A Low Temperature Rise Mixture for Mass Concrete

Fly ash-based hydraulic cement generates significantly less heat than portland cement

by John Gajda, Michael Weber, and Ivan Diaz-Loya

Mass concrete placements often require significant efforts to control temperature rise and differentials due to the heat of hydration of cementitious materials. The adiabatic (meaning no heat loss) temperature rise of a typical portland cement concrete mixture with a 4000 psi (27.6 MPa) 28-day design strength is on the order of 80 to 100°F (44 to 55°C). So, to ensure a mass concrete element doesn't exceed the maximum temperature limit of 158°F (70°C) specified in ACI 301-10, "Specifications for Structural Concrete," the placement temperature for such a mixture might need to be quite low—perhaps below 58°F (15°C) for the 100°F (55°C) temperature rise concrete.

Using conventional portland cement-based binders, it's difficult to limit temperature rise while still having concrete that's workable and pumpable. Even when aggregate gradations are optimized to minimize the cementitious material content and large percentages of portland cement are replaced with Class F fly ash or slag cement, the temperature rise of a concrete mixture can be about 70°F (39°C) and control measures still may be required. However, alternative binder systems have been shown to allow significant reductions in temperature rise, potentially eliminating or reducing the measures normally needed for mass concrete construction.

Temperature Rise

A project was recently carried out by CTLGroup, Consumers Concrete, and CeraTech to evaluate the temperature rise of comparable batches of *ekkomaxx*™ concrete and portland cement concrete (PCC). Both batches were produced with typical proportions of aggregates; however, the cementitious materials in the *ekkomaxx* concrete consisted entirely of a liquid-activated Class C fly ash system meeting the performance requirements of ASTM C1157/C1157M-11, "Standard Performance Specification for Hydraulic Cement." In *ekkomaxx* mixtures, the Class C fly ash is activated through the use of a hydrocarboxylic acid salt at a very low concentration—typically 5 to 15% of the total mixing water in a batch. As the word "salt" implies, the activator is pH-neutral. The reaction products of Class C fly ash activated with hydrocarboxylic acid salt are calcium aluminosilicate hydrates. Class C fly ash hardens by the simple addition of water, and the function of the additive is to delay the setting time. This allows the formation of more of these hydrates and thus enhances strength.

Both batches were produced at a commercial ready mixed concrete plant. The PCC was selected as representative of a typical concrete mixture used in mass concrete placements for bridge substructures or building foundations. To keep the mixtures simple, no water-reducing admixture was used with either concrete. The mixture proportions for both concretes are shown in Table 1. Slump values, as measured per ASTM C143/C143M, "Standard Test Method for Slump of Hydraulic-Cement Concrete," were 4.0 and 4.5 in. (102 and 114 mm) for the *ekkomaxx* and the PCC mixtures, respectively. No air-entraining admixture was used in either concrete mixture, so the air contents and unit weights were not measured. Compressive strengths for both concretes (Table 2) were obtained using standard 6 x 12 in. (150 x 300 mm)

Table 1:
Concrete mixture proportions

Material	*ekkomaxx* concrete	PCC
Portland cement (Type I/II), lb/yd^3 (kg/m^3)	—	461 (273.5)
Fly ash (Class C), lb/yd^3 (kg/m^3)	658 (390)	—
Fly ash (Class F), lb/yd^3 (kg/m^3)	—	197 (117)
Coarse aggregate (No. 57 limestone), lb/yd^3 (kg/m^3)	1701 (1009)	1701 (1009)
Fine aggregate (natural sand), lb/yd^3 (kg/m^3)	1521 (902)	1397 (829)
Water (potable), lb/yd^3 (kg/m^3)	188.5 (112)	276 (164)
CeraTech additive, fl oz/100 lbs fly ash (mL/100 kg)	44.7 (2906)	—
Retarder, fl oz/100 lbs fly ash (mL/100 kg)	6.0 (390)	—
Total cementitious material, lb/yd^3 (kg/m^3)	658 (390)	658 (390)
w/cm	0.29	0.42
Fly ash content, % of total cementitious material	100	30

cylinders tested per ASTM C39/C39M-14, "Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens."

The temperature rise of the concrete mixtures was evaluated using a CTLGroup standard procedure which involved:

- Placing each mixture in a large cubical mold that was insulated sufficiently to provide a nearly adiabatic environment; and
- Measuring concrete and ambient temperatures on an hourly basis for about 2 weeks.

The test specimens were 3 x 3 x 3 ft (0.9 x 0.9 x 0.9 m) cubes cast in 4 x 4 x 4 ft (1.2 x 1.2 x 1.2 m) molds lined with 6 in. (152 mm) of extruded polystyrene board insulation (Fig. 1 to 3). Specimens were instrumented with Engius intelliRock™ temperature sensors placed at the center of mass, centroids of the top and bottom surfaces, and a bottom corner of each cube. The ambient temperature was also monitored using an additional Engius intelliRock™ temperature sensor placed in a shaded location nearby the cubes.

Table 3 and Fig. 4 summarize the temperature histories at the center of mass of each cube. The peak temperatures for the *ekkomaxx* and the PCC mixtures were 135°F (57°C) and 163°F (73°C), respectively.

Figure 5 presents the calculated adiabatic temperature rise of the concretes. The adiabatic temperature rise was corrected for maturity based on the Arrhenius equation in ASTM C1074-11, "Standard Practice for Estimating Concrete Strength by the Maturity Method," and an activation energy of 33,500 J/mol.

Table 2:
Concrete compressive strength results, average of two cylinders per age per concrete

Age at testing	*ekkomaxx* concrete, psi (MPa)	PCC, psi (MPa)
1 day	2510 (17.3)	2870 (19.8)
7 day	5970 (41.2)	4740 (32.7)
28 day	7250 (50.0)	5180 (35.7)

Fig. 1: The plywood form was lined with three layers of 2 in. (50 mm) extruded polystyrene board insulation and the joints of the inner layer were sealed with foam-in-place insulation. The temperature sensors are mounted on fixed plastic rods located near the center of one face and the center of mass of the final specimen

Fig. 2: Concrete placement for a 3 x 3 x 3 ft (0.9 x 0.9 x 0.9 m) specimen

Fig. 3: After the form was filled with concrete, the top surface of the test cube was covered with three layers of 2 in. (50 mm) extruded polystyrene board insulation. The joints in the layers were staggered to prevent convective heat transfer or infiltration (refer to Fig. 1)

Table 3:
Measured hourly temperatures at the center of mass of test cubes. Concrete temperatures at delivery were 82°F (28°C) and 89°F (32°C) for *ekkomaxx* and PCC, respectively

Elapsed time after setting of concrete	*ekkomaxx* concrete, °F (°C)	PCC, °F (°C)
0 hour*	82 (28)	90 (32)
6 hours	124 (51)	129 (54)
12 hours	133 (56)	144 (62)
1 day	135 (57)	158 (70)
2 days	133 (56)	163 (73)
3 days	131 (55)	162 (72)
4 days	127 (53)	158 (70)
7 days	120 (49)	147 (64)
14 days	104 (40)	126 (52)

*Setting time of concrete (concrete temperature began to increase)

The time and temperatures in the *ekkomaxx* cube were such that the equivalent age was measured through 48 equivalent age days (and data beyond this point were estimated). The time and temperatures in the PCC cube were such that the equivalent age of the concrete was close to 90 equivalent age days.

Approximation Equation

In a 6 ft (1.8 m) thick or greater placement using PCC, temperature rise of concrete can be approximated by:

$Rise = 0.16^{*}\,(Cement + 0.5^{*}F_{Ash} + 0.8^{*}C_{Ash} + 1.2^{*}SFMK + Factor^{*}Slag)$, °F

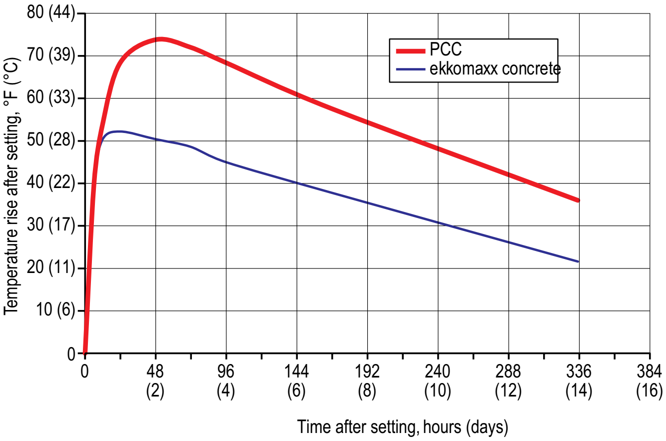

Fig. 4: Temperature rise after setting, measured at the core of the portland cement and *ekkomaxx* concrete test cubes

Where:

- *Cement* is Type I/II portland cement, lb/yd^3;
- F_{Ash} is Class F fly ash, lb/yd^3;
- C_{Ash} is Class C fly ash (no distinction is made for the calcium oxide content of the fly ash, which is the main heat generating portion), lb/yd^3;
- *SFMK* is silica fume or metakaolin, lb/yd^3;
- *Slag* is slag cement (no distinction is made for Grade 100 or Grade 120), lb/yd^3; and
- *Factor* is a variable which depends on the percentage of cement being replaced (1.0 to 1.1 for 0 to 20% cement replacement, 1.0 for 20 to 45% cement replacement, 0.9 for 45 to 65% cement replacement, and 0.8 for 65 to 80% cement replacement).

The equation typically estimates the temperature rise of the concrete that occurs at about 7 to 10 equivalent age days. In the case of this project, the equation somewhat over-predicted the temperature rise of PCC. No efforts were made to determine why this occurred, but possibilities include a non-perfect synergy between the cement and fly ash or the cement has a lower-than-typical heat of hydration. This shows that the equation provides a "ballpark" estimate rather than the exact temperature rise.

The temperature rise of the *ekkomaxx* concrete is reasonably predicted by the previously described temperature rise equation when the factor for the Class C fly ash is changed from 0.8 to 0.55. Further investigation is needed to determine if the 0.55 factor is a reliable estimate for the *ekkomaxx* concrete when the fly ash source or admixture quantity changes.

Thermal Modeling

To predict temperatures and temperature differences in several common types of mass concrete placements, thermal modeling was performed using CTLGroup's mass concrete nonlinear finite element modeling software and the adiabatic temperature rise data in Fig. 5. These placements included a 3 ft (0.9 m) wide wall, a 5 ft (1.5 m) thick

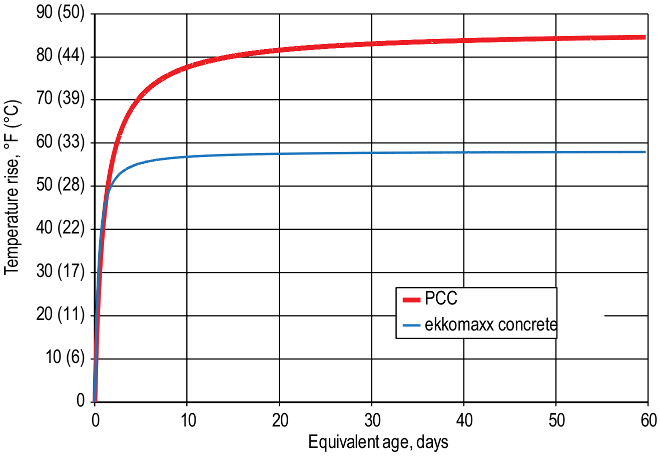

Fig. 5: Calculated adiabatic temperature rise of the portland cement and *ekkomaxx* concretes

footing, and a 6 ft (1.8 m) diameter drilled shaft in the ground, and a 7 ft (2.1 m) diameter column. The models were based on assumptions that ambient conditions during placements were typical of Midwestern spring/fall or summer, and that the top and side surfaces of the placements would have either no insulation or one layer of typical insulating blankets. Winter placement configurations were not modeled because they force the use of surface insulation to comply with standard cold weather specification requirements.

The spring/fall placement conditions were an average air temperature of 50°F (10°C), adjoining materials at 50°F (10°C), a 20°F (11°C) daily temperature swing (between the daily high and daily low air temperatures), no wind, overcast skies, and an initial concrete temperature of 70°F (21°C). The summer placement conditions were an average air temperature of 80°F (27°C), adjoining materials at 70°F (21°C), a 20°F (11°C) daily temperature swing (between the daily high and daily low air temperatures), no wind, overcast skies, and an initial concrete temperature of 90°F (32°C). To accurately evaluate the temperature difference, the maximum distance between adjoining nodes in each finite element model was 2 in. (50 mm).

Results of thermal modeling without insulation were compared with the ACI 301-10 requirements for mass concrete to determine if the placement should be considered mass concrete. In this regard, if the described placement conditions caused a maximum temperature greater than 158°F (70°C) or a temperature difference greater than 35°F

(19°C), the placement was considered mass concrete. In this case, a lower initial concrete temperature, surface insulation, or both, would be required to limit temperatures and/or temperature differences.

The results of the thermal modeling to determine which combinations of concrete, placement conditions, and season would lead to temperatures qualifying the placements as mass concrete are presented in Table 4 and 5. As can be seen, the 3 ft (0.9 m) wide walls would not be considered mass concrete per ACI 301-10. The drilled 6 ft (1.8 m) diameter shafts with *ekkomaxx* concrete also would not be considered mass concrete; however, the drilled shafts with PCC would be considered as mass concrete because the temperature differential exceeded 35°F (19°C). The results also show that the 5 ft (1.5 m) thick footing and 7 ft (2.1 m) diameter column would be considered as mass concrete.

Tables 6 and 7 show the results of additional thermal modeling of the 5 ft (1.5 m) footing and 7 ft (2.1 m) column. The placements were assumed to be fully covered by one layer of a typical winter concreting insulating blankets to reduce the temperature differentials. The indicated time of thermal control is the time that the insulation must remain in place to satisfy the requirements of ACI 301-10. That is the time when the hottest portion of the concrete cools to within 35°F (19°C) of the average air temperature. In all cases, the time of thermal control with *ekkomaxx* concrete was shorter than that of PCC, and this is due to the lower temperature rise of *ekkomaxx* concrete. In addition, to bring the maximum

Table 4:
Results of modeling without insulation to determine if placement behaves as mass concrete during spring/fall placement conditions

Placement type	Concrete type	Maximum temperature, °F (°C)	Time of maximum temperature, days	Maximum temperature differential, °F (°C)	Time of maximum temperature differential, days	Mass concrete per ACI 301-10
3 ft (0.9 m) wide wall	PCC	115.6 (46.4)	0.9	29.3 (16.3)	0.9	No
	ekkomaxx	112.4 (44.7)	0.6	27.4 (15.2)	0.8	No
5 ft (1.5 m) thick footing	PCC	130.5 (54.7)	1.4	45.2 (25.1)	1.9	Yes
	ekkomaxx	119.4 (48.6)	0.9	37.4 (20.8)	1.8	Yes
6 ft (1.8 m) diameter drilled shaft	PCC	124.9 (51.6)	1.1	35.8 (19.9)	1.0	Yes
	ekkomaxx	117.5 (47.5)	0.8	30.6 (17.0)	0.8	No
7 ft (2.1 m) diameter column	PCC	134.2 (56.8)	1.4	55.1 (30.6)	1.8	Yes
	ekkomaxx	121.6 (49.8)	1.0	45.6 (35.3)	1.8	Yes

Table 5:
Results of modeling without insulation to determine if placement behaves as mass concrete during summer placement conditions

Placement type	Concrete type	Maximum temperature, °F (°C)	Time of maximum temperature, days	Maximum temperature differential, °F (°C)	Time of maximum temperature differential, days	Mass concrete per ACI 301-10
3 ft (0.9 m) wide wall	PCC	147.5 (64.2)	0.8	29.8 (16.5)	0.9	No
	ekkomaxx	137.9 (58.8)	0.5	25.3 (14.0)	0.8	No
5 ft (1.5 m) thick footing	PCC	157.8 (69.9)	1.1	42.2 (23.4)	1.8	Yes
	ekkomaxx	142.4 (61.3)	0.8	32.6 (18.1)	0.9	No
6 ft (1.8 m) diameter drilled shaft	PCC	153.2 (67.3)	0.9	38.4 (21.3)	0.9	Yes
	ekkomaxx	141.0 (60.6)	0.6	31.9 (17.7)	0.7	No
7 ft (2.1 m) diameter column	PCC	161.7 (72.1)	1.2	52.9 (29.4)	1.8	Yes
	ekkomaxx	144.2 (62.3)	0.9	40.8 (22.6)	1.8	Yes

Table 6:
Results of modeling of mass concrete during spring/fall placement conditions

Placement type	Concrete type	Maximum temperature, °F (°C)	Time of maximum temperature, days	Maximum temperature differential, °F (°C)	Time of maximum temperature differential, days	Time of thermal control, days
5 ft (1.5 m) thick footing	PCC	134.6 (57.0)	1.7	17.9 (9.9)	2.9	24.1
	ekkomaxx	120.7 (49.3)	1.0	15.0 (8.3)	1.9	15.7
7 ft (2.1 m) diameter column	PCC	138.9 (59.4)	1.7	31.2 (17.3)	2.9	11.6
	ekkomaxx	123.0 (50.6)	1.2	25.4 (14.1)	1.9	9.2

Table 7:
Results of modeling of mass concrete during summer placement conditions

Placement type	Concrete type	Maximum temperature, °F (°C)	Time of maximum temperature, days	Maximum temperature differential, °F (°C)	Time of maximum temperature differential, days	Time of thermal control, days
5 ft (1.5 m) thick footing	PCC	160.4 (71.3)	1.3	16.1 (8.9)	1.9	16.3
	ekkomaxx	143.2 (61.8)	0.9	12.6 (7.0)	0.9	10.5
7 ft (2.1 m) diameter column	PCC	164.6 (73.7)	1.5	29.4 (16.3)	2.9	10.8
	ekkomaxx	144.9 (62.7)	1.1	22.7 (12.6)	1.9	8.3

temperature to a few degrees below the 158°F (70°C) limit per ACI 301-10, the initial temperature of the PCC would have to be reduced by 5°F (2°C) for the footing and by 10°F (5°C) for the column.

Summary

Our tests show that the *ekkomax*x concrete mixture provides promising reductions in temperature rise compared to conventional portland cement-based concrete. These reductions could allow designers and contractors to minimize or eliminate the need for both expensive precooling and extended duration of thermal control by insulation or cooling pipes.

In addition, as is evident from the analyses summarized in Tables 4 through 7, elements that would normally be considered as mass concrete can be constructed using a concrete with a low temperature rise, and using such a concrete can allow contractors to reduce the time necessary to protect the concrete against large temperature differentials or to avoid needing to reduce the initial temperature of the concrete.

Acknowledgments

The authors wish to thank Tom W. Thomas, CEO, and Keith Davis, Technical Services Director, Consumers Concrete Corp., Kalamazoo, MI, for materials and staff support; and Jerry Loderman Construction for providing the custom formwork.

Selected for reader interest by the editors.

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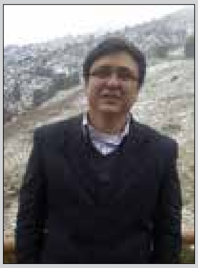

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