

Study on Compressive Strength Prediction for Steam Curing

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Abstract. Steam curing process is generally adopted for precast concrete products to improve productivity. For setting reasonable production cycles and selecting economical formulation, it is important to predict the strength of mortar / concrete at early stage. Compressive strength estimation by the Maturity method is being widely used in conventional research. However, it is pointed out that accuracy is relatively low for estimating the strength of concrete under steam curing condition. Therefore, in this study, a relation between effective material ages based on the Maturity and Arrhenius's law and both initial and long-term strength were evaluated. As a result, it was confirmed that the Arrhenius's law shows higher estimation accuracy than the Maturity method. Furthermore, it was confirmed that the prediction method using effective material ages based on the Arrhenius's law which takes the activation energy into consideration has higher estimation accuracy.

1. Introduction

In recent years, the population of Japan is on a downward trend and the declining birthrate and the aging of the population are advancing. Also, at the construction site, the declining birthrate and aging population are progressing, hence lack of skilled workers is being concerned. It is worried that current skilled workers account for 33% of the total over the age of 45 and 1.1 million people may leave the job after 10 years. The labor on the construction site is required for certain skills to set up forms, to assemble reinforcing bars and to perform complex tasks. Also, the Tokyo Olympic Games will be held in Japan in 2020. Therefore, improvement of the productivity of the structure is in social demand in the construction industry.

Precast concrete products attract attention to shorten the construction term of the structure. Since precast concrete is fabricated and managed in the factory, it doesn't influence of the weather, it is manufactured in a high accuracy. Therefore, precast concrete products are said to be of high quality. On the other hand, as a countermeasure to cost savings, blast furnace slag and fly ash are used as supplemental cementitious materials [1]. Also, to improve the productivity of precast concrete products, two-cycle production system using same formwork is being applied, in case of need [2]. In the two-cycle production system, it is necessary to apply the steam curing process to remove the product from the mold within adequate period. Prediction of the strength of the product makes it possible to clarify the removal timing of the mold. Therefore, strength prediction is key point from the viewpoint of productivity improvement demolding strength from the viewpoint of installation and dismantling of formwork, cost aspect, quality and quality assurance. Also, it is important to grasp the control of concrete products [3]. concrete with the same material and mix proportions, generally, it is said that "the compression strength obtained is equal if the Maturity are the same even when the temperature changes "[5]. However, the difference in



cement types is not considered, and if the type of cement and the curing temperature change, the hydration reaction rate also differs. Therefore, the strength development time varies depending on the curing temperature. Therefore, there is strength prediction formula based on the effective material age using the Arrhenius' law as another compressive strength predicting expression expressing the curing time for obtaining the predetermined strength. Since this formula is based on the hydration reaction of cement, its reaction rate is to express the temperature dependence of the chemical reaction. The Maturity method and the Arrhenius' law have equations for predicting the time, as for effective material age, the prescribed strength development, respectively.

Generally, the strength prediction formula used for predicting the compressive strength development time is mostly a Maturity method where calculation with effective material age is easy [6-10]. Many studies on the prediction of the initial strength development of concrete under various curing conditions are reported using the Maturity method. However, there are few reports on research on Maturity method under steam curing. A few reports on the concrete strength development time using the cumulative temperature method and the Arrhenius law are issued so far. In general, it is said that both the Maturity method and the Arrhenius' law do not change the strength development time. However, there have been few reports on studies investigating the relationship between strength development time and compressive strength under the different temperature conditions using both equations. Therefore, in this study, this experiment used three types of curing conditions, two kinds of cement and blast furnace slag fine powder and mixing of mortar. Then, then, this experiment measured the relationship between compressive strength and curing time with respect to the strength development time of the Maturity method and the Arrhenius' law, the Young's modulus and the propagation velocity with respect to the change in the physical properties on the curing temperature, and applicability of the range of use of the strength prediction formula, were investigated

In general, the strength of concrete increases with the age, but it is known that there is a correlation with the curing temperature, and the time to reach a predetermined strength differs depending on the curing temperature [4]. As a factor influencing the strength development of concrete, the curing condition including steam curing program of concrete in the early age can be mentioned. The strength development of concrete depends on the curing temperature and curing time, and in the case of.

2. Outline of experiment

2.1. Material use and mix proportions

Materials used and mix proportions are shown in table 1 and table 2 respectively. As a material, Ordinary portland cement, high early strength cement, fine blast furnace slag powder were used. As the admixture, high range water reducing agent for concrete products was used, and an admixture was added for each mortal specimen so as to have adequate workability. In recent years, cases of use of blast furnace cement B type are increasing in Japan from the viewpoint of durability improvement. Blast

Table 1. Matertials used.

Materials		Properties	Density (g/cm ³)
Cement	N	Ordinary Portland cement	3.16
	H	High-early-strength cement	3.14
Mineral admixture	Sg	Blast furnace slag fine powder (4000cm ² /g)	2.90
Fine aggregate	S	River sand from Yamakitamati Kanagawa	2.69
Chemical admixture	Ad	High range water reducing agent	-

furnace cement B type (hereinafter referred to “BB”, c.f. table 2 is one in which 45% of ordinary portland cement is replaced with blast furnace slag fine powder. In this research, this cement was also used to confirm an influence of type of cement on strength development. was prepared. The ratio of sand and cement was set to 1: 1 by setting the water cement ratio to 3 levels of 30, 40, and 50%, and the sand cement ratio (S / C) to 2.0. Also, in this experiment, the amount of cement was made constant, weighed value was obtained, afterwards, the mixing was carried out.

2.2. Curing conditions

All the material used were controlled and managed temperature so that the mixing temperature became the same as the curing temperature, then mixing was carried out. However, if the mixing temperature is set to 45°C or higher, there is concern of false set, so the maximum mixing temperature must be 40°C or less. After preparing the specimen, it was cured in a steam chamber. The curing parameters are shown in Figure 1. Curing was performed at designated temperature until a predetermined time, and then the specimen was moved to a constant temperature chamber kept at 20°C.

Table 2. Mix proportions.

Type of cement	W/C (%)	S/C	C (g)	Ad (C×%)
N	30	2.0	7000	0.7
	40			0.5
	50			0
H	30			0.7
	40			0.5
	50			0
BB*	30			0.7
	40			0
	50			

*Replaced 45wt% of N with Sg

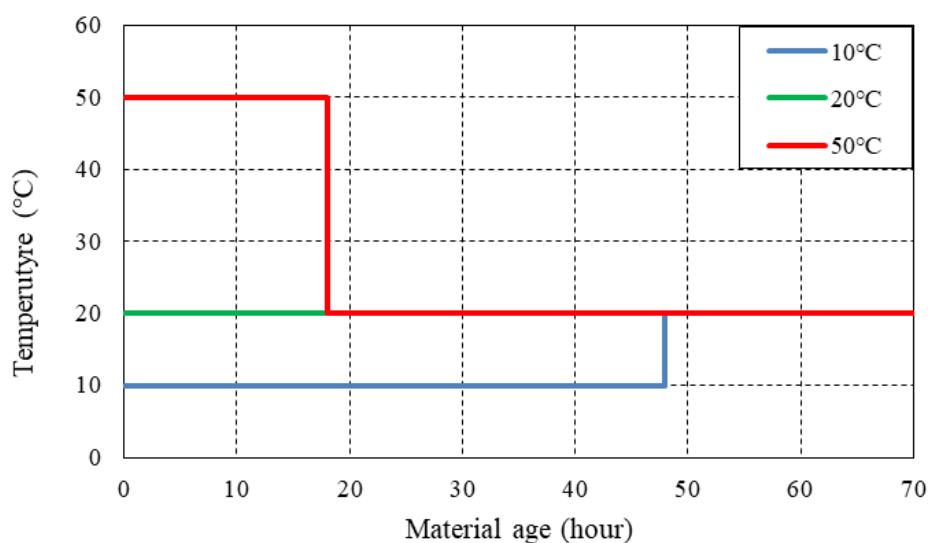


Figure 1. Curing temperature.

2.3. Experiment combinations

Three kinds of cements used in this experiment, the mixing conditions of mortar are as shown in table 3. Since the curing conditions are shown in Figure 1, it was decided to consider a combination of blending conditions of 26 patterns in total.

2.4. Test items

For the test items, both 0 hit and 15 hits mortal flow value and the mixing temperature were measured in the fresh mortar. After curing, compressive strength, Young's modulus, and ultrasonic wave propagation velocity were measured respectively. Cylindrical specimens with $\phi 50 \times 100$ mm were used for compressive strength and Young's modulus, and specimens for ultrasonic wave propagation velocity of $50 \times 55 \times 500$ mm were prepared and measured. Since the age of the test material varies depending on the curing temperature, it is shown in table 3.

3. Method for predicting strength development

Evaluation of compressive strength prediction at initial material age of mortar under steam curing was conducted by using Maturity method generally known as conventional prediction expression of strength as followings.

$$M = \int_0^t (T_k + 10) dt \quad (1)$$

here,

M: Maturity [$^{\circ}\text{C} \cdot \text{hr}$]

T_k: environmental temperature [$^{\circ}\text{C}$]

Δt : curing time [hr]

3.1. Effective material age

Effective material age was considered to effective for evaluating the mechanical properties of concrete subjected to unsteady temperature history. Generally, effective age refers to the age obtained by converting the influence of the curing temperature on the hydration reaction so as to be equivalent to the degree of hydration when the curing temperature was 20 $^{\circ}\text{C}$.

In this study, applicability was evaluated by using already proposed effective material age (t_e). The existing effective material age calculation formula is shown below.

3.1.1. Effective material age ①

Effective material age expression (1) is calculated based on the Maturity method as an empirical rule, and is obtained by dividing the constant by the value of the Maturity method. Therefore, the Maturity method and the effective material age formula ① have the same tendency. Therefore, in this study, the examination by the accumulated temperature method was omitted and decided to consider the effective material age formula ① shown in (2) as a representative t_e .

$$t_e = \int_0^t \frac{(T_k + 10)}{30} dt \quad (2)$$

Table 3. Curing temperature and material age.

Curing temperature ($^{\circ}\text{C}$)	Material age (hour)
10	48, 168, 336, 672
20	10, 18, 168, 336, 672
50	5, 10, 18, 168, 336, 672

3.1.2. Effective material age ②

The effective material age formula ② is expressed as the temperature dependence of hydration reaction of concrete on the basis of the Arrhenius' s law as shown in equation (3). This formula is derived by assuming the activation energy to 33 kJ / mol.

$$t_e = \int_0^t \exp \left[13.65 - \frac{4000}{273 + T_k} \right] dt \quad (3)$$

3.1.3. Effective material age ③

The effective material age formula ③ is also based on the Arrhenius' s law of the formula (4). However, regarding the calculation of activation energy (U_h), numerous studies including experimental studies have been reported so far. On the other hand, in fib Model Code 2010, it is pointed out that relational expressions should be determined separately by experiments when cement with a high mixing ratio of admixtures showing pozzolanic activity is used or when influence of temperature is important at designing are doing. Therefore, in this experiment, since it gives a high temperature history due to steam curing, the influence due to being different from the assumed activation energy is concerned, therefore in calculating the activation. energy, in order to modify the effective material age formula ②, it was obtained by the rule of thumb advocated by Saelta's calculated [13] by the following equation (5).

$$t_e = \int_0^t \exp \left[\frac{U_h}{R} \left(\frac{1}{293} - \frac{1}{T_k} \right) \right] dt \quad (4)$$

$$\frac{U_h}{R} = 4600 \left[\frac{30}{T_k - 263} \right]^{0.39} \quad (5)$$

4. Result and discussions

4.1. Compressive strength

The results of the compressive strength test are shown in Figure 2. The vertical line shows the compressive strength and the horizontal line shows the test material age logarithmically. Figure 2 shows 3 results at deferent curing temperatures.

Comparing the compressive strength with W/C, compressive strength tended to be higher as W/C was smaller. In addition, when comparing with the same mix proportions, the initial compressive strength was higher as the curing temperature was higher in all case. However, in the case of high-temperature steam curing, the initial strength shows relatively high, but the long-term strength is compared, the compressive strength is reduced by about 20% on average as compared with the 10 °C curing, hence the internal structure can be considered to sparse. This is because in the case of high temperature steam curing, the pore structure inside the mortar was rapidly built at the initial stage, so the internal structure is considered to be sparse. On the other hand, for the case of curing at 10 °C and 20 °C, it is considered that the internal structure is dense because slow pore structure is constructed.

Therefore, when considering the compressive strength for a long time, it can be said that the compressive strength is higher as the curing temperature is lower. However, since the state of the pore structure cannot be obtained exactly by only the compressive strength, the relationship between compressive strength and Young's modulus is as follows.

4.2. Ultrasonic wave propagation velocity

The test results of the ultrasonic wave propagation velocity are shown in Figure 3. The vertical line shows compressive strength and the horizontal line shows logarithmic representation of the test material age. Figure 3 shows curing at 10°C. from the left, curing at 20°C, and curing at 50°C. For all mix

proportions, the ultrasonic wave propagation velocity increases as the compressive strength increases. As the compressive strength increases, the internal structure becomes dense, so the ultrasonic wave propagation velocity is considered high

4.3. Yong's modulus

The Young's modulus results are shown in Figure 4, indicating 3 results at deferent curing temperatures. As the ultrasonic wave propagation velocity increases in all formulations, the value of Young's modulus also increases. It is known that when the value of Young's modulus is large, the object is hardly deformed, so that the compressive strength is large. Therefore, since the fact that the Young's modulus is rising means that the compressive strength is also rising, it can be considered that the internal structure is dense. Since it is known from the whole formulation that the ultrasonic wave propagation velocity increases in proportion to the Young's modulus, the internal structure of the specimen can be considered to be dense.

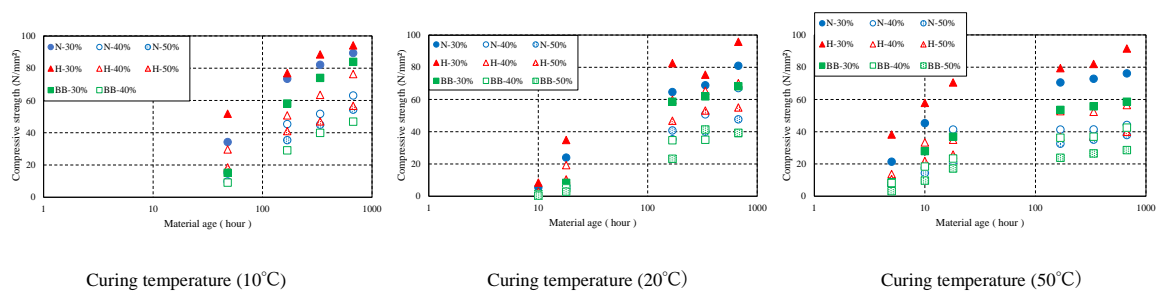


Figure 2. Relationship between material age and compressive strength.

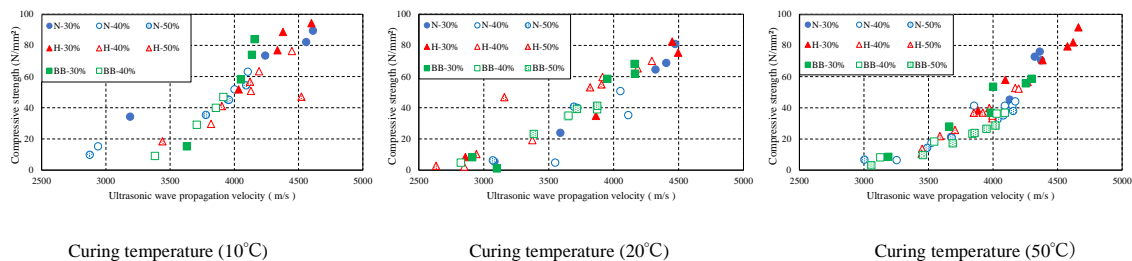


Figure 3. Relationship between compressive strength and ultrasonic wave propagation velocity.

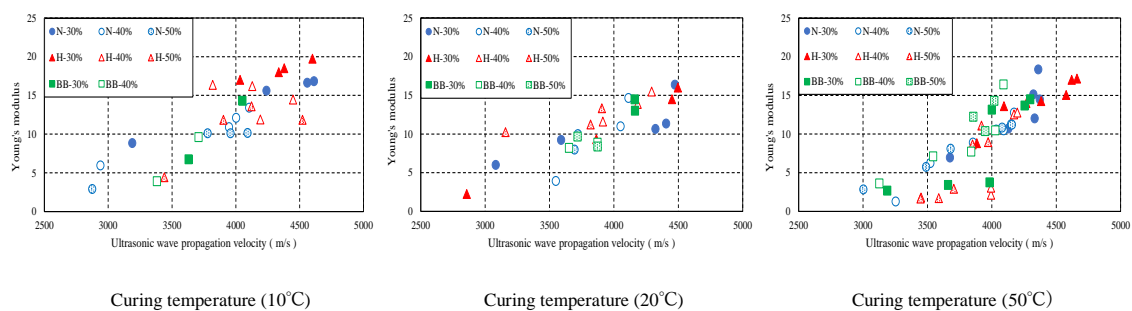


Figure 4. Relationship between Young's modulus and ultrasonic wave propagation velocity.

4.4. Comparison result of strength development prediction using three kind of “Effective material age”

The relationship between effective material age by 3 formulas and compressive strength are shown in Figure 5 and Figure 6. As in consequence, the estimated strength at 20 °C, which is the reference temperature of the effective material age formula, and the compressive strength at 10 °C and 50 °C are compared at the time of effective age of each calculated by the Maturity method and the Arrhenius’ s law. Since both the Maturity method and the Arrhenius’s law used at this time set the reference temperature to 20°C, hence there is no difference in effective material age at 20°C under curing. Each regression line ($\sigma = a \cdot \log(t_e) + b$) are calculated by using the compressive strength at 20°C and at the age of measurement and reflect reference temperature of 20°C.

Overlaps on the regression line when the temperature is the same 20°C, even if the age of age changes. Also, when the temperature is different, the effective material age is corrected based on the effective material age formula. At that time, substitute the effective material age (t_e) corrected for the case where the temperature is different to 20°C, and calculate the estimated strength. When the estimated strength is close to the actual measurement value, the applicable range of the effective material age formula is wide. Also, when the estimated strength is far from the measured value, the applicable range of the effective material age formula is narrow. In addition, by plotting the effective material age and the measured value on the regression line, when the deviation from the regression line is large, the application range is narrow, and the estimation accuracy of the intensity compression strength is low.

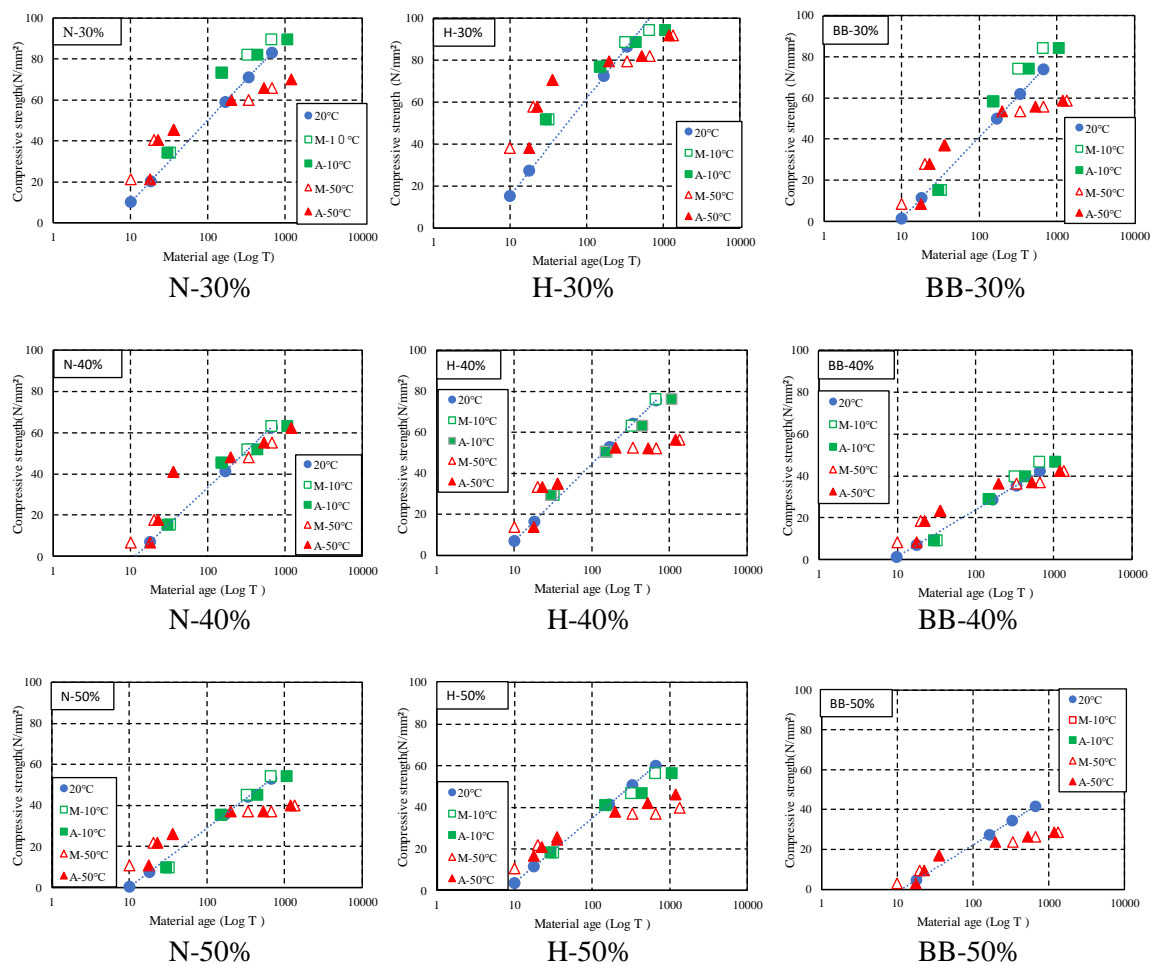


Figure 5. Relationship between compressive strength and effective material age
(As activation energy at 20 °C).

Therefore, the nearer to the regression line of 20, it can be considered that it is higher estimation accuracy of the compressive strength than other curing temperatures, and it can be said that versatility is high. Figure 5 shows those using the effective material age formula with activation energy at 20°C of the Arrhenius's law, Figure 6 shows the effective material age formula of the Arrhenius's law, of which is considering adequate activation energy based on each curing program. Table 4 shows accuracy of strength prediction based on the results of both Figure 5 and Figure 6. Those that are not filled in the plot show the maturity method, and those filled with paint indicates the Arrhenius law. The standard deviation of prediction errors by 3 methods are shown in Table 4, and from Figure 5, it is confirmed that the Arrhenius's law is the one with small deviation of the regression line in all formulations. Therefore, when comparing the maturity method and the Arrhenius's law as in the past research, it can be said that the Arrhenius's law is better for the strength estimation accuracy [14].

These results also show that the Arrhenius's law shows better accuracy of estimating the compressive strength than the maturity method. Also, when the curing temperature is compared between 10 °C and 50 °C, the deviation from the regression line is larger at 50 °C, indicating that the compressive strength estimation accuracy is poor. Furthermore, when the prediction accuracy in Figure 5 and Figure 6 is compared, it was confirmed that estimation accuracy improves with consideration of activation energy. In consequence, it was found that the Arrhenius's law has better accuracy of the estimation of the

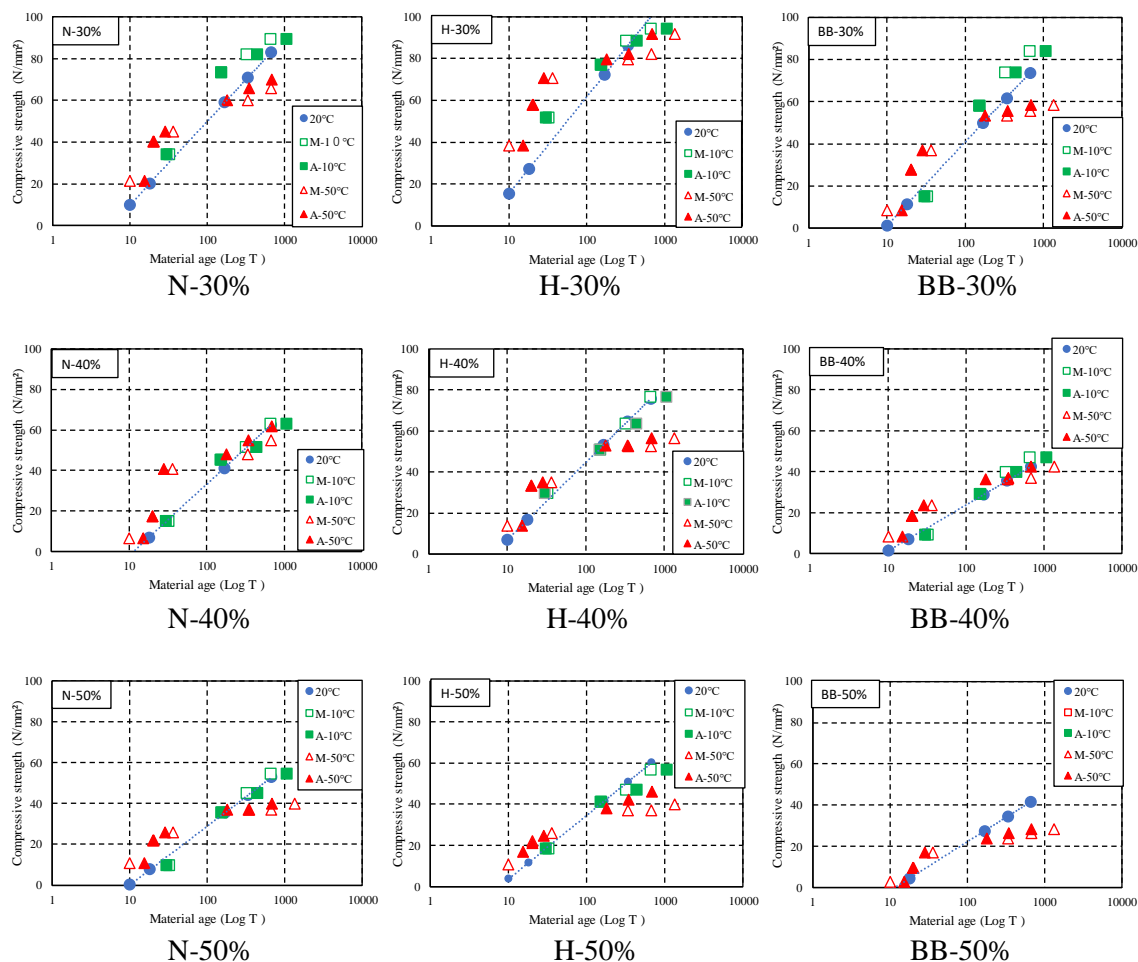


Figure 6. Relationship between compressive strength and effective material age
(Considering adequate activation energy based on each curing program).

Table 4. Accuracy of strength prediction based on three kinds of effective material age.

Type of cement	Temperature (°C)	W/C (%)	Standard deviation of prediction error (N/mm ²)		
			Maturity method	Arrhenius's law	
				Activation energy at 20°C	Consider adequate activation energy
N	10	30	6.3	8.3	5.5
		40	3.3	5.1	2.8
		50	1.6	3.2	0.9
H		30	2.7	3.8	2.2
		40	1.8	0.8	2.4
		50	1.9	3.2	1.5
BB		30	4.8	7.1	3.9
		40	1.1	1.9	1.0
N		50	30	8.1	7.3
	40		10.8	9.8	9.8
	50		4.9	4.1	3.7
H	30		9.9	9.6	9.4
	40		7.9	8.0	7.4
	50		5.2	5.1	4.7
BB	30		9.2	9.2	8.7
	40		5.3	4.7	4.2
	50		4.4	4.0	3.9

compressive strength than the Maturity method, and the activation energy is deeply related to the compressive strength estimation.

5. Conclusion

In this study, the influence of the curing temperature by the Maturity method and Arrhenius's law was investigated and the relationship between the cumulative temperature and the effective material age was examined. As a result, the following was found out.

- (1) It was found that the ultrasonic propagation speed increases in proportion to the Young's modulus. And internal structure of the specimen can be considered to be dense.
- (2) About the accuracy of estimating the compressive strength, the Arrhenius's law has better accuracy of estimating the compressive strength than the Maturity method
- (3) Accuracy of compressive strength estimation based on effective material age the greater the difference between the curing temperature and the reference temperature (20°C), the poorer the accuracy of estimating the compressive strength.
- (4) Among the active ingredient age formula of the Arrhenius's law, it was found that the accuracy estimation accuracy becomes even better when the effective material age formula considering the activation energy is used.

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