Journal of Materials Science and Engineering B 7 (3-4) (2017) 81-88
doi: 10.17265/2161-6221/2017.3-4.005

Evaluation of Fire-Performance by Cone-Calorimeter Tests and Thermal Conductivity of Polymer-Modified Mortars and Various Concretes

Sanjay PAREEK

College of Engineering, Nihon University, Koriyama, Fukushima-ken 963-8642, Japan

Abstract: In this study, experimental study is carried out in order to understand the behavior of various concretes and mortars under elevated temperatures with emphasis on thermal conductivity of each type of material during fire. The reaction to fire test by cone-calorimeter method and thermal conductivity of normal concrete, high-density concrete, light-weight aerated mortar, ordinary cement mortar and polymer-modified mortars have been taken into consideration. The heat release rate and total heat release of normal concrete, high-density concrete, light-weight aerated mortar and ordinary cement mortar specimens was remarkably lower than 200kW/m^2 and 8MJ/m^2, respectively and showed no explosive spalling or cracking on the surface of specimens. Polymer-modified mortar specimens showed an increase in heat release rate and total heat release with the increase of polymer-cement (P/C) ratio. Furthermore, SBR-20% and PAE-20% specimens showed an explosive spalling behavior. Thermal conductivity of high-density concrete and polymer-modified mortars was higher than normal concrete and mortar.

Key words: Heat-release rate (kW/m^2), total heat release (MJ/m^2), thermal conductivity, polymer-modified mortar, concrete.

1. Introduction

Japan has been an active earthquake prone nation with numerous natural disasters occurring frequently throughout the country. Major earthquakes are accompanied by huge fires causing a tremendous loss of life and property. On the hand, the design standards have been shifting from design base to performance base design specifications for the repair and rehabilitation of RC (reinforced concrete) structures by polymer-modified mortars for improving the durability and life-span of RC structures. Polymer-modified mortars have been widely used for the repair and rehabilitation of deteriorated RC structures, which show an explosive spalling behavior when subjected elevated temperatures in the instances of fire [1, 2]. This kind of explosive behavior has been explained to be due to the development of high pressure by steam inside the mortar matrixes and stresses developed during elevated temperatures [3, 4]. Simultaneously, it is also supposed that the thermal stresses develop due to the expansion of heat exposed surface and the cooler inner core [5].

In this study, experimental study is carried out in order to understand the behavior of various concretes and mortars under elevated temperatures with emphasis on thermal conductivity of each type of material during fire. The reaction to fire test by cone calorimeter method and thermal conductivity of normal concrete, high-density concrete, light-weight aerated mortar, ordinary cement mortar and polymer-modified mortars have been taken into consideration.

2. Experimental Program

2.1 Materials and Mix Proportions

Cement used for all the mixes was an ordinary portland cement as specified in JIS (Japanese Industrial Standard) R5201 (Physical testing methods

Corresponding author: Sanjay PAREEK, Dr. Eng., associate professor, research fields: concrete engineering, concrete science and composite materials.

for cement). Table 1 gives the mix proportions of ready-mixed concrete with a design strength of 24 N/mm^2. Crushed sand as fine aggregate (sieve size ≥ 5 mm) and coarse aggregate (sieve size 5-20 mm) from Shirakawa were used as aggregates for concrete. An AE (air-entraining water reducing agent) was used as an admixture. Table 2 gives the mix proportions of HC (high-density concrete). Photo 1 shows the appearance of high-density aggregate (μ = 4.5 g/cm^3). The fine aggregate (sieve size ≥ 2 mm) and coarse aggregate (sieve size 8-20 mm) from Sweden were used for high-density concrete mixes. An AE-H (high range water reducing agent) was used as an admixture for high-density concrete. Table 3 gives mix proportions of LM (light-weight aerated mortar). Toyoura standard sand was used as fine aggregate for the light-weight aerated mortar mixes. In order to entrain high volume of air for the light-weight mortars, FA (alkyl-ether based foaming agent) was used as an admixture. Table 4 gives the mix proportions of ordinary cement mortar. Silica sand (sieve size ≥ 2.5 mm) was used as fine aggregates. Table 5 gives the mix proportions of polymer-modified mortars. Silica sand (sieve size ≥ 2.5 mm) was used as fine aggregates. Three types of polymer dispersions, SBR (styrene butadiene rubber) latex, EVA (ethylene vinyl acetate) emulsion and PAE (poly-acrylic ester) emulsion were used as polymeric admixtures or cement modifiers. Table 6 shows the properties of polymer dispersions. A silicone anti-foaming agent was added to the polymer dispersions in the ratio of 0.5% to the total solids of polymer dispersions. As the water content of polymer-modified mortars is an influential factor for fire performance, a constant water-cement ratio was used for preparation of all the mortars.

Table 1 Mix proportions of normal concrete.

G_{max} (mm)	W/C (%)	Air (%)	s/a (%)	μ (g/cm^3)	Unit amount (kg/m^3)				
					W	C	S	G	AE
20	57.9	4.5	48.8	2.3	184	318	855	963	3.180

Table 2 Mix proportions of HC (high-density concrete).

G_{max} (mm)	W/C (%)	Air (%)	s/a (%)	μ (g/cm^3)	Unit amount (kg/m^3)				
					W	C	S	G	AE-H
20.0	53.1	1.0	40.4	3.9	186	350	1,356	2,003	1.320

Photo. 1 High-density aggregate (μ = 4.5 g/cm^3).

Table 3 Mix proportions of LM (light-weight aerated mortar).

W/C (%)	Air (%)	C/S	μ* (g/cm^3)	Unit amount (kg/m^3)			
				W	C	S	FA
58.2	20≤	1:2	0.9	291	500	1,000	10.0

* Measured value.

Table 4 Mix proportions of ordinary cement mortar.

W/C (%)	Air (%)	C/S	μ (g/cm^3)	Unit amount (kg/m^3)			
				W	C	S	AE
58.2	7.0	1:3	2.1	285	490	1,470	-

Table 5 Mix proportions of polymer-modified mortars.

P/C (%)	W/C (%)	C/S	μ* (g/cm^3)			Amount of unit (kg/m^3)				
			SBR	EVA	PAE	W	C	S	P	FA
5	335.0	1:3	2.0	2.1	2.1	150	500	1,500	50	2.5
10			2.1	2.1	2.1	125	500	1,500	100	2.5
15			2.1	2.1	2.1	100	500	1,500	150	2.5
20			2.2	2.0	2.1	75	500	1,500	200	2.5

* Measured value.

Table 6 Properties of polymer dispersions.

Type of polymer dispersion	Density (20 °C)	pH (20 °C)	Viscosity (20 °C, mPa/s)	Total solids (%)
SBR latex	1.02	8.9	118	46.9
EVA emulsion	1.06	4.9	748	45.4
PAE emulsion	1.03	8.1	1,205	44.5

2.2 Preparation of Specimens

Concrete and mortars of beam size 100 × 100 × 400 mm were molded respectively and then subjected to a 2d-moist [20 °C, 90% R.H.] + 5d-water [20 °C] + 21d-dry [20 °C, 60% R.H.] cure. Furthermore, all the specimens were placed in an oven for drying at 40 °C until a constant weight was obtained (weight change of ≥ 0.2%/d). Fig. 1 shows the shape and dimensions of the specimens for heating as specified in ISO 5660-1:2002 [Reaction to fire tests-Heat release, smoke production and mass loss-Part 1: Heat release rate (Cone calorimeter method)]. Concrete and mortar specimens of 99 × 99 mm (±1 mm) and thickness of less than 50 mm were cut from the 100 × 100 × 400 mm beams. Specimens used for thermal conductivity tests were also of the same dimensions.

2.3 Testing Procedures

2.3.1 Reaction to Fire Test by Cone Calorimeter Method

Fig. 2 shows the schematic view of the cone calorimeter test set-up. Tests were conducted in accordance to ISO 5660-1:2002 [Reaction to fire tests-Heat release, smoke production and mass loss-Part 1: Heat release rate (Cone calorimeter method)]. Tests were performed for 1,200 s (20 min) by uniformly heating the specimens under a 50 kW/m^2 radiation heating.

2.3.2 Thermal Conductivity Test

Thermal conductivity tests of respective type of concrete and mortars were performed by a transient hot-wire method in accordance to JIS A 1412 (Test method for thermal resistance and related properties of thermal insulations—Part 2: Heat flow meter apparatus).

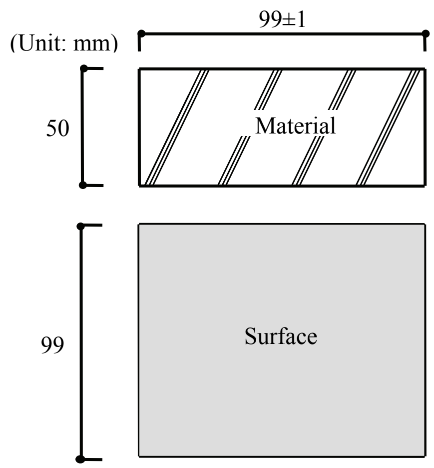

Fig. 1 Shape and dimension of test specimen.

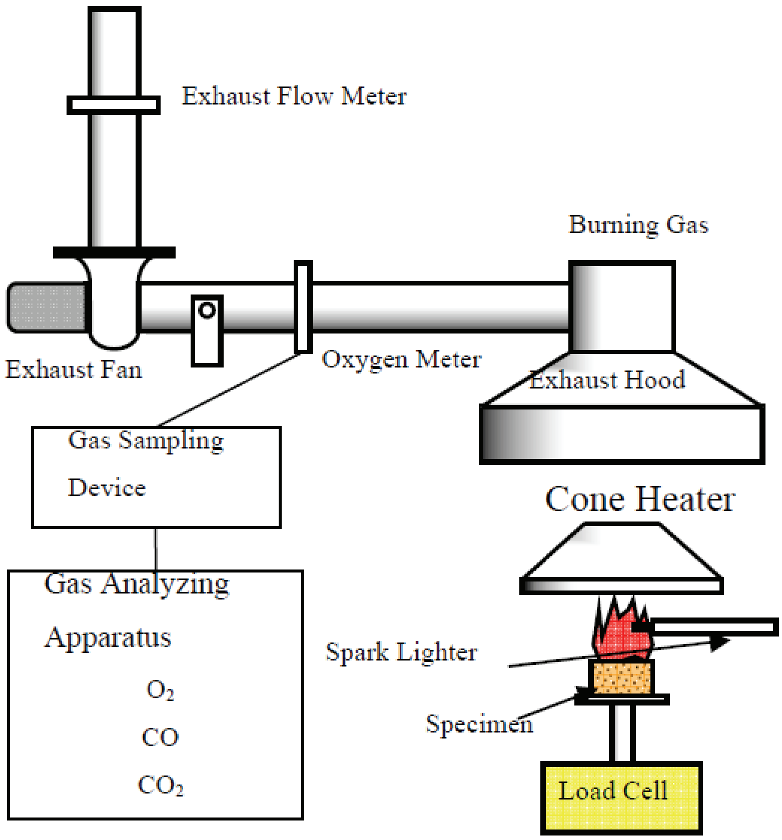

Fig. 2 Schematic view of cone calorie meter.

Fig. 3 shows the conceptual diagram of the thermal conductivity test set-up by stationary hot-wire method. A thermal heat flow sensor is located in the hot and cold plate of the measuring equipment and the test specimen is set-up between the two plates. The thermal conductivity (λ) is measured by applying a temperature gradient between the two plates and can be calculated according to the following equation:

$$\lambda = (Q_h + Q_c) / 2 \cdot L / \Delta T \qquad (1)$$

where, λ is thermal conductivity (W/mK), Q_h and Q_c are the measured heat flow (Q/m), L is the thickness (m) of the specimen and ΔT is the temperature difference between hot surface side (T_h) and cold surface side (T_c).

3. Results and Discussion

3.1 Reaction to Fire Test Results by Cone Calorimeter Method

Fig. 4 illustrates the heating time vs. heat release rate and total heat release of normal concrete, high-density concrete, light-weight aerated mortar and ordinary cement mortar specimens. Irrespective of the type of concrete or mortar, all the test results of the specimens were graded as noncombustible, as the heat release rate and total heat release were distinctively below 200 kW/m^2 and 8 MJ/m^2, respectively. In addition,

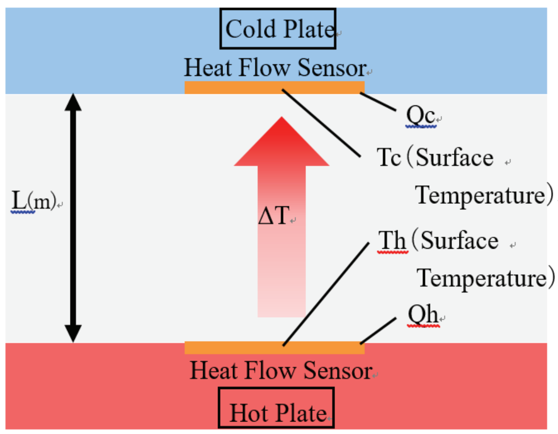

Fig. 3 Conceptual diagram of thermal conductance by stationary hot wire method.

Table 7 Quality grading based on building standard law.

Grading for fire-preventive material	Total heat release (MJ/m^2)	Heat release rate (kW/m^2)
Failed	Total Heat release exceeds 8 MJ/m^2 or more within 5 min from the start of heating.	Maximum heat release rate within 5 min from the start of heating exceed 200 kW/m^2 for longer than 10 s.
Flame-retardant material	Total heat release shall be 8 MJ/m^2 or less for 5 min from the start of heating.	Maximum heat release rate for 5 min from the start of heating shall not exceed 200 kW/m^2 for longer than 10 s.
Quasi-noncombustible material	Total heat release shall be 8 MJ/m^2 or less for 10 min from the start of heating.	Maximum heat release rate for 10 min from the start of heating shall not exceed 200 kW/m^2 for longer than 10 s.
Noncombustible material	Total heat release shall be 8 MJ/m^2 or less for 20 min from the start of heating.	Maximum heat release rate for 20 min from the start of heating shall not exceed 200 kW/m^2 for longer than 10 s.
Common	Cracks and holes penetrating through the specimen are absent from the start of heating.	

none of the concrete or mortar specimens showed explosive spalling or cracking on the surface of specimens.

Fig. 5 shows the heating time vs. heat release rate and total heat release of SBR-modified mortar specimens. An increase in heat release rate and total heat release was observed with the increase of P/C (polymer-cement) ratio and this can be seen distinctively at heating time of 1,200 s (20min). The SBR-modified mortar specimens with a P/C 20% were graded as quasi-noncombustible as it exceeded the limit of total heat release rate of 8 MJ/m^2 at the heating time of 820 s after which an explosive spalling of the mortar surface of the specimens was observed. This is due to the high volume content of the SBR in the mortar, which is mainly composed of carbon and hydrogen making it combustible and a combined effect of in-built steam pressure in the matrix of the mortar.

Fig. 6 exhibits the heating time vs. heat release rate and total heat release of EVA-modified mortar specimens. The results of increase in heat release rate and total heat release with an increase of P/C ratio showed a similar behavior to SBR-modified mortars. Furthermore, the EVA-modified mortar specimens with a P/C 20% were graded as quasi-noncombustible as it exceeded the limit of total heat release rate of 8 MJ/m^2 before the heating time of 1,200 s (20 min). However, the EVA-20% modified mortar specimens did not show an explosive spalling unlike the SBR-20% modified mortar specimens. This is as a result of degradation of polymeric chains of vinyl acetate, which is the main component of EVA, releasing acetic acid and water as result of the pyrolysis of vinyl ester of EVA-modified mortars at elevated temperatures.

Fig. 7 illustrates the heating time vs. heat release rate and total heat release of PAE-modified mortar specimens. Alike the SBR and EVA-modified mortars, an increase in heat release rate and total heat release was observed with the increase of P/C ratio. An explosive spalling of PAE-20% specimens which is noticed at an elapsed heating time of 630 s was graded as quasi-noncombustible.

3.2 Thermal Conductivity Test Results

Fig. 8 shows the thermal conductivity of normal concrete, high-density concrete, light-weight aerated

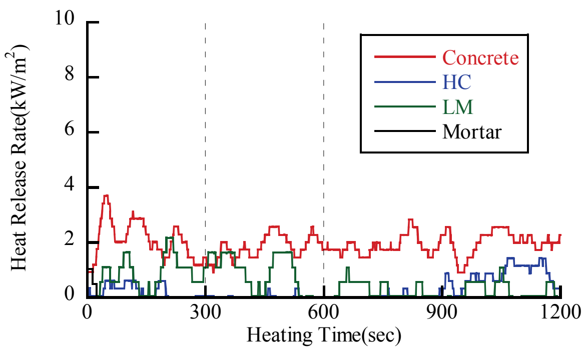

Fig. 4 Heating time vs. heat release rate and total heat release of normal concrete, high-density concrete, light-weight aerated mortar and ordinary cement mortar.

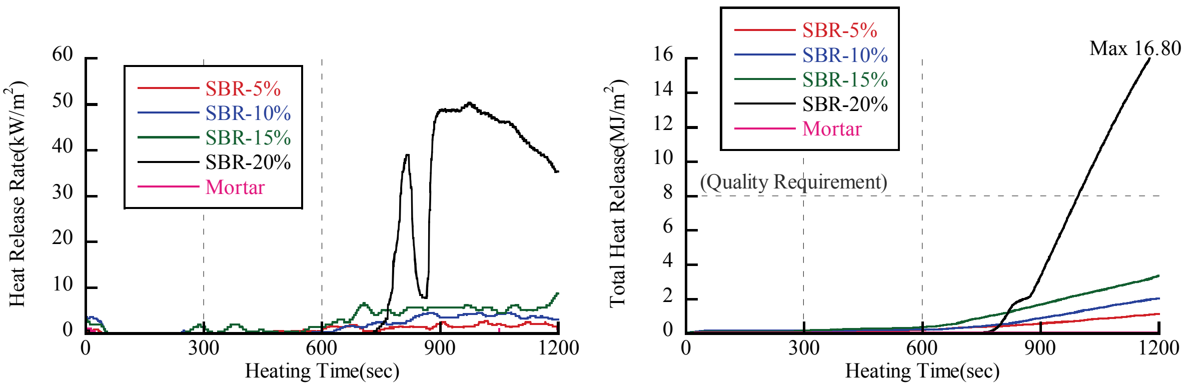

Fig. 5 Heating time vs. heat release rate and total heat release of SBR-modified mortars.

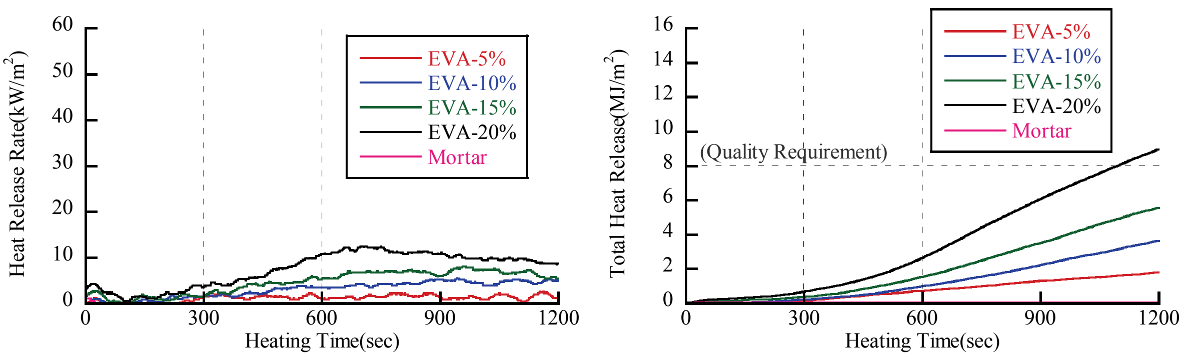

Fig. 6 Heating time vs. heat release rate and total heat release of EVA-modified mortars.

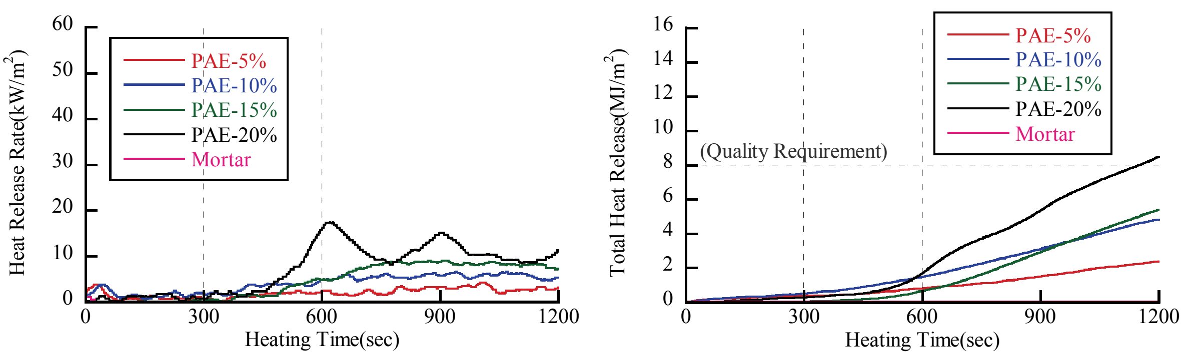

Fig. 7 Heating time vs. heat release rate and total heat release of PAE-modified mortars.

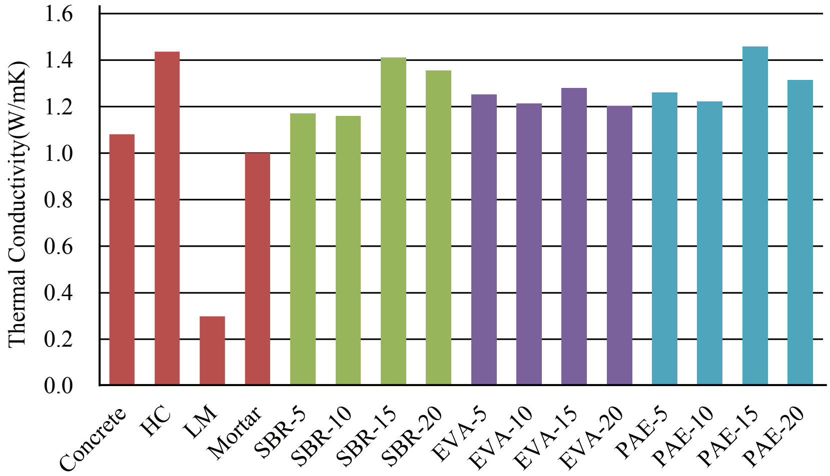

Fig. 8 Thermal conductivity of various concretes and mortars.

Table 8 Experimental results and grading of materials.

Identification			Total heat release (MJ/m^2)	Max. heat release rate (kW/m^2)	Grading
Concrete	Normal concrete		1.95	3.45	Noncombustible
	High-density concrete		0.60	1.43	Noncombustible
Mortar	Light-weight aerated mortar		0.75	2.06	Noncombustible
	Ordinary cement mortar		0.48	3.23	Noncombustible
Poymer-modified mortar	SBR	P/C 5%	1.13	2.94	Noncombustible
		10%	3.57	3.34	Noncombustible
		15%	3.34	8.73	Noncombustible
		20%	16.80	50.27	Quasi-noncombustible
	EVA	P/C 5%	1.81	3.56	Noncombustible
		10%	3.65	5.49	Noncombustible
		15%	5.55	8.59	Noncombustible
			8.95	12.97	Quasi-noncombustible
	PAE	P/C 5%	2.38	4.28	Noncombustible
		10%	4.83	7.71	Noncombustible
		15%	5.38	9.88	Noncombustible
		20%	8.47	17.39	Quasi-noncombustible

mortar, ordinary cement mortar and polymer-modified mortar specimens. In comparison to the thermal conductivity of normal concrete, high-density concrete were 33% higher and light-weight aerated mortar was 72% lower showing a proportional relationship to the density. In general, polymer-modified mortars, irrespective of P/C ratios, had a higher thermal conductance in comparison to the normal concrete. SBR and PAE-modified mortars with P/C ratios of 5% and 10% had lower thermal conductance as compared to 15% and 20%. EVA-modified mortars did not show a drastic difference in thermal conductivity with a change in P/C ratio. The explosive spalling behavior of SBR and PAE-modified mortars with a P/C ratio of 20% is presumed to be due to higher thermal conductivity of heat into the inner layers and building steam pressure along with the larger volume of polymer content.

4. Conclusions

From this study, cone-calorimeter tests for heat release rate and total heat release and thermal conductivity of normal concrete, high-density concrete, light-weight aerated mortar, ordinary cement mortar and polymer-modified mortar specimens were tested and following remarks can be concluded:

The heat release rate and total heat release of normal concrete, high-density concrete, light-weight aerated mortar and ordinary cement mortar specimens was remarkably lower than 200 kW/m^2 and 8 MJ/m^2, respectively and showed no explosive spalling or cracking on the surface of specimens.

Polymer-modified mortar specimens showed an increase in heat release rate and total heat release with the increase of P/C ratio. Furthermore, SBR-20% and PAE-20% specimens showed an explosive spalling behavior and were graded as quasi-noncombustible.

Thermal conductivity of high-density concrete and polymer-modified mortars was higher than normal concrete and mortar.

Acknowledgments

The author would like to express his acknowledgments for the experimental work carried out by Mr. Yutaro ANDO (Past Graduate Student of RC Structures and Materials Lab) of Tokyo Tekko Co. Japan. A part of the research was supported by KAKENHI Grant-in-Aid for Scientific Research (A) 16H02376.

References

[1] Shirai, A., Ohama, Y., and Kokubun, Y. 2010. "Effects of Flame Retardants on Fire-Protecting Performance of Polymer Modified Mortars." In *Proceedings of 13th ICPIC,* 119-26.

[2] Faris, A., Ali, N., and Abid, A. 2011. "Explosive Spalling of Normal Strength Concrete Slabs Subjected to Severe Fire." *Materials and Structures* 44: 943-56.

[3] Wang, R., Kawakami, H., Ozawa, M., and Morimoto, H. 2006. "Experimental Study on Spalling Mechanism of Concrete." *Proceedings of the Japan Concrete Institute* 28 (1): 1703-8.

[4] Omer, A. 2007. "Effects of Elevated Temperatures on Properties of Concrete." *Fire Safety Journal* 42 (8): 516-22.

[5] Jansson, R., and Boström, L. 2015. "Three Experiments to Validate Basic Functions in Fire Spalling Models." 4th International Workshop on Concrete Spalling due to Fire Exposure, 342-9.