Translated paper

Effects of the Mineral Composition of Cement on the Temperature Dependency of Strength Development

Madoka Taniguchi^{1*}, Osamu Katsura², Takahiro Sagawa³ and Yukio Hama⁴

Received 1 December 2021, accepted 1 February 2022

doi:10.3151/jact.20.117

Abstract

The use of low heat Portland cement has been promoted in recent years. However, there is no general method to predict the strength development of the concrete using cement that is composed of a wide range of minerals and the application of the ‘maturity method (accumulated temperature)’ has proved difficult for low heat Portland cement. Therefore, the authors consider the application of the equivalent age to predict the strength development of concrete using various type of cement. The strength development of mortar using cement that is composed of a wide range of minerals under different curing temperatures are then examined. As a result, the temperature dependency of strength development of various cements is explained by the equivalent age. The values of the apparent activation energy of cement are dependent on its mineral composition. This paper is the English translation from the authors’ previous work [Taniguchi, M., Katsura, O., Sagawa, T. and Hama, Y., (2011). “Effects of the mineral composition of cement on the temperature dependency of strength development.” *Journal of Structural and Construction Engineering* (Transactions of AIJ), 76(661), 443-448. (in Japanese)].

1. Introduction

The compressive strength of concrete is dependent upon the hydration of cement and is greatly affected by temperature. In winter concreting, strength development is slowed by low temperatures. Accordingly, measures to obtain the required strength at the planned age are important in carrying out the work without impediment. For this reason, the establishment of a method for predicting strength development in concrete is essential. It is widely known that the strength of concrete can be predicted using the maturity method, a method that expresses the effects of temperature and time in a complex manner (Neville 2011). Maturity expresses the effects of temperature and time on strength development as a complex function, and even if historical temperature differs for concretes of identical composition, if the maturity of these is identical than the compressive strengths obtained will be equivalent.

There have been many studies on strength prediction using the “Maturity” method, for example, those of Nurse (1949), Bergstrom (1953), Plowman (1956) and

Carino (1984). In recent years, there have been many field applications and studies on improving the accuracy, as reported by Soutsos (2016, 2020), Li (2016) and Liu (2020), for example. However, there is a limited range of cements and it is not in the realm of experimental formulas. Therefore, the maturity method for concrete with a wide range of cement types has not been sufficiently studied.

This study focuses on the relationship between the coefficient of temperature dependence of the maturity function and the character of cement. The differences in the temperature dependence of concrete strength development according to type of cement used, reexamined these differences using mineral composition as an indicator and sought to propose a method for describing the temperature and time dependence of strength development using a simple function. Testing with cement paste waste conducted, to evaluate the temperature dependence of reactions of cement minerals (C_3S and C_2S) that are responsible for strength development. Next, using mortar, 11 types of Portland cement with widely diverse mineral compositions from three manufacturers in Japan were evaluated. A model employing equivalent age and Gompertz curves (Hansen 1977; Katsura 1993) was used to evaluate the temperature dependence of strength development and examined the effects of mineral composition.

2. Review of the maturity method

2.1 Maturity function

The method was proposed by Nurse (1948), was named “Maturity” by Saul (1951) and was further developed by Bergstrom (1953).

The formula proposed for the calculation of maturity

¹Senior Research Manager, Hokkaido Research Organization, Kita 19 Nishi 11, Kita-ku, Sapporo, Hokkaido, Japan.

*Corresponding author, E-mail: madoka@hro.or.jp

²Senior Research Manager (retired), Hokkaido Research Organization, Japan.

³Associate Professor, Maebashi Institute of Technology, 460-1 Kamisadorimachi, Maebashi, Gunma Prefecture, Japan.

⁴Professor, Muroran Institute of Technology, 27-1 Mizumotocho, Muroran, Hokkaido, Japan.

is shown below.

$$M = \sum (T - T_0) \Delta t \quad (1)$$

where M is maturity, T is the average temperature ($^{\circ}\text{C}$) of the concrete during the time interval Δt and T_0 is the datum temperature.

The formula is an empirical formula, with reference temperature set to -10°C for general concrete by Saul (1951) and Bergstrom (1953). In Japan, Koh (1959) introduced this method and developed it as an accumulated temperature method at construction sites for use as a concrete construction planning and management technique with cold weather conditions considered. The maturity represented by Eq. (1) is called “accumulated temperature”.

As another function to represent maturity, Hansen *et al.* (1977) developed the following equation.

$$t_e = \sum \exp \left[\frac{-E}{R} \left(\frac{1}{T} - \frac{1}{T_r} \right) \right] \Delta t \quad (2)$$

where t_e is equivalent age, T is the average temperature of the concrete during the time interval Δt (Kelvin), E is the apparent activation energy (J/mol), R is the gas constant (8.31 J/K/mol) and T_r is the reference temperature (Kelvin).

This equation derives the ratio of reaction speed at the reference temperature to the reaction rate at a different curing temperature and converts this to age (called “equivalent age”) at the reference temperature.

Each of the two equations expressing maturity has a coefficient indicating temperature dependence. In terms of accumulated temperature, the datum temperature T_0 represents the temperature dependence and in terms of equivalent age according to the Arrhenius equation, the apparent activation energy E represents it.

Based on testing of concrete in which cement type and admixture were varied, Carino (1984) investigated functions expressing maturity and developed a method for calculating the datum temperature T_0 using accumulated temperature and apparent activation energy using equivalent age. This became ASTM C1074: Standard practice for estimating concrete strength by the maturity method (ASTM 2011).

As for the datum temperature for the accumulated temperature, it is generally used as -10°C (Saul 1951; Bergstorm 1953), but it is known that it does not always fit (Kasai 1967; Kamada *et al.* 1990; Yahia 2006). It is also reported that low heat cements (Tanaka *et al.* 1996; Koyama *et al.* 1997) and fly ash concrete (Ogawa *et al.* 2021) also cannot have a datum temperature of -10°C . Especially at early ages, the accumulated temperature cannot represent the temperature dependency of blast furnace slag concrete (Soutsos *et al.* 2016).

For equivalent age using apparent activation energy, the Arrhenius equation, which expresses the temperature dependence of chemical reactions, is used in engineering. The value for apparent activation energy can be

obtained from a strength development model and from the results of strength testing with temperature set to 3 levels.

Hansen *et al.* (1977) proposed the following equation for apparent activation energy.

When $T < 20^{\circ}\text{C}$,

$$E = 33.5 + 1.47(20 - T) \quad [\text{KJ} / \text{mol}] \quad (3a)$$

When $T \geq 20^{\circ}\text{C}$,

$$E = 33.5 \quad [\text{KJ} / \text{mol}] \quad (3b)$$

This value is used for the equivalent age in CEB-FIP Model Code 1990 (CEB 1993). The apparent activation energy value, which indicates temperature dependence, varies greatly with water-cement ratio, even in concretes made using the same cement (Carino *et al.* 1992). The apparent activation energy value changes over time and is said to be affected by temperature (Kjellsen *et al.* 1993; Chanvillard *et al.* 1997). In addition, Kada-Benameur *et al.* (2000) state that the value of apparent activation energy is constant at hydration ratios between 0.05 and 0.5 but varies with curing temperature. Wirquin *et al.* (2002) show that little difference exists in activation energy calculated in tests with differing hydration ratios, using compressive strength and calorific value measurement. Kim *et al.* (2001) used the findings of previous researchers' experiments on concrete made with ASTM Type I cement to express apparent activation energy as an exponential function that decreases with age.

Schindler (2004) states that the effect of mineral composition on the value of apparent activation energy can be expressed by the following formula, where E is apparent activation energy (J/mol), p_{C_3A} is the percentage of aluminates in the cement, p_{C_4AF} is the percentage of ferrite in cement and $Blaine$ is the Blaine specific surface area of cement (m^2/kg).

$$E = 22100 \cdot p_{C_3A}^{0.30} \cdot p_{C_4AF}^{0.25} \cdot Blaine^{0.35} \quad (4)$$

From this, values of 45271 J/mol for Type I cement, 41788 J/mol for Type II, 49955 J/mol for Type III, 39978 J/mol for Type IV and 37329 J/mol for Type V were obtained. There is an inconsistency in that the apparent activation energy value of low-heat Portland cement (Type IV), which has highly temperature-dependency, appears smaller than that of Type I cement. Ito (2004) states that the value for concrete made with ordinary Portland cement in Japan is approximately 34 kJ/mol, while that for low-heat Portland cement is approximately 40 kJ/mol.

In a study involving supplementary cementitious materials, Barnett *et al.* (2006) showed that the value of apparent activation energy increases nearly linearly with increases in replacement ratio of blast furnace slag. In experiments using C_3S cement and pozzolanic fine powder, Kiriya *et al.* (2019) found that apparent activation energy was affected by the reaction of the poz-

zolantic fine powder and was dependent upon and varied with the development of compressive strength and the curing temperature.

A consensus regarding cement type and apparent activation energy value has not been obtained. Complicated calculations become necessary if it is assumed that the value of activation energy varies with curing temperature, etc.; accordingly, for purposes of application as an engineering strength development method, it is desirable that typical characteristic values can be expressed using certain rules.

2.2 Strength development model

Estimating strength through engineering maturity requires that the relationship between maturity and strength be derived in advance. Modeling the maturity-compressive strength relationship enables summarization of the relationship with temperature dependence and enables derivation of estimated strength.

As a model that expresses the relationship between maturity and strength, Plowman (1956) shows the following relational expression for accumulated temperature and strength, where F is concrete compressive strength, M is accumulated temperature and a , b are coefficients determined by cement type and water-cement ratio.

$$F = a + b \log M \quad (5)$$

In this function, strength increases without limit with the passage of age. Carino (1956) indicates the hyperbolic equation shown below.

$$F = F_u \frac{k(M - M_0)}{1 + k(M - M_0)} \quad (6)$$

In Eq. (6), F_u is maximum compressive strength, M_0 is accumulated temperature at which strength development is considered to have started and k is a rate constant.

This equation also holds with accumulated temperature set to age (days) and has been standardized as a basic equation in ASTM C1074. In the CEB-FIP Model Code 1990 (CEB 1993), maturity is expressed by Eqs. (3a) and (3b), while compressive strength at a given age is expressed by the following equation, where $f_c(t)$ is compressive strength at age (t), t is age, f_{c28} is specified design strength and s is a coefficient related to cement type.

$$f_c(t) = \exp \left[s \left(1 - \left(\frac{28}{t} \right)^{\frac{1}{2}} \right) \right] f_{c28} \quad (7)$$

Katsura (1993) shows a relational expression approximated by the Gompertz curve, which, like the logistic curve, is a growth curve. The approximated Gompertz curve equation is shown below, where F_{inf} is the final strength, M is accumulated temperature and a , b are empirical constants.

$$F = F_{inf} \cdot \exp \left(-a \cdot \left(\frac{1}{M} \right)^b \right) \quad (8)$$

The strength of high-strength concrete, which is considered to exhibit initial strength development more rapidly than ordinary concrete, can be estimated with good precision by the Gompertz curve. When the accumulated temperature portion is changed to age in the form of this equation, the result is nearly identical to the equation applied by Hansen (1977) for equivalent age.

The text above has shown typical examples of existing maturity-strength relational expressions used in engineering at construction sites. These curves include those empirically approximated from their shapes and those derived by assuming the reaction rate equation of the reaction of the cement. However, as these are expressed using the relationship between maturity and strength as empirical equations, application is limited to the scope of the base empirical data.

3. Cement

Eleven different types of Portland cement were used: one type of high-early-strength Portland cement (hereinafter “high-early-strength cement”) (H), two types of ordinary Portland cement (hereinafter “ordinary cement”) (N1, N2), four types of moderate-heat Portland cement (hereinafter “moderate-heat cement”) (M1 to M4) and four types of low-heat Portland cement (hereinafter “low-heat cement”) (L1 to L4). **Table 1** shows density, the Blaine specific surface area and the mineral composition of the four key minerals as quantified by X-ray diffraction and Rietveld refinement for each cement. Paste testing was performed for the three types N2, M3 and L4. Mortar testing was performed for all 11 types.

4. Investigation using cement paste

4.1 Overview of the experiment

The temperature-time dependence of the reaction of cement minerals (C_3S and C_2S) was evaluated. Hydration analysis was performed on the cement using X-ray diffraction and Rietveld analysis.

4.1.1 Preparation of hydrated samples

The water-cement ratio of the paste was 0.5. Mixing was performed in accordance with JIS R5201. After mixing, a 4×4×16 cm specimen was prepared and sealed curing was performed at 20°C for about half a day for ordinary cement and about one day for moderate-heat and low-heat cement. After removal of the mold, the cement was cut to thicknesses of about 3 mm, placed in zipper-sealed vinyl bags with a saturated solution of calcium hydroxide and cured to a predetermined age in a water tank adjusted to a predetermined temperature. **Table 2** shows the experimental parameter. After curing, hydration was stopped using acetone and D-drying was

Table 1 Density, Blaine specific surface area and mineral composition of cement.

Type of cement	Symbol	Density (g/cm ³)	Blaine specific surface area (cm ² /g)	Mineral composition (Rietveld) (%)				
				C ₃ S	C ₂ S	C ₃ A	C ₄ AF	Total
High-Early-Strength Portland Cement	H	3.12	4780	76	3	7	8	94
Ordinary Portland Cement	N1	3.17	3450	68	13	4	11	96
	N2	3.16	3460	68	13	6	10	97
Moderate-Heat Portland Cement	M1	3.23	3030	54	28	2	12	96
	M2	3.21	3710	40	43	5	8	96
	M3	3.24	3100	43	41	1	13	98
	M4	3.23	3080	55	26	2	14	97
Low-Heat Portland Cement	L1	3.23	3420	27	58	2	8	95
	L2	3.24	3590	25	58	2	9	94
	L3	3.22	3500	32	52	3	9	96
	L4	3.24	3330	32	52	3	10	97

Table 2 Experimental parameters.

W/C	Curing temperature (°C)	Age (day)
0.5	20	1, 3, 7, 28, 56, 91, 182
	5	7, 28, 56, 91, (182)
	50	3, 7, 14, 28, (91)

Note: The number of days of aging shown within brackets indicates the settings for M1 to M4 and L1 to L4 in Table 1.

performed. After drying, the samples were coarsely ground in an iron mortar, then finely ground in a ball mill.

4.1.2 Measurement of reaction rate

Measurement of X-ray diffraction was performed by adding corundum (10% internal percentage) as an internal standard substance. Measurement conditions consisted of X-ray source Cu-K α , tube voltage 40kV, tube current 40mA, scanning field (2 θ) 5 to 65°, step size 0.02° and counting time 2 seconds. A rotational sample table and monochromator were used. Rietveld analysis was performed using RIETAN-2000 (Izumi *et al.* 2000). The minerals targeted for analysis and quantification were C₃S, C₂S, C₃A, C₄AF, calcium hydroxide, monosulfate and calcite. Values according to Sagawa *et al.* (2009) were used as the initial data values for the crystal structure of the cement minerals.

The method of calculating the reaction rates of the cement minerals followed the method of Sagawa *et al.* (2009). The obtained quantitative values were corrected for an internal standard amount and loss on ignition and were calculated from their ratio to the quantitative values of unhydrated cement minerals.

Loss on ignition was measured using TG-DTA. Measurement conditions consisted of a rate of temperature rise of 20°C/min over the range from normal temperature to 1000°C under an atmosphere of N₂ flow (200 ml/min). Reduction of mass between normal temperature and 1000°C was defined as loss on ignition.

4.2 Results and discussion

The temperature dependence of C₃S and C₂S reactions was evaluated using the temperature-time function. **Figure 1** shows the relationship between accumulated temperature and the reaction rates of C₃S and C₂S for each cement, with datum temperature set to -10°C. This was expressed as accumulated temperature with datum temperature in Eq. (1) set to -10°C.

The reaction rate obtained was observed to decline mid-way in some cases, which can be considered due to measurement error. However, it was determined that the overall tendency of temperature dependence could be understood.

It was shown that the reaction rates under differing curing temperatures can be expressed nearly unequivocally by accumulated temperature in the case of C₃S, but not in the case of C₂S.

Rates were next expressed using equivalent age, as shown in Eq. (2). For the value of apparent activation energy required in calculations, values from literature [C₃S: 26.5 kJ/mol; C₂S: 60.1 kJ/mol (Sagawa *et al.* 2009)] were used.

Figure 2 shows the relationship between equivalent age and reaction rate. Using equivalent age, it was possible to express the progress of hydration at different curing temperatures nearly unequivocally for both C₃S and C₂S.

It is clarified that the temperature dependence of the C₂S reaction cannot be expressed by an accurate temperature, but can be expressed by an equivalent age using an appropriate apparent activation energy. This may be the reason why the strength development of concrete with low heat cement cannot be expressed by the accumulated temperature with the datum temperature of -10°C (Tanaka *et al.* 1996; Koyama *et al.* 1997).

Therefore, the equivalent age is desirable for the maturity function related to the reaction of cements with various mineral compositions. The following discussion will focus on the equivalent age.

Table 3 Experimental parameters.

Type of cement	Symbol	Curing temperature (°C)	Age (day)
High-Early-Strength Portland Cement	H	5	7, 14, 56, 119, 182
Ordinary Portland Cement	N1 N2		
Moderate-Heat Portland Cement	M1	20	1, 3, 7, 28, 56
	M2		
	M3	35	2, 3, 14, 35
	M4		
Low-Heat Portland Cement	L1	50	2, 3, 7, 28
	L2		
	L3		
	L4		

5. Investigation using mortar

5.1 Overview of the experiment

5.1.1 Materials and samples

The 11 types of cement shown in **Table 1** were used. Mixing and sample preparation were performed in accordance with Section 10 of JIS R5201-1997: Physical testing methods for cement. As the number of specimens was large, mixing was performed using a 45-liter tilting mixer.

5.1.2 Testing method

Table 3 shows the experimental parameter. The mold was removed at age of one day. Curing in water was

performed at 5°, 20°, 35° and 50°C to the specified age, after which compressive strength was measured according to JIS R5201-1997. The test ages were as shown in **Table 3**. Samples were prepared with TC thermocouples embedded in the central portion. Temperatures were measured at 10-minute intervals immediately after casting and were recorded and managed using a data logger.

5.2 Strength development and temperature dependence of mortar

5.2.1 Cement type and equivalent age

Figure 3 shows the relationship between age and compressive strength for each cement used.

Fig. 1 Relationship between accumulated temperature and the reaction rates of C_3S and C_2S for each cement, with datum temperature set to $-10^{\circ}C$.

In high-early-strength cement (H), strength develops quickly at 35°C and 50°C and slightly more slowly at 5°C, but temperature dependence is low. In ordinary cement (N), temperature dependence was observed, with a tendency toward slowness at 5°C and acceleration at 35°C and 50°C. Moderate-heat cement (M) was

more temperature dependent than ordinary cement; low-heat cement (L) was even more markedly temperature dependent.

For nearly all cements, strength at age of 28 days cured at 50°C and strength at age of 35 days cured at 35°C, were lower than strength at age of 56 days cured

Fig. 2 Relationship between equivalent age and reaction rate of C_3S and C_2S for each cement.

Fig. 3 Relation between age and compressive strength.

Table 4 The apparent activation energy E , the route means square (RMS), correlation coefficients and coefficients a and b of the Gompertz curve.

Type of cement	E	RMS	Correlation coefficient	Coefficients of Gompertz curve	
	(J/mol)			a	b
H	33121	0.91	0.929	-0.92	-0.92
N1	39344	1.72	0.955	-1.82	
N2	37555	0.92	0.981	-1.51	
M1	38198	0.52	0.996	-2.51	
M2	43513	1.02	0.996	-2.68	
M3	43330	1.12	0.995	-3.26	
M4	39009	1.36	0.976	-2.95	
L1	47515	1.71	0.970	-4.48	
L2	46780	1.73	0.987	-6.03	
L3	43823	1.05	0.994	-4.30	
L4	42900	1.06	0.982	-4.59	

at 20°C. It is well known that the curing temperature of the initial age affects long-term strength (Neville 2011). This study hypothesized that this effect could be lessened through curing at 20°C for one day, followed by curing at the respective curing temperatures. However, an initial high temperature was observed to have an effect. The reason for this is not clear within the scope of this study.

The above results were used to obtain the apparent activation energy that expresses temperature dependence.

With standard curing at 20°C, this was approximated by the Gompertz curve shown in Eq. (8'), with coefficients a and b that determine the shape of the curve determined by the nonlinear least-squares method.

$$F(t) = F_{inf} \cdot \exp(a \cdot T_e^b) \quad (8')$$

Here, $F(t)$ is compressive strength at age t , F_{inf} is the final strength, T_e is equivalent age and a , b are empirical constants.

As for the coefficients a and b of the Gompertz curve, b was almost constant regardless of the cement type. Accordingly, b was fixed here and a was determined for each cement used. Through this, the relationship between age and strength development with curing at 20°C was obtained for each mortar. Next, ages with other curing temperatures were converted into equivalent ages through Eq. (2) and the apparent activation energy value for each mortar was derived using the least-squares method so that the experimental value of

compressive strength at each equivalent age fit the relationship between age and strength with 20°C curing. This was set as the apparent activation energy E obtained for each cement. However, with curing at 35°C and 50°C, stagnation of strength development was observed from age of 28 days. As this is considered to be the effect of factors other than the temperature dependence examined here, experimental results for an age of up to 14 days were used.

The apparent activation energy E was obtained for each cement, the compressive strength calculated from Eq. (8') using equivalent age (hereinafter "calculated strength"), the route mean square (RMS) of measured strength, correlation coefficients and coefficients a and b of the Gompertz curve are shown in Table 4.

Figure 4 shows the measured strength and calculated strength for each cement type. Good correspondence between calculated strength and measured strength was indicated. As a result, the relational expressions between obtained apparent activation energy and strength, and between age and strength were deemed good expressions of the experimental results, and the following investigation was performed.

To investigate the effects of mineral composition on the value of apparent activation energy, we performed regression analysis using the proportions of minerals as explanatory variables. Table 5 shows the correlation coefficients among the explanatory variables to investigate interactions among the explanatory variables. The correlation coefficient between each mineral ratio and

Fig. 4 Relation between measured strength and calculated strength for each type of cement.

Table 5 Correlation coefficients among the explanatory variables to investigate interactions among the explanatory variables and correlation coefficient between each mineral ratio and apparent activation energy.

	C ₃ S	C ₂ S	C ₃ A	C ₄ AF	E _a
C ₃ S	1	-0.999	0.640	0.233	-0.938
C ₂ S	-0.999	1	-0.646	-0.225	0.942
C ₃ A	0.640	-0.646	1	-0.519	-0.632
C ₄ AF	0.233	-0.225	-0.519	1	-0.221

Table 6 Correlation between coefficient *a* and the minerals.

	C ₃ S	C ₂ S	C ₃ A	C ₄ AF
<i>a</i>	0.939	-0.931	0.676	0.139

apparent activation energy is also shown.

Looking at the correlation between mineral ratios and activation energy, the correlation coefficient with C₃S and C₂S ratio was as high as 0.9 or more, while nearly no correlation was seen with C₄AF ratio (correlation coefficient of 0.221). Looking at the correlation among explanatory variables, the C₃S and C₂S ratios are highly correlated and interactive. Accordingly, multiple regression analysis was performed using C₂S ratio and C₃A ratio as explanatory variables. It was found that the C₂S ratio was significant at the 1% level, but the C₃A ratio was not significant even at the 5% level. The value of apparent activation energy is expressed only by the C₂S ratio, with the regression following equation, in which C₂S is the percentage of C₂S in the cement.

$$E = 206.9 \times C_2S + 34091.1 \quad (9)$$

Figure 5 shows the relationship between equivalent age and compressive strength, calculated using the apparent activation energy calculated by Eq. (5). The dotted line in the figure indicates results at 20°C. For all cements, it was possible to nearly unequivocally express

strength development under varied curing temperatures at an equivalent age of up to approximately 28 days.

5.2.2 Cement type and strength development curve

In order to investigate differences in the shapes of the strength development curves according to type of cement, regression analysis of the relationship between mineral composition and coefficient *a* of the Gompertz curves obtained in Section 5.2.1 was performed, using the ratios of minerals as explanatory variables. **Table 6** shows the correlation coefficients between coefficient *a* and the minerals. Correlation was highest with the C₃S ratio; a slight correlation was also observed with C₃A. In multiple regression analysis using the C₃S and C₃A ratios as explanatory variables, only the C₃S ratio was significant at the 1% level.

Figure 6 shows the relationship between coefficient *a* and the C₃S ratio, as well as the reciprocal of the C₃S ratio. The correlation coefficient between coefficient *a* and the reciprocal of the C₃S ratio is -0.956; the multiple correlation coefficient is 0.910. Coefficient *a* was expressed by the following regression equation, in

Fig. 5 Relationship between equivalent age and compressive strength.

Fig. 6 Relation between C_3S or $1/C_3S$ and coefficient a .

Fig. 7 Strength development curves for H, N1, M3 and L1.

which C_3S is the percentage of C_3S in the cement.

$$a = -157.1 / C_3S + 0.629 \quad (10)$$

Figure 7 shows the strength development curves for H, N1, M3 and L1, with a set to the value according to Eq. (4) and b constant at -0.54 . This was calculated with 28-day strength at 20°C set to 30N/mm^2 . The C_3S ratio is shown in the legend. This clearly expresses that the higher the C_3S ratio in high-early-strength cement, the faster the rise in strength, with strength development tendencies dependent on the cement types shown in **Fig. 4**.

6. Conclusions

From the experimental study herein presented the following main conclusions can be drawn:

1. The cement paste testing showed that the temperature-time dependence of the C_2S reaction cannot be expressed by accumulated temperature. From this, the authors were able to explain that the temperature-time dependence of concrete strength development in low-temperature cement with a high C_2S ratio cannot be expressed by accumulated temperature.
2. Mortar testing using different types of cement showed that the temperature-time dependence of

strength development can be expressed by equivalent age and that the apparent activation energy at the time can be calculated from the C_2S ratio of cement.

3. The shape of the strength development curve, which expresses the relationship between age and strength development, differs with type of cement. When it approximated the Gompertz curve, it was possible to calculate the coefficient that determines the curve shape from the C_3S ratio.

Acknowledgements

We would like to thank Nippon Steel Cement Co., Taiheiyo Cement Co., Mitsubishi Ube Cement Co. and Floric Co. for their cooperation in providing materials and conducting the experiments.

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