# Analytical and Experimental Study on Estimating the Compressive Strength of Early Age Concrete by the Maturity Method

Biswas Rajib Kumar,*　Takahiro Saito,*　Ryutaro Matsumoto*

Abstract

In this study an approach is proposed to expedite the construction of mountain tunnels by estimating the early age (less than one day) strength of concrete, subject to various temperatures and curing methods. The relationship between various curing temperatures and the development of concrete strength at a very early age is not fully understood; current approaches may be incapable of predicting the compressive strength of early age concrete. Numerical and experimental investigations were carried out to establish a relationship between the early age compressive strength of concrete and concrete maturity while taking varied temperature histories of concrete curing into account. The results obtained from numerical analyses and experimental investigations were in good agreement. Finally, to predict the very early age compressive strength of lining concrete, we propose different equations for different water to cement ratios.

Keywords; Lining concrete, concrete maturity, FEM analysis, early age

## 1. Introduction

Estimating concrete strength *in situ* at an early age can be important for several reasons, including for determining whether formwork can be removed, post-tensioning, handling precast members, and other actions. Overestimates of early age concrete strength can affect construction safety; underestimates of early age concrete strength can generate delay and additional cost.

To accelerate the construction process and reduce construction costs, it is often important to remove the formwork at the earliest possible time. The compressive strength required for lining concrete at demolding to avoid surface peeling is typically considered to be more than 2 MPa.[1)]

First proposed in the 1940s, the maturity method calculates concrete strength by accounting for the effects of both time and temperature. R.W. Nurse examined the steam-curing of concrete and plotted the product of time and temperature against concrete strength after three days of storage at room temperature.[2)] A.G.A. Saul examined the principles underlying the steam-curing of concrete at atmospheric temperature and defined maturity as the product of the concrete age and average temperature above freezing.[3)]

Many studies address maturity-based estimates of concrete strength. Tekle et al. [4)] investigated the application of the maturity method to estimate the early age compressive strength of concrete slabs in cold weather, considering in particular the relationship between *in situ* strength and strength calculated by the maturity method at an early age (one to three days) and in cold weather (below 10°C). Sun et al. [5)] investigated the effects of temperature and relative humidity on the development of the compressive strength of surface layer cement mortar. However, most of these studies considered concrete of more than one day in age.

This study aims to establish the maturity function for concrete at an early age (less than one day) with varying water cement ratios and temperature histories. This study carried out both experimental studies and numerical analysis to establish a concrete maturity function for estimating the compressive strength of concrete at an early age.

## 2. Experimental study

### 2.1 Water to cement ratio of 0.5

Medium-flow concrete was used with ordinary portlard cement and crashed rock sand. Table 1 gives the mix proportions used in the experimental study.

**Table 1: Concrete mix properties (W/C = 0.5)**

| Slump flow (cm) | Air volume (%) | W/C (%) | s/a (%) | $G_{max}$ (mm) | Materials (kg/m$^3$) | | | | Materials (g/m$^3$) | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | water (W) | cement (C) | sand (S) | gravel (G) | Water reducer | AE agent |
| 35−50 | 4.5±1.5 | 50.0 | 52.2 | 25 | 175 | 350 | 904 | 838 | 3,500 | 7 |

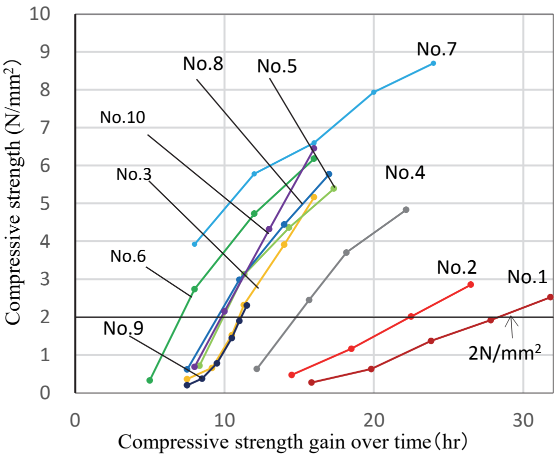
---

*Technical research institute civil engineering research group

The experimental program entailed the compressive strength testing of concrete cylinders. The cylinder specimens prepared measured φ100 × 200 mm.

Table 2 gives the experimental cases considered in the experimental program for W/C = 0.5. Ten experimental cases were considered, encompassing initial concrete temperatures from 10°C to 30°C and curing temperatures from 10°C to 50°C. Kneading temperatures were kept within ±3°C of the target temperature. The initial curing temperatures for Cases 1 to 8 were maintained at the target temperature. For Cases 9 and 10, curing temperatures began at 25°C. In Case 9, the curing temperature gradually reached 30°C after 5 hours. In Case 10, the curing temperature gradually reached 40°C after 12 hours. The curing method was hot air curing at a relative humidity of 70%.

To measure the hydration heat of the concrete, we placed temperature sensors at the center of the cylinder specimens. We performed compressive strength tests in accordance with JIS A 1108 and tested the early age compressive strength of concrete from five hours until 32 hours to confirm that the desired strength (2 MPa) was achieved. Three specimens were tested for each data point. Initial concrete temperatures and curing temperatures significantly affected compressive strength (Figure 1). In cases other than Cases 1 and 2, concrete specimens achieved the requisite strength of 2 MPa in 16 hours. More interestingly, in Cases 6 and 7, the desired strength was achieved in eight hours.



The maturity method was developed in the 1940s to account for the combined effects of temperature and time on the compressive strength of RC structures subjected to different curing temperatures. Concrete maturity can be understood as the sum of the products of temperature and time. This method is known as the Nurse-Saul function. A figure for concrete maturity can be calculated as follows:

$$M(t)=\sum_{0}^{t}(T-T_0)\Delta t \qquad (1)$$

where M(t) is concrete maturity at time t, T is the average concrete temperature over time interval (Δt), and $T_0$ is the datum temperature. Datum temperature is generally defined as the lowest temperature at which concrete is able to gain strength. According to the Canadian Standards Association, it is critical to have temperatures above 5°C to avoid major damage to concrete, especially in the first 24 hours.[6] Figure 2 shows the maturity curve obtained from the experimental study. In this study, the datum temperature was set to 3°C. The best fit of the data obtained is at 3°C. From Figure 2, we can estalish the following relationship between concrete maturity and compressive strength, where y represents the compressive strength of the concrete and x denotes concrete maturity:

$$y = 0.0177x - 2.4677 \qquad (2)$$

### 2.2 Water to cement ratio of 0.4

Many RC structures are constructed at a water to cement ratio of 0.4. For this reason, we undertook another study with W/C = 0.4. The concrete used was similar to the concrete used for W/C = 0.5. We considered a total of four cases based on actual contruction practice. The maximum size of the coarse aggregate was 25 mm. Table 3 gives the specifics of the concrete mix. The initial temperature was kept at 20°C for all cases—Cases 1, 2, 3, and 4. Curing temparatures were 20°C, 30°C, 40°C, and

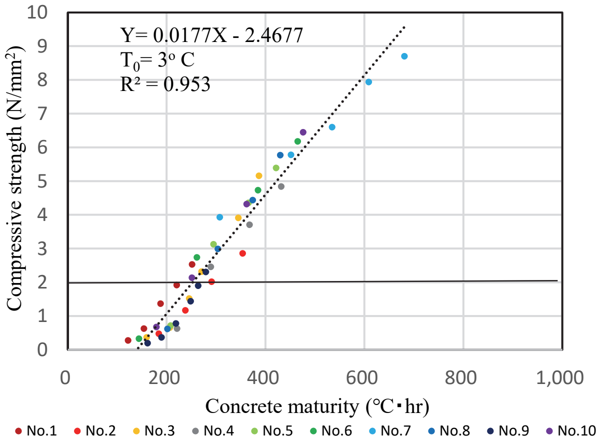


Table 2: Cases considered for the experimental study (W/C = 0.5)

| Case No | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Initial concrete temperature (°C) | 10 | 15 | 15 | 20 | 20 | 20 | 20 | 30 | 15 | 15 |
| Curing temparature (°C) | 10 | 15 | 30 | 20 | 30 | 40 | 50 | 30 | 25-30 | 25-40 |

**Table 3: Concrete mix properties (W/C = 0.4)**

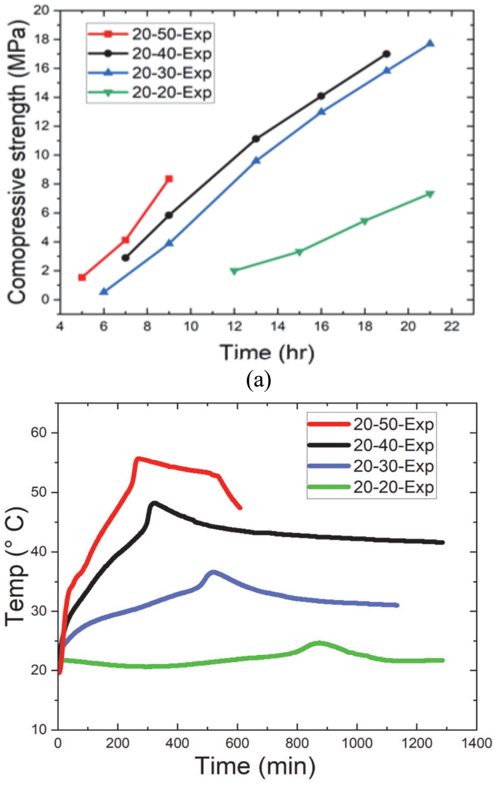
| Slump flow (cm) | Air volume (%) | W/C (%) | s/a (%) | $G_{max}$ (mm) | Materials (kg/m$^3$) | | | | Materials (g/m$^3$) | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | water (W) | cement (C) | sand (S) | gravel (G) | Water reducer | AE agent |
| 35−50 | 4.5±1.5 | 40.0 | 52.2 | 25 | 175 | 350 | 904 | 838 | 3,500 | 7 |

**Table 4: Cases considered for W/C = 0.4**

| | Initial concrete Temperature (℃) | Curing temperature (℃) |
|---|---|---|
| Case 1 | 20 | 20 |
| Case 2 | 20 | 30 |
| Case 3 | 20 | 40 |
| Case 4 | 20 | 50 |

50°C, respectively, for the Cases 1, 2, 3, and 4. The temperature of the concrete was measured as for W/C = 0.5. The curing method was likewise similar.

Figure 3 presents the results obtained from the experimental study. Figure 3 shows that curing temperature significantly affects early age compressive strength. In Case 1, the 2 MPa strength target was reached in all cases in roughly 12 hours. The time required to obtain the desired concrete strength was reduced by 33%, 42%, 58%, respectively, when curing temperatures were increased from 20°C to 30°C, 40°C, and 50°C; high curing temperatures tend to boost the rate of cement hydration. Nevertheless, it should be noted that high curing temperature has negative impact on 28 days compressive strength of concrete as shown in Figure 4. High temperature concrete curing results in high concentrations of hydrates near the cement grains, leading to the formation of large pores.$^{7)}$ These larger pores may ultimately reduce compressive strength (Figure 4).



(a)

(b)

**Figure 3: Experimental results for (a) compressive strength gain over time nnd (b) hydration heat**

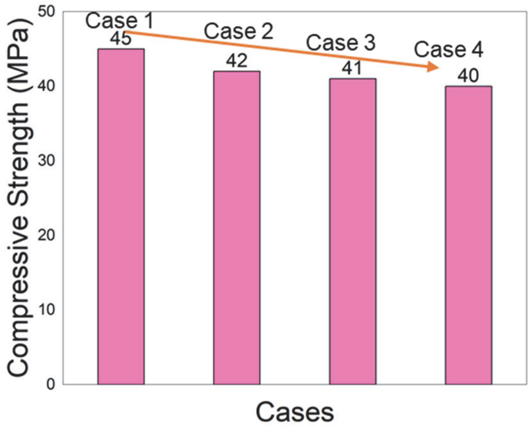


**Figure 4: Effect of curing temperature on compressive strength at 28 days**

The hydration process begins at the moment cement and water mix. During the hydration process, the cement paste is heated by an exothermic hydration reaction. To obtain a temperature history, we measured the temperature of the concrete wih time-temperature sensors placed in the middle of the concrete cylinders. Figure 3(b) shows that higher curing temperatures boost heat release from the specimens. Case 1 has the slowest heat release, with a peak temperature recorded

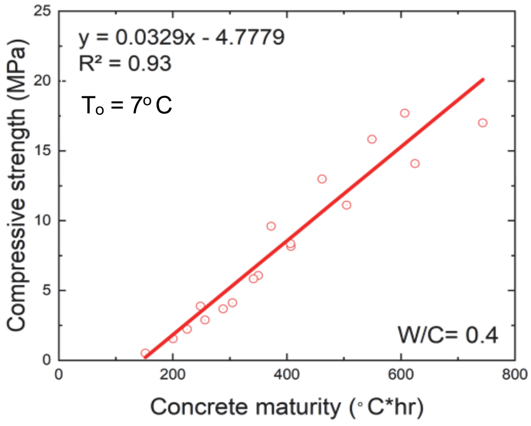


**Figure 5: Concrete maturity function for W/C = 0.4**

roughly 15 hours after casting. The heat release increases significantly as curing temperatures increase. Maximum temperatures were increased by 48%, 104%, and 148%, respectively, when curing temparatures increased from 20°C to 30°C, 40°C, and 50°C. The time required to reach the peak temparature fell dramatically with higher curing temparatures.

Figure 5 shows the concrete maturity function obtained from the experimental study. The datum temperature in this study was set to 7°C. Here, also, the linear function fits the data quite well. As shown in Figure 5, we can establish the following relationship between concrete maturity and compressive strength, where y represents the compressive strength of concrete and x denotes concrete maturity:

$$y = 0.0329x - 4.7779 \tag{3}$$

## 3. FEM modeling

Numerical analysis was performed in the LINK3D software package, which is capable of predicting the structural behavior of concrete under different weather conditions. This software has two modules: DuCOM and COM3. DuCOM is ideal for modeling the microscopic behavior of concrete, including the progress of cement hydration reactions, the formation of void structures in hardened bodies, and internal moisture states, as well as macroscopic views of reinforced concrete. COM3 is ideal for nonlinear structural analyses of RC structures. This system was developed to simulate the behavior of concrete structures, starting from cement hydration through maintenance and management. Figure 6 is a schematic diagram of LINK3D.

### 3.1 Modeling hydration heat

We can calculate the hydration heat of each component of cement from the following equations presented by Maekawa et al. 7):

$$H_i = \gamma_i \beta_i \lambda_i \mu_i H_{iT_0} Q_i \exp\{-\frac{E_i}{R}(\frac{1}{T} - \frac{1}{T_0})\} \tag{4}$$

$$Q_i = \int H_i dt \tag{5}$$

In Equation 4, Ei represents the activation energy of component i, R denotes the gas constant, $H_{iT0}$ is the reference heat generation rate of component i at constant temperature $T_0$, $\Upsilon_i$ represents the effects of chemical admixture in the hydration process, $\beta_i$ is the coefficient for reduced heat generation due to the reduced availability of free water, $\lambda_i$ represents the heat generation rate from the powder admixture, and $\mu_i$ is the coefficient related to the heat generation rate. In Equation 4, Ei/R represents thermal activity considered within the framework of the model developed by Suzuki et al. 9) (Figure 7).

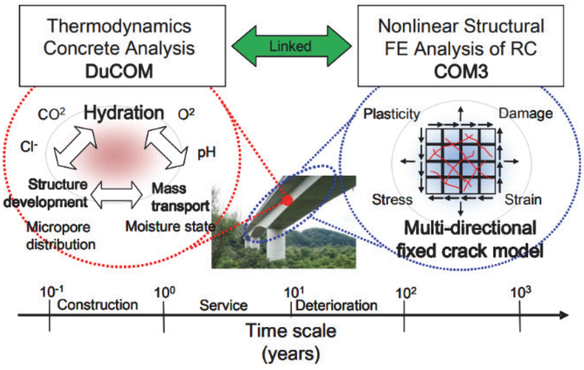


**Figure 6: Overview of LINK 3D8)**

### 3.2 Modeling Compressive Strength

We can calculate the compressive strength of concrete from the following equation:

$$f_c = f_\infty \{1 - \exp(-\alpha D_{\text{hyd.out}}{}^{\beta})\} \tag{6}$$

where $f_\infty$ represents ultimate strength and $\alpha$ and β are material constants. Here, $D_{hyd.out}$ is the ratio of space occupied by the outer bulk hydrates to the initial capillary space. We can present this as follows:

$$D_{\text{hyd.out}} = \frac{V_{\text{hyd.out}}}{V_{cap.\text{ini}}} = \frac{V_{\text{hyd.total}} - V_{\text{hyd.in}}}{V_{\text{cap.ini}}} \tag{7}$$

Here, $V_{hyd.out}$ is the volume of the hydration products that form outside the original cement particles, $V_{hyd.total}$ is the total volume of the hydration products, $V_{hyd.in}$ is the volume of hydration products that form inside the original cement particles (equivalent to the reacted volume fraction of the mineral compounds), and $V_{cap.ini}$ is the volume of the initial capillary space. The initial capillary space can be expressed with the water to cement ratio of the concrete mix given as follows:

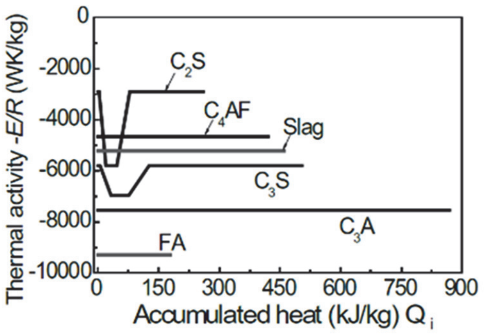


**Figure 7: Thermal activity for the reaction of each compound7)**

$$V_{\text{cap.ini}} = \frac{\frac{W}{C}\cdot\rho_c}{\frac{W}{C}\cdot\rho_c+1} \qquad (8)$$

## 4. Numerical analysis to validate experimental results

Numerical analysis was pweformed using the LINK3D software package. Figure 8 shows the analysis model.

Figure 9 shows a clear and strong correlation between the results of the experimental study and FEM analysis. FEM analysis is capable of precisely predicting the strength gained by the concrete specimens. For W/C = 0.5, in Case 8, the compressive strength observed in 16 hours in the experimental study was about 6 MPa; in the FEM analysis, the compressive strength obtained was about 5 MPa. Other cases demonstrated equally solid agreement between experimental study and numerical analysis. The numerical studies tended to slightly underestimate the experimental data, but the data obtained numerically is well within safety margins for the purposes of actual construction.

For W/C = 0.4, in Case 1, in which the initial and curing temparatures are 20°C, the 21-hour compressive strength obtained in the experiemental study is 8.15 MPa; in the numerical study, the 21-hour compressive strength obtained is about 7 MPa. In the experimental study, we obtained the desired compressive strength (2 MPa) at 12 hours. With FEM analysis, we obtained the required strength at 13 hours. In Case 2, the difference between the values for 21-hour compressive strength is less than 18%. In Cases 3 and 4, the difference between the experimental and numerical analysis results is less than 6%. The results for required strength exhibit a strong correlation.

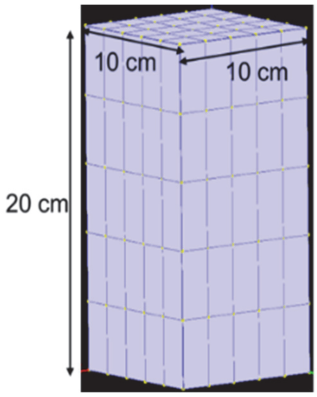
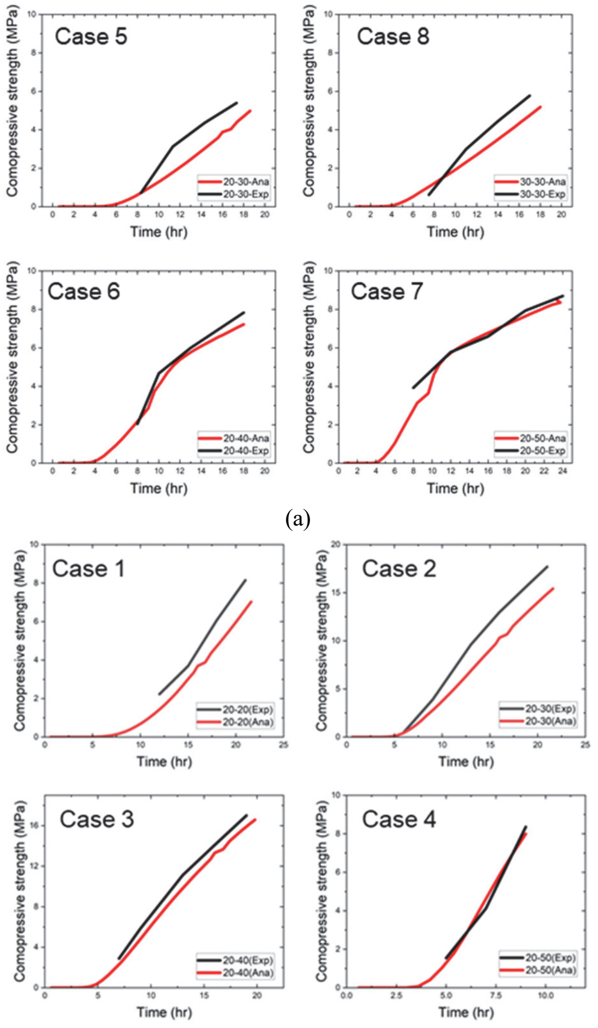


Figure 8: Analysis model in LINK 3D

We also see strong agreement between the experimental and analysis results in the case of heat release (Figure 10). Numerical analysis is capable of accurately predicting the heat released by concrete specimens subjected to different curing



(a)

(b)

Figure 9: Comparison of experimental and numerical results for (a) W/C = 0.5 and (b) W/C = 0.4

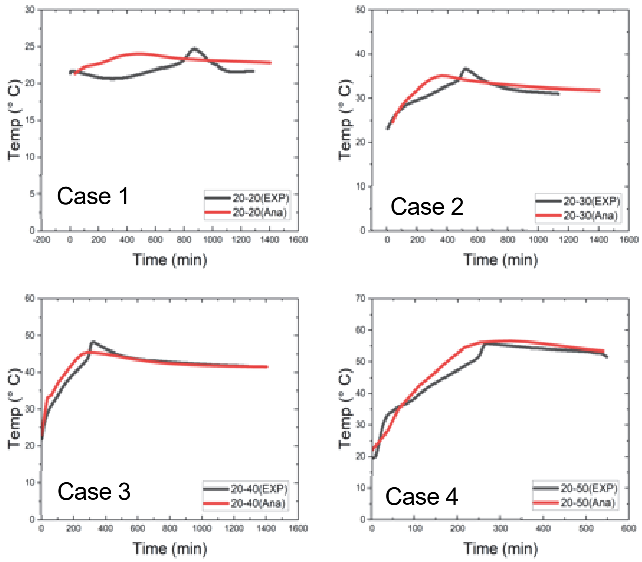


Figure 10: Comparison of heat release between experimental study and numerical analysis

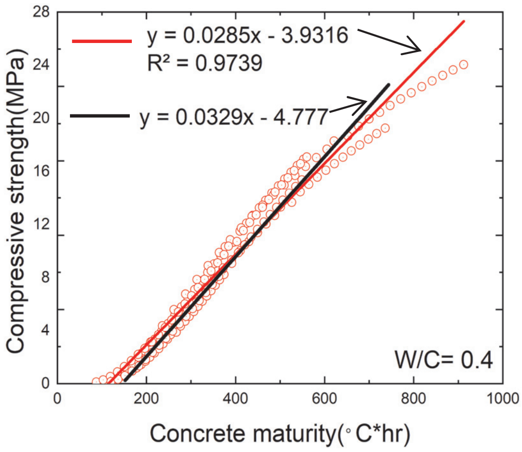


**Figure 11: Comparison of relationship between compressive strength and concrete maturity with W/C = 0.4**

temperatures. The largest difference in heat release is less than 6%. In the experimental study, the duration of peak heat release shrinks as curing temparatures increase. As Figure 10 shows, the trends for numerical analysis are similar.

Figure 11 compares the relationship between the compressive strength given by Equation 3 and numerical analysis. As in the experimental study, the datum temperature for calculating concrete maturity is set to 7°C. The analysis shows a linear relationship between compressive strength and concrete maturity. Overall, the equation derived via numerical modeling agrees with the equation derived from the experimental studies.

## 5. Conclusions

The key conclusions obtained from the experimental and numerical analysis can be summarized as follows:

① Experimental and numerical analysis established a relationship between compressive strength and concrete maturity at an early age (less than one day).

② The results of both experimental studies and numerical analysis are in good agreement.

③ For W/C = 0.5, concrete gains a compressive strength of 2 MPa within 16 hours when subjected to a curing temperature of 20°C or greater and an initial temperature of 15°C or greater.

④ For W/C = 0.4, concrete can gain a compressive strength of 2 MPa within 12 hours when subjected to a curing temperature of 20°C or more and an initial temperature of 20°C or more.

⑤ Datum temperatures may change depending on the properties of the concrete mix. The maturity method can be improved by evaluating datum temperatures.

In the future, we plan to undertake experimental and numerical studies for W/C = 0.6 and for blast furnace slag cement.

## 【References】

1) Japan Society of Civil Engineering: standard specifications for tunneling, p. 193, 2016 (in Japanese).
2) Nurse RW. Steam-curing of concrete. Mag Concr Res. Vol. 1, No. 2, 1949.
3) Saul AGA. Principles underlying the steam-curing of concrete at atmospheric pressure. Mag Concr Res. Vol. 2, No. 6, 1951.
4) Tekle, B. H., Al-Deen, S., Anwar-Us-Saadat, M., Willans, N., Zhang, Y., Lee, C. K.: Use of maturity method to estimate early age compressive strength of slab in cold weather. Structural Concrete, Vol. 23, No. 2, 2022.
5) Sun, B., Noguchi, T., Cai, G., & Chen, Q.: Predicting early the compressive strength of mortars at different curing temperatures and relative humidity by a modified maturity method. Struct Concr. Vol. 1, No. 13, 2020.
6) CSA A23.1/A23.2. Concrete Materials and Methods of Concrete Construction / Test Methods and Standard Practice for Concrete. 5060 Spectrum Way, Suite 100, Mississauga, Ontario, Canada: CSA Group; 2019.
7) Meakawa, K., Ishida T. and Kishi T.: Multi scale modeling of structural concrete, CRC Press, London, 2009.
8) Ohno, M., Chijiwa, N., Suryanto B. and Meakawa, K., H.: An Investigation into the Long-Term Excessive Deflection of PC Viaducts Using 3D Multi-scale Integrated Analysis. Journal of Advanced Concrete Technology, Vol. 10, 47-58, 2012 .
9) Suzuki, Y., Tsuji, Y., Meakawa, K. and Okumura, H.: Quantification of heat evolution during hydration process of cement in concrete. Proceedings of the JSCE, Vol. 414, 1990.