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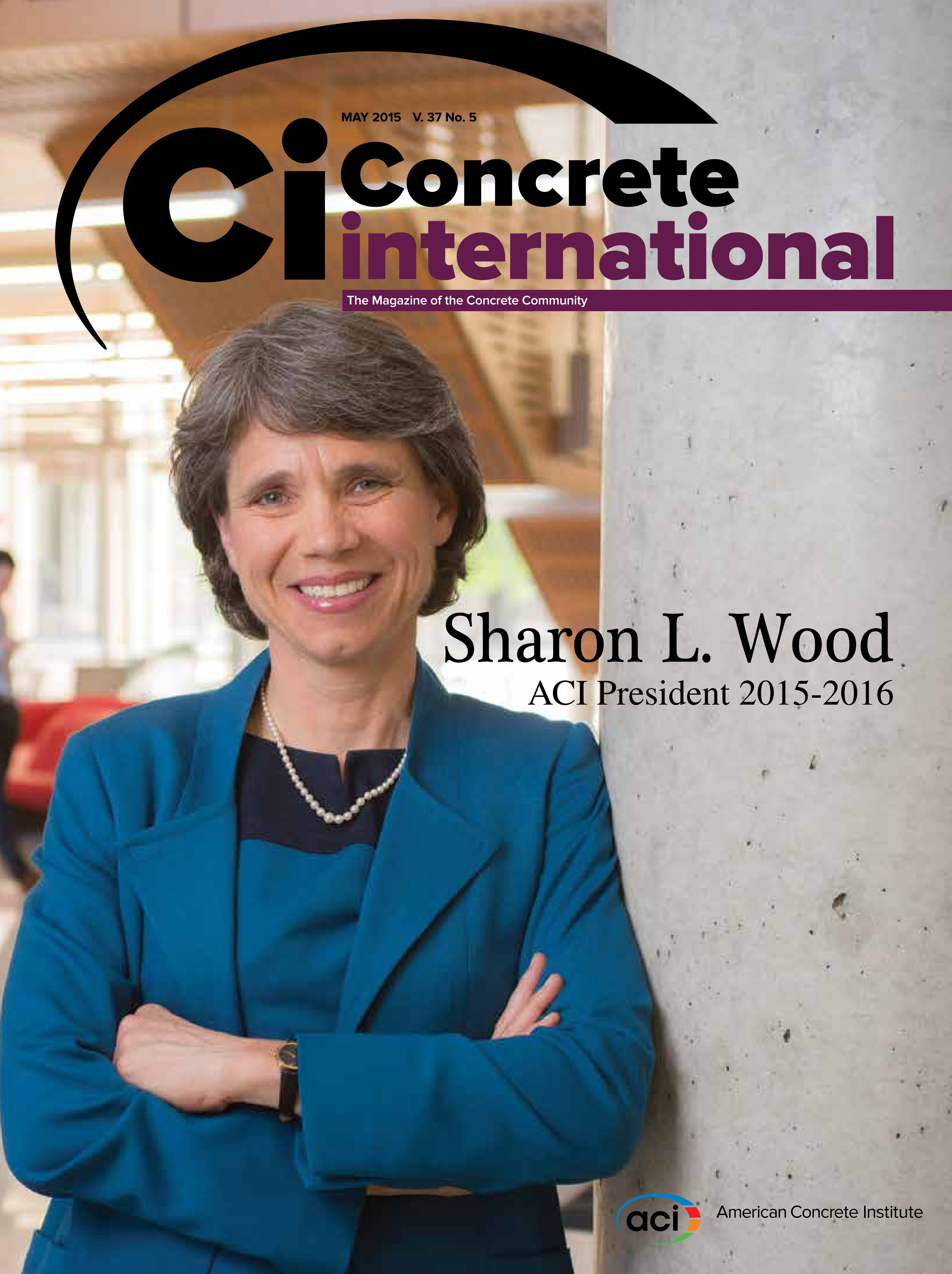

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Nomogram for Maximum Temperature of Mass Concrete

Calculation tool allows quick and reliable preliminary estimates

by Wilson Ricardo Leal da Silva and Vít Šmilauer

The term "mass concrete" applies to any concrete element with volume, boundary conditions, and mixture properties that will create early-age temperature profiles that are likely to compromise durability. Such profiles may have large temperature gradients and high maximum temperatures—primarily the result of the exothermic hydration process of the binders and the low thermal conductivity of concrete—resulting in cracking and loss of durability. Even concrete elements that are only 0.5 m (1.64 ft) thick[1] can exhibit mass concrete temperature profiles.

Experience has shown that the maximum differential temperature is a function of the cooling rate—this is normally controlled using insulation. Experience has also shown that, in the absence of internal cooling, the maximum concrete temperature is largely a function of the concrete composition and the initial concrete temperature. The maximum temperature that should be allowed in a structure depends on its application and the environmental conditions to which it is exposed.[2] To avoid delayed ettringite formation (DEF) in concrete structures that will be exposed to high humidity or alternate wetting-and-drying cycles, for example, the maximum temperature should be limited to 70°C (158°F). For more details on practical guidelines for mass concrete, refer to RILEM PRO-085[2] and ACI 207.1R-05.[3]

Understanding and predicting the thermal behavior of mass concrete can help designers and contractors reduce the probability and incidence of crack formation, thus helping to ensure concrete durability. Thermal analyses of mass concrete are often carried out using finite element method (FEM) models in combination with cement hydration models. Recently, the affinity hydration model has been shown to be reliable in the prediction of temperature evolution in mass concrete structures.[4] Nonetheless, the procedures related to designing a reliable simulation model are rather impractical when considering preliminary investigations, which demand quick calculations.

Hence, from a practical perspective, we believe that rough estimates of mass concrete temperature could be used to guide preliminary mixture design while avoiding complicated calculations. With this idea in mind, we developed an easy-to-use temperature nomogram for mass concrete. The nomogram allows predicting the maximum temperature achieved in mass concrete structures by taking into account mixture composition and ambient conditions. The nomogram calculations have been embedded in a mobile app, available for free in Apple's App Store.

Temperature Nomogram

The temperature nomogram accounts for the following parameters:

- Cement type, C_T;
- Unit mass of total binder content, m_{binder}, kg/m^3;
- Effective percentage of supplementary cementitious material (SCM), S;
- Element thickness, t, m;
- Initial concrete temperature, T_i, °C; and
- Average ambient temperature, T_a, °C.

Some details must be addressed in regard to the SCM in a mixture. Experimental results suggest that the heat contribution of the SCM depends on the type of material being used. Figure 1 depicts a comparison of the cumulative heat (per gram of binder) of Type I portland cement (OPC) and blended cements.[5-8] In general, while materials such as Class F fly ash, limestone, and quartz show little to no effect on hydration heat, Class C fly ash, silica fume, and ground-granulated blast furnance slag (slag) show considerable contributions.

The exact contribution of an SCM to hydration heat depends on the SCM properties and chemical composition. In

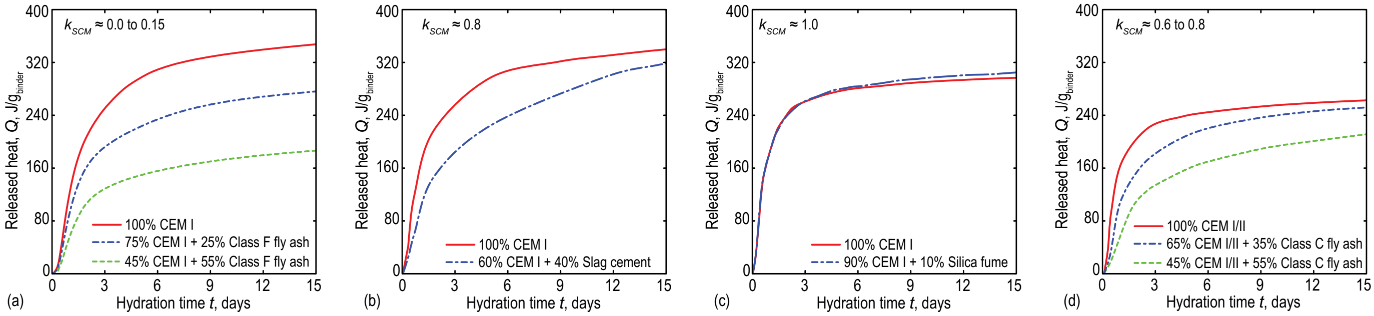


Fig. 1: Isothermal calorimetry results of OPC blended with: (a) Class F fly ash; (b) slag; (c) silica fume; and (d) Class C fly ash

other words, SCMs with similar designations can contribute differently in terms of hydration heat. The effective percentage of SCM, S, is computed by Eq. (1)

$$s = \frac{1}{m_{binder}} \sum_{i=1}^{n} m_{SCM,i}\left(1 - k_{SCM,i}\right) \quad (1)$$

where the index i corresponds to the i-th SCM used as cement replacement and $m_{SCM,i}$ is the unit mass of the i-th SCM, kg/m^3. The definition of $m_{SCM,i}$ is analogous to the pozzolan cementing efficiency factor k from CEB Bulletin No. 222,[9] but with the difference that hydration heat is used as a reference measure rather than compressive strength. In other words, $k_{SCM,i}$ enables adjustment of S depending on the efficiency of the SCM used in the concrete mixture. We suggest the following values for k_{SCM}:

- 0.00 for SCMs with little heat contribution—for example, Class F fly ash, limestone, and quartz;
- 0.50 for SCMs with moderate reactivity—for example, finely ground Class F fly ash;
- 0.80 for SCMs with moderate to high reactivity—for example, slag and Class C fly ash; and
- 1.00 for SCMs with high reactivity (comparable to OPC)—for example, silica fume.

The suggested values of k_{SCM} were computed based on experimental results shown in Fig. 1 for a measurement time up to 15 days, which is a reasonable time considering concrete structures accounted for in the nomogram will not be hydrating under adiabatic conditions. The suggested values of k_{SCM} were also used as a reference for nomogram validation, discussed later in this article.

The temperature nomogram approximates the results from numerical analyses based on FEM models and the affinity hydration model.[4,10] Equation (2) was used as a basis in the thermal analyses performed to compute thermal field evolution with the maximum temperature.

$$\lambda(x)\Delta T(x,t) + \bar{Q}(x,t) = \rho(x) c_V(x) \frac{\partial T(x,t)}{\partial t} \quad (2)$$

where $T(x, t)$ is the unknown temperature field, in K; $\lambda(x)$ is the material thermal conductivity, W/(m·K); $\rho(x)$ is the material density, kg/m^3; $c_V(x)$ is the specific heat capacity, J(kg·K); and $\bar{Q}(x, t)$ is the heat source, which corresponds to

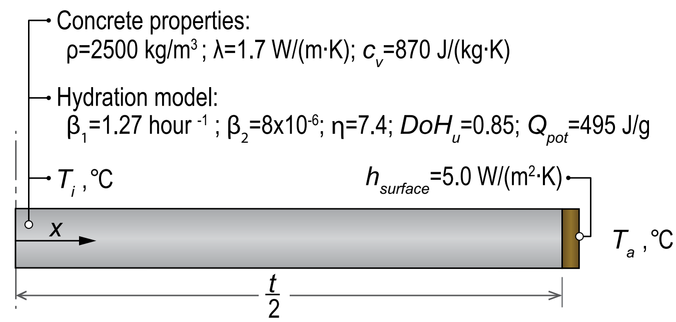


Fig. 2: Reference model used in FEM simulations to build the temperature nomogram

the hydration heat. The FEM analyses have been validated on numerous examples, and the performance has been excellent.[4,11]

The affinity hydration model (Eq. (3)) allows prediction of the degree of hydration of cement, DoH, and the corresponding hydration heat.[12] The rate of hydration heat development at a given temperature T reads

$$\frac{1}{Q_{pot}} \cdot \frac{\partial Q}{\partial t} = \frac{\partial DoH}{\partial t}$$
$$= \beta_1 \left(\frac{\beta_2}{DoH_u} + DoH \right) \left(DoH_u - DoH \right) \exp\left(-\eta \frac{DoH}{DoH_u} \right) \exp\left(\left(\frac{E_a}{R} \right) \left(\frac{1}{298.15} - \frac{1}{T} \right) \right) \quad (3)$$

where β_1 is an empirical coefficient, hours^{-1}; β_2 is a dimensionless empirical coefficient; DoH_u is the ultimate degree of hydration, %; η is a dimensionless coefficient for the microdiffusion of free water through formed hydrates; E_a is the activation energy, kJ/mol; R is the gas constant, equal to 8.31 J/(mol·K); and Q_{pot} is the potential hydration heat, J/g. Details on the affinity hydration model can be verified through our free desktop application CEMHapp.[12]

Figure 2 shows the reference physical model used to build the temperature nomogram. Basically, the one-dimensional (1-D) model simulates a hydrating concrete element capped with a 20 mm (0.8 in.) thick plywood formwork on both sides. Concrete properties such as heat capacity c_V, thermal conductivity λ, and density ρ considered in the simulation are standard values for structural concrete, while the parameters of the affinity hydration model were collected from our previous publications.[4] Such parameters relate to CEM I 42.5R[13]

(42.5 MPa average strength at 28 days and 306 m^2/kg Blaine fineness), which is used as a reference cement in our simulations.

The numerical analyses comprise mass concrete mixtures with binder contents of up to 500 kg/m^3 (842.7 lb/yd^3) and cement replacement ranging from 0 to 75%. Also, structural members with thickness varying from 0.5 to 4.0 m (1.64 to 13.1 ft), fresh concrete temperature from 5 to 30°C (41 to 86°F), and ambient temperature from 0 to 40°C (32 to 104°F) were investigated. Next, we applied linear fitting methods to compute the coefficients of the curves that compose the nomogram.

Results from the linear fit are summarized in Table 1 and the temperature nomogram is displayed in Fig. 3. The scatter plot of the maximum temperature from FEM simulation ($T_{max,FEM}$) and nomogram prediction (T_{max}) is shown in Fig. 4. Statistical analysis of the difference between nomogram-predicted and FEM simulation results ($\Delta T = T_{max} - T_{max,FEM}$) yields a prediction error of ±6.8°C (±12.2°F) for a 90% confidence level. When the input variables T_i and T_a are limited to the range of 15 to 30°C (59 to 86°F), the nomogram prediction error drops to ±4.3°C (±7.7°F) for a 90% confidence level.

Because the hydration kinetics vary with cement type, we evaluated two other types of binders—CEM I 32.5R (32.5 MPa average strength at 28 days and 280 m^2/kg Blaine fineness) and CEM I 52.5R (52.5 MPa average strength at 28 days and 530 m^2/kg Blaine fineness). Notice that the cement designation used in this nomogram is based on the European standard EN 197-1.[13]

The cement classes CEM I 32.5R, 42.5R, and 52.5R considered in our analyses have the same mineral composition ($C_3S \approx 66\%$, $C_2S \approx 13\%$, $C_3A \approx 5\%$, $C_4AF \approx 12\%$) but different Blaine fineness. In terms of hydration kinetics, CEM I 32.5R, 42.5R, and 52.5R would be comparable to that of cement Types II, I, and III, respectively, according to the ASTM C150/C150M classification.[15]

We found that the relationships between the nomogram temperature and the maximum temperature calculated using FEM models are rather linear for either cement. Based on Fig. 5, nomogram predictions (Fig. 3) can be adjusted for these cement types using the following coefficients: a_{C_T} of 0.91 and b_{C_T} of 0.60°C for CEM I 32.5R, and a_{C_T} of 1.12 and of b_{C_T} 1.39°C for CEM I 52.5R.

Table 1:
Standard coefficients of the temperature nomogram

S, %	a_S, MJ/kg	t, m	a_t, m³°C/MJ	b_t, MJ/m³	T_i, °C	a_{Ti}	b_{Ti}, °C	T_a, °C	a_{Ta}	b_{Ta}, °C
0	0.495	0.5	0.210	78.379	5	0.859	−3.790	0	1.136	−11.091
25	0.371	1.0	0.282	54.527	10	0.922	−3.945	10	1.054	−5.391
50	0.247	1.5	0.323	46.830	15	0.974	−2.908	20	1.000	0.000
75	0.124	2.0	0.335	47.807	20	1.000	0.000	25	0.968	3.484
		4.0	0.361	49.429	25	1.004	4.440	30	0.933	7.668
					30	0.991	9.902	40	0.850	18.943

As an alternative to the graphical calculation provided by the nomogram in Fig. 3, T_{max} can be computed using Eq. (4)

$$T_{max} = a_{C_T}\left(a_{T_a}\left(a_t a_{T_i}(a_S m_{binder} + b_t) + b_{T_i} + b_{T_a}\right)\right) + b_{C_T} \quad (4)$$

where the indexes of the coefficients a_{index} and b_{index} are related to the input parameters of the nomogram—C_T, m_{binder}, S, t, T_i, and T_a. The nomogram coefficients from Eq. (4) are listed in Table 1. The coefficients corresponding to intermediate values for the input parameters can be determined by linear interpolation.

Finally, aiming at providing an easy-to-use and pragmatic solution for field engineers, we developed a mobile application featuring the temperature nomogram. The mobile application is titled “Mass Concrete App – Temperature Module” and is available in Apple’s App Store for free (Fig. 6).[16] The Mass Concrete App enables predicting maximum temperature in mass concrete structures in both SI and U.S. customary units.

Validation

The temperature nomogram was applied to predict the maximum temperature of six mass concrete structures located in Brazil and Czech Republic. They comprise a concrete dam, an office building foundation slab, a 1050 m^3 (37,065 ft^3) foundation block, two 1.0 m^3 (35.3 ft^3) concrete blocks, and a scaffold bridge slab (Fig. 7). Information on the evaluated structures was collected from our previous work and is listed in Table 2.[4,10,11] The type and amount of SCM used in each concrete mixture are also listed in Table 2. The previously suggested values of k_{SCM} were used to compute S per Eq. (1).

For example, Table 2 indicates that Mixture V1 has a total binder content of 180 kg/m^3 (303.4 lb/yd^3), comprising a blend of CEM I 32.5R with 28% and 22% cement replacements with Class F fly ash (k_{SCM} of 0.0) and slag (k_{SCM} of 0.80), respectively. Thus, from Eq. (1)

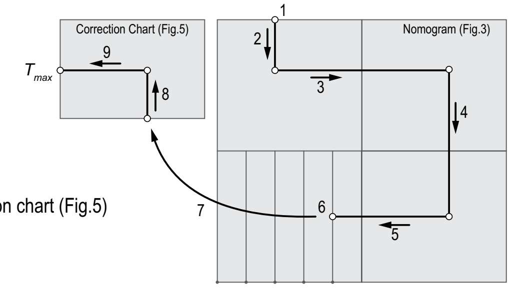
$$S = \left(28\%\left(1-0.0\right) + 22\%\left(1-0.80\right)\right) = 32.4\%$$

The input parameters from Table 2 can be directly used in the Mass Concrete App – Temperature Module (Fig. 6) to predict maximum concrete temperature.

The nomogram prediction of maximum temperature for the case study V3 (foundation block in Fig. 7(c)) is presented in Fig. 3, while the corresponding corrected prediction is indicated in Fig. 5. The coefficients used in Eq. (4) to predict the maximum temperature for all case studies are shown in Table 3. These coefficients were computed based on a linear interpolation of the values indicated in Table 1. The prediction error between nomogram-predicted and measured maximum temperature ($\Delta T = T_{max} - T_{max,measured}$) for each case study is listed in the last column of Table 2.

To use these charts:

1. Enter with total binder content, m_{binder}, kg/m³
2. Move down and read S (computed using Eq. (1))
3. Move right to element thickness, t, m
4. Move down to initial concrete temperature, T_i, °C
5. Move left to average ambient temperature, T_a, °C
6. Read predicted maximum temperature, T'_{max}, °C
7. For cement type other than CEM I 42.5R, proceed to correction chart (Fig.5)
8. Enter T'_{max} from Step 6, move up and read cement type, C_T
9. Move left and read corrected T_{max}, °C



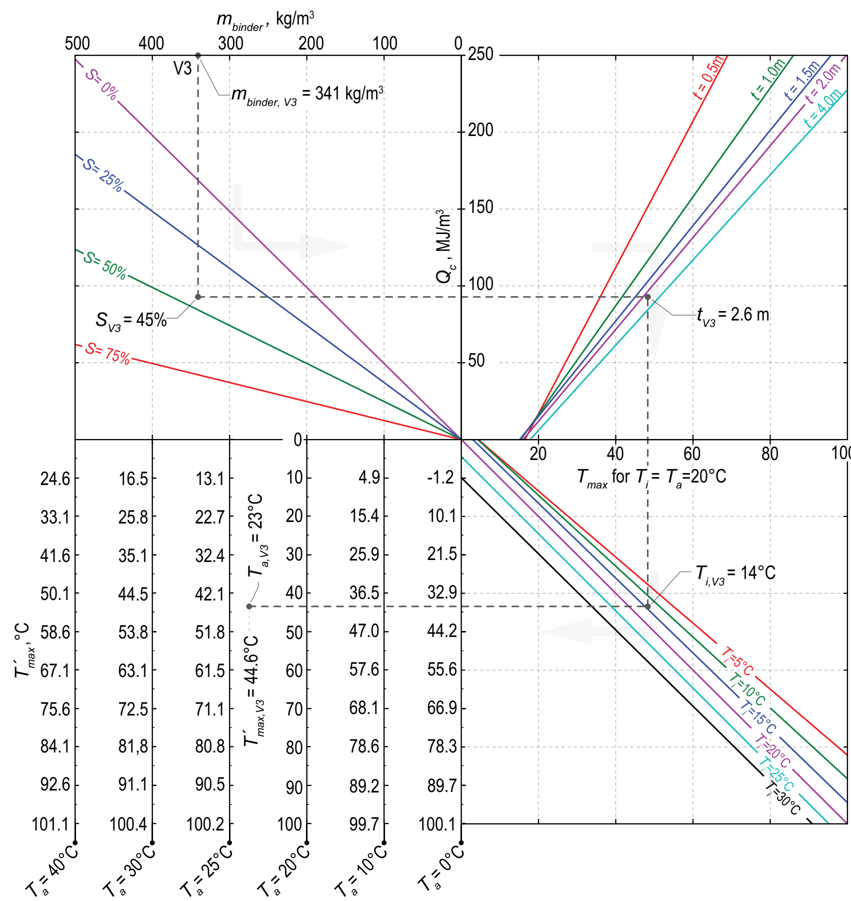


Fig. 3: Nomogram for predicting maximum temperature of mass concrete structures, including example based on mixture V3 data

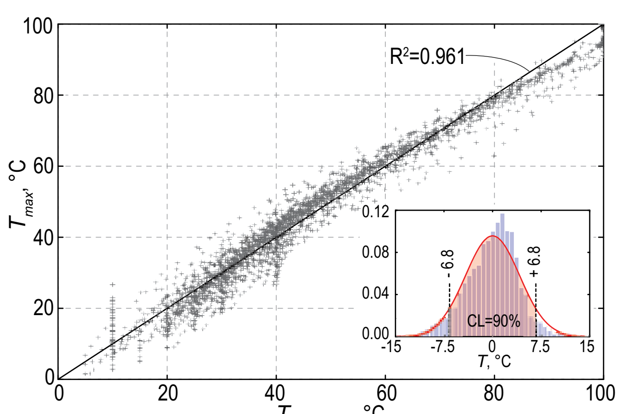


Fig. 4: Scatter plot of maximum temperature results based on FEM simulation $T_{max,FEM}$ versus results based on the nomogram T_{max}

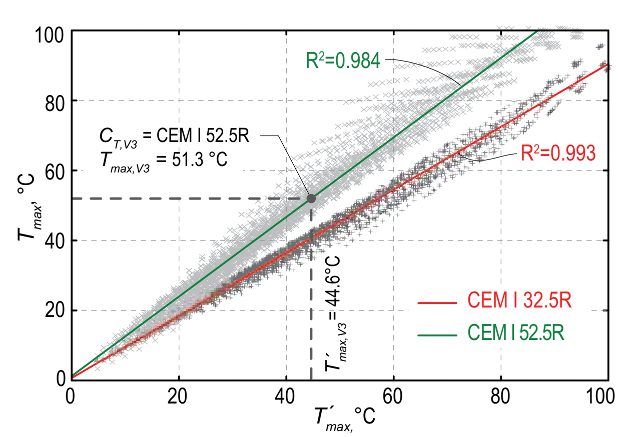


Fig. 5: Scatter plot of maximum temperature results for mixtures comprising CEM I 32.5R and CEM I 52.5R, including example based on mixture V3 data (refer to Fig. 3)

Results from Table 2 indicate an average prediction error of 3.9°C (1.6°F). Such a value falls within the error of ±4.3°C (±7.7°F) estimated for nomogram predictions when using T_i and T_a values ranging from 15 to 30°C (59 to 86°F), which is the case of the investigated structures. The difference between predicted and measured temperature is likely due to factors such as different boundary conditions (for example, surface insulation, concrete thermal properties, and continuous

Table 2:

Comparison between measured ($T_{max, measured}$) and monogram-predicted (T_{max}) maximum temperatures for the evaluated mass concrete structures

Concrete mixture	Binder type: cement + SCM*	m_{binder}, kg/m³	S, %	t, m	T_i, °C	T_a, °C	$T_{max,measured}$, °C	T_{max}, °C	ΔT, °C
V1	CEM I 32.5R + 28% Class F fly ash + 22% slag	180	32.4	2.00	18.0	25.0	40.0	34.1	-5.9
V2	CEM I 42.5R + 21% Class F fly ash + 19% slag	380	24.7	0.75	15.0	24.0	45.0	47.5	+2.5
V3	CEM I 52.5R + 45% Class F fly ash†	341	45.0	2.60	14.0	23.0	51.0	51.3	+0.3
V4	CEM I 52.5R + 45% Class F fly ash†	420	45.0	1.00	23.0	23.0	55.5	58.9	+3.5
V5	CEM I 42.5R	310	0.0	1.00	18.0	15.0	50.2	55.6	+5.4
V6	CEM I 42.5R + 5% limestone filler	400	5.0	0.70	15.0	25.0	56.2	57.2	+1.0

V1: Orlík Dam, Czech Republic, Fig. 7(a)

V2: Foundation slab, AZ Tower, Brno, Czech Republic, Fig. 7(b)

V3: 1050 m³ (37,065 ft³) foundation block, Torre d'Napoli, Balneario Camboriú, SC, Brazil, Fig. 7(c)

V4: 1.0 m³ (35.3 ft³) concrete block A, Federal University of Santa Catarina, Florianópolis, SC, Brazil, Fig. 7(d)

V5: 1.0 m³ (35.3 ft³) concrete block B, Czech Technical University in Prague, Prague, Czech Republic, Fig. 7(e)

V6: Bridge slab, Nové Spojení, Prague, Czech Republic, Fig. 7(f)

*Mass percentage of total binder

†55% CEM I 52.5R + 45% Class F fly ash blend corresponds to CP IV RS cement type (CEM I blended with fly ash, with low heat of hydration)[14] used in V3 and V4 structures[4]

Notes: 1 m = 3.3 ft; 1 kg/m³ = 1.69 lb/yd³

Fig. 6: Screenshot of Mass Concrete App – Temperature Module (available as a free download at https://appsto.re/dk/tEMB1.i)

Table 3:

Coefficients calculated by linear interpolation of the standard coefficients from Table 1

Concrete mixture	a_{CT}	b_{CT}, °C	a_S, MJ/kg	a_t, m³°C/MJ	b_t, MJ/m³	a_{Ti}	b_{Ti}, °C	a_{Ta}	b_{Ta}, °C
V1	0.910	0.600	0.335	0.334	47.807	0.990	−1.163	0.968	3.484
V2	1.000	0.000	0.373	0.241	66.453	0.974	−2.908	0.974	2.787
V3	1.120	1.390	0.272	0.342	48.294	0.964	−3.116	0.980	2.091
V4	1.120	1.390	0.272	0.282	54.527	1.002	2.664	0.980	2.091
V5	1.000	0.000	0.495	0.282	54.527	0.990	−1.163	1.027	−2.695
V6	1.000	0.000	0.470	0.234	68.839	0.974	−2.908	0.968	3.484

V1: Orlík Dam, Czech Republic, Fig. 7(a)

V2: Foundation slab, AZ Tower, Brno, Czech Republic, Fig. 7(b)

V3: 1050 m³ block, Torre d'Napoli, Balneario Camboriú, SC, Brazil, Fig. 7(c)

V4: 1.0 m³ (35.3 ft³) block A, Federal University of Santa Catarina, Florianópolis, SC, Brazil, Fig. 7(d)

V5: 1.0 m³ (35.3 ft³) block B, Czech Technical University in Prague, Prague, Czech Republic, Fig. 7(e)

V6: Bridge slab, Nové Spojení, Prague, Czech Republic, Fig. 7(f) casting) from the ones considered in the reference FEM simulations (Fig. 1) used to build the nomogram. The prediction error is likely to tend toward the limit value of ±6.8°C (±12.2°F) for a 90% confidence level when concrete is exposed to extreme temperature conditions such as T_a at 0 or 40°C (32 or 104°F) and T_i at 5 or 30°C (41 or 86°F). However, additional validation results are necessary to support this assumption.

Fig. 7: Investigated mass concrete structures: (a) V1: Orlík Dam, Czech Republic; (b) V2: Foundation slab, AZ Tower, Brno, Czech Republic (*photo courtesy of R. Hela*); (c) V3: 1050 m^3 (37,065 ft^3) foundation block, Torre d'Napoli, Balneario Camboriú, SC, Brazil (*photo courtesy of Formula F10 Empreendimentos*); (d) V4: 1.0 m^3 (35.3 ft^3) concrete block A, Federal University of Santa Catarina, Florianópolis, SC, Brazil; (e) V5: 1.0 m^3 (35.3 ft^3) concrete block B, Czech Technical University in Prague, Prague, Czech Republic; and (f) V6: Bridge slab, Nové Spojení, Prague, Czech Republic (*photo courtesy of D. Prause*)

From a practical perspective, a maximum prediction error of ±6.8°C (±12.2°F) for a 90% confidence level is rather small considering that the nomogram covers important variables for maximum concrete temperature. Hence, the temperature nomogram can support engineers on decisions about concrete mixture design, casting procedure, and initial concrete temperature.

Conclusions

The temperature nomogram allows for predicting the maximum temperature of mass concrete structures produced with different types and amounts of cementitious materials, with thicknesses ranging from 0.5 to 4.0 m (1.64 to 13.1 ft), and initial concrete temperatures ranging from 0 to 40°C (32 to 104°F). Predictions made using a 1-D numerical solution and the nomogram vary by ±6.8°C (±12.2°F) for a 90% confidence level. Field validations indicate a prediction error of 3.9°C (1.6°F).

The nomogram is intended to provide a quick and reliable preliminary estimate of maximum temperature. However, if the clinker mineral composition differs significantly from common values used in our simulations, a dedicated FEM simulation would provide more accurate prediction of maximum concrete temperature.

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