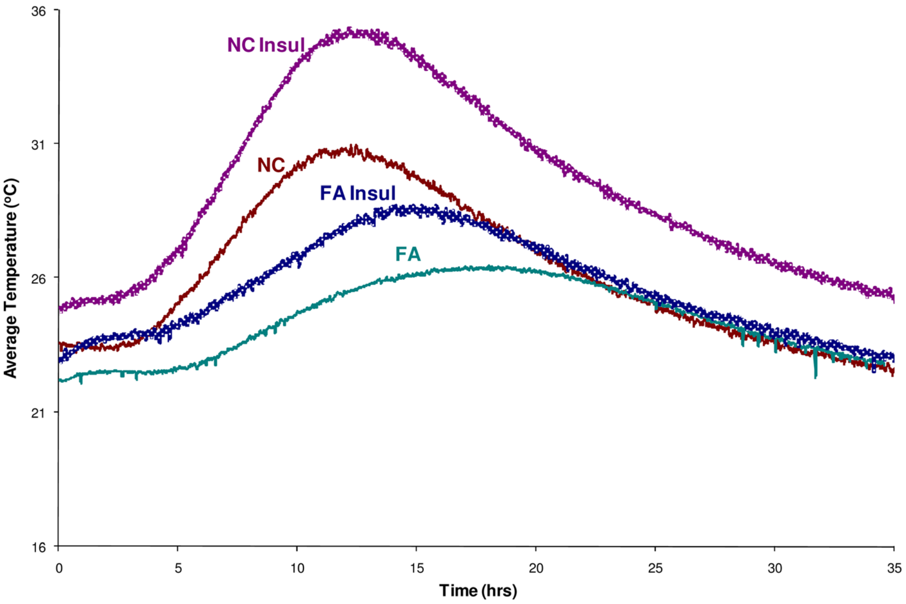


FIG. 13 Average thermocouple temperature versus time for walls formed with wood formwork with NC and FA with and without insulation (Insul).



mix, the peak temperature and TDI increased by 15 % and 19 %, respectively. When insulation was used with the FA mix, the peak temperature increased by 9 %, whereas the TDI decreased by 12 %. The reasons for this decrease are not clear, and it warrants further investigation.

WOOD FORMED VERSUS STAY-IN-PLACE SYSTEM: COMPARISON

Figure 11 is a plot of the average temperature development for the SIP system and wood formed walls of various wall thicknesses. For both the wood and SIP system formed walls, there was an increase in temperature development with an increase in wall thickness due to the increased thermal mass of the additional concrete from the larger walls. The results show that the wood formed specimens achieved greater temperature development than the SIP specimens, particularly when the NC mix was used. In general, the addition of FA appeared to slow the hydration process, reducing the total temperature developed, and caused the specimen to reach a lower peak temperature at a later time in both wood and SIP walls. In the 200-mm SIP FA specimen, a slightly higher temperature development was achieved than in the wood formed specimen. When the composition was varied, there was a greater difference in the TDI for the wood walls (an average of a 49 % difference) than for the SIP walls (average of a 31 % difference). This might indicate that the SIP system is able to contain more moisture and develop more cumulative heat than the wood formwork during the hydration process when FA is used.

In general, the inclusion of insulation for both wood and SIP systems increased the peak temperature during hydration and contributed to greater temperature development. In general, the peak temperatures for specimens containing insulation occurred later than in specimens without insulation. For the specimens tested, the inclusion of insulation with the SIP system appeared to have a more significant effect on temperature development and peak temperature than in the wood system. This finding might be a result of the wood system itself providing insulation and the additional insulation having little effect. It is interesting to note that the SIP system used with the FA mix and insulation achieved greater temperature development than the wood forming system used with the NC mix and no insulation. These results are an indication that the SIP system used in combination with FA and insulation more positively contributes to the hydration process than standard wood forms used with an NC mix.

The compression test results for cored specimens and the analyzed temperature data are presented in **Table 5**. The wood formed walls generally achieved greater temperature development than the SIP formed walls for all wall sizes. To understand this correlation, we determined the R value of each formwork material. The R values for the PVC SIP and 2 in. of EPS insulation are reported as 0.60 and approximately 8, respectively [2], and that for 20-mm (0.75-in.) plywood is reported as 0.90 [11]. The lower R value of the SIP indicates that it is less resistant to thermal change than wood, and this might explain why it achieved less temperature development overall in non-insulated systems. These R values, along with the R value of the insulation used in this project, are noted in **Table 1**.

COMPRESSION TESTING

Cast Cylinders

When 40 % cement was replaced with FA, the compressive strength decreased from an average of 32 ± 3 MPa to 29 ± 6 MPa at 56 days.

Cores

Cores were taken from four 200-mm walls and four 250-mm walls with 50 mm of insulation (and 200 mm of concrete): two each from SIP NC, SIP FA, wood NC, and wood FA. These cores were tested and averaged for each wall. The compression testing data are summarized in **Table 5**. It should be noted that the compressive strengths reported in **Table 5** are for an age of 36 h and thus are significantly lower than those measured for cast specimens tested after 56 days. One of the other

TABLE 5

Compressive strength data from cored samples (36 h after casting) and the corresponding temperature data.

Sample		Compressive Strength f'_c, MPa	Standard Deviation, MPa	TDI/A1, °C-h	Average Peak Temperature T_p, °C	Average Time at Peak t_p, h
Normal concrete	SIP	17.86	4.83	42.24	29.45	14.34
	Wood	20.13	7.38	43.50	31.00	11.84
Fly ash	SIP	12.07	2.69	24.31	25.42	17.87
	Wood	12.41	1.72	34.53	26.57	17.99
NC insulated	SIP	15.05	0.92	64.01	32.54	16.00
	Wood	12.51	7.52	44.52	28.80	17.33
FA insulated	SIP	20.40	0.35	51.68	35.50	12.80
	Wood	5.85	0.24	30.25	28.89	14.87

methods of comparison for these walls was the TDI (A1 in **Table 5**), which has been explained already.

When we treated the compressive strength for FA insulated wood specimens as an anomaly, a reasonable correlation between f'_c measured for cored samples and TDI was observed. This correlation existed only when the same concrete type and formwork configurations were considered. The general trend shows that when the TDI increased there was an increase in compressive strength. However, when we compared the insulated walls to the non-insulated walls, we noted that similar compressive strengths were measured for dissimilar TDIs. This may be attributed to the limited number of cores and the high standard deviation observed in the compressive test results (as high as 60 % for the NC insulated wood specimen). Establishing a straightforward correlation between f'_c and TDI was difficult because the TDI corresponded to thermal activity up to the peak (the time to peak ranged between 11 and 18 h), whereas all coring occurred at 36 h. Further research is necessary to clearly establish this correlation.

Conclusions

1. The proposed TDI was an effective method of analyzing the temperature data. TDI could be effectively used to minimize the effect of different ambient conditions and to capture the hydration that occurs immediately after the dormant hydration stage. The wood forming system contributed to higher peak temperatures, which occurred later than in the PVC SIP forming system. The extent of the hydration process did appear to be greater in the wood system for an NC mix. This corroborates well with the R values for both forming systems.
2. The SIP system used in combination with a high-volume FA mix and insulation achieved greater temperature development than the non-insulated wood forming system used with NC. These results indicate that the insulated SIP system used with FA more positively contributed to the hydration process than the non-insulated wood formed system used with the NC mix.
3. Special attention is required to ensure strength gain before stripping forms, especially for thin walls cast using concrete containing a high volume of FA.

Further Research

In addition to wood and one type of SIP formwork, further research should be done to compare the effect of other forming systems used in the industry on the maturity of concrete. In particular, larger wall sizes should be tested to better simulate the conditions experienced in the field. Stripping time variability should be incorporated into this testing. The validity of the TDI should be examined in tests conducted under extreme ambient conditions to simulate colder winter climates and warmer summer climates. Further research with a larger sample size of cored specimens is suggested in order to clearly establish the relationship between concrete compressive strength and TDI.

ACKNOWLEDGMENTS

The writers thank Octaform Systems Inc. for sponsoring this project and for providing the materials and technical expertise for this project. The writers also acknowledge the contributions of the Seattle University senior design team comprising Kristian Lowrie, David Sommer, and Nikki Wheeler.

References

[1] Kuder, K. G., Gupta, R., Sodders, C., Hawksworth, R., Henderson, S., and Whitney, J., "Effect of PVC Stay-in-Place Formwork on Mechanical Performance of Concrete," *J. Mater. Civ. Eng.*, Vol. 21, No. 7, 2009, pp. 309–315.

[2] Octaform Systems Inc., "Technical Guide," http://www.octaform.com/index.php?page=technical-guides (Last accessed 1 Oct 2009).

[3] Mindess, S., Young, F. J., and Darwin, D., *Concrete*, Prentice-Hall, Upper Saddle River, NJ, 2003.

[4] Malhotra, M., "Reducing CO_2 Emissions: The Role of Fly Ash and Other Supplementary Cementitious Materials," *Concrete Int.*, Vol. 28, No. 9, 2006, pp. 42–45.

[5] Mehta, P. K., "Global Concrete Industry Sustainability: Tools for Moving Forward to Cut Carbon Emissions," *Concrete Int.*, Vol. 31, No. 2, 2009, pp. 45–48.

[6] Khan, A. A., Cook, W. D., and Mitchell, D., "Thermal Properties and Transient Thermal Analysis of Structural Members During Hydration," *ACI Mater. J.*, Vol. 95, No. 3, 1998, pp. 293–303.

[7] Wang, K., Zhi, G., Grove, J., Ruiz, J. M., Rasmussen, R., and Ferragut, T., *Developing a Simple and Rapid Test for Monitoring the Heat Evolution of Concrete Mixtures for Both Laboratory and Field Applications*, N.C.P.T. Center, Iowa, 2006.

[8] ASTM C192/C192M: Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory, *Annual Book of ASTM Standards*, ASTM International, West Conshohocken, PA, 2012.

[9] ASTM C31/C31M: Standard Practice for Making and Curing Concrete Test Specimens in the Field, *Annual Book of ASTM Standards*, ASTM International, West Conshohocken, PA, 2012.

[10] Lowrie, K., Sommer, D., and Wheeler, N., *Effect of PVC Stay-in-Place Formwork on the Hydration of Concrete*, Seattle University, Seattle, WA, 2007.

[11] TECO, "Panel R Values," http://www.tecotested.com/prod-info (Last accessed 15 June 2010).