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Prediction Model of Compressive Strength of Concrete Composed of Portland Composite Cement, Marine Sand, and Sea Water Using Maturity Method

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Abstract

The utilization of portland composite cement, marine sand and sea water lead to concrete production more economical in the remote island, both in terms of time and cost. The prediction of concrete compressive strength in Indonesia has been provided in SNI 03-2834-2000. This code is used for predicting the compressive strength development of normal concrete with used ordinary Portland cement. This paper presents the predicted result of concrete compressive strength at ages of 28 and 90 days based on the compressive strength data and time-temperature factor at age of 1 and 2 days and provides a mathematical model to determine the coefficient of compressive strength development prediction. The cylindrical specimens were prepared with a mixture of Portland composite cement, marine sand, and sea water under closed room curing that is kept at a constant temperature of 25°C and the humidity of 70±1%. At prediction based on early age 1 day compressive strength, comparison between the actual compressive strength and the predicted compressive strength shows the difference value were 0.6% and 0.2% for 28 and 90 days compressive strength, respectively. At prediction based on early age 2 days compressive strength, comparison between the actual compressive strength and the predicted compressive strength shows the difference value were 2.2% and 1.5% for 28 and 90 days compressive strength, respectively.

Keywords: Marine sand, sea water, temperature, time, portland composite cement.

INTRODUCTION

The continuous and rapid development of infrastructures demand the importance of efficient material supply from different sources. The consumption and transportation of the fresh water and river aggregates to the remote islands increase the price of concrete work. The utilization of seawater and marine sand can decrease the concrete work price in the lowland areas and the remote island those lacks of clean water or fresh water and mountain sand or river sand. Experimental tests conducted by Tjaronge *et al*. [1] and Erniaty *et al*. [2, 3, 4] showed that sea water can be used as mixing water and curing water, also the unwashed marine sand can be used as fine aggregate. The chloride and SO_4 content in the sea water reacted with cement hydrates to produce Friedel's salt and ettringite, and they have no negative effect on the compressive strength development at the age of 1 day to 28 days [1].

In order to overcome the continuous dumping of waste material, this research also uses Portland composite cement (PCC) [1]. Fly ash is an environmental pollutant industrial which is generated in the thermal power plants. Some cement factories have been made attempt to produce the blended cement containing of fly ash as cement compounds in order to reduce CO_2 emissions from the production of cement clinker, to reduce the consumption of raw materials such as clay, and to contribute a cleaner environment through the recycling of waste materials such as fly ash. The incorporation of fly ash in blended cement achieves ecological benefit and material saving [5, 6].

It is important to ensure the concrete quality as soon as possible and concrete construction work would be more optimally if concrete strength after casting could be controlled. Hence engineers can check the compressive strength of concrete without waiting 28 days and decided to conduct further activities based on the compressive strength test result at early age. This can improve the work efficiency of a contractor.

Prediction of concrete compressive strength development in Indonesia is provided in Table 1 (SNI 03-2834-2000). During two decades, the coefficient in this code was used to predict the compressive strength development of normal concrete using portland cement, type I, II, III and V, with coarse aggregate of crushed stone or uncrushed stone (gravel) [7] and no literature related to the prediction coefficient for compressive strength development of concrete using PCC. The prediction coefficient based on the concrete age should be developed to predict the compressive strength development of concrete consists of PCC, marine sand, and sea water.

Table 1. Prediction coefficient of concrete compressive strength in SNI 03-2834-2000 [7]

Cement type	Type of coarse aggregate	On age (day)				Type of sample
		3	7	28	90	
Portland cement type I, II and V	Uncrushed stone	0.51	0.7	1	1.21	Cylinder
	Crushed stone	0.51	0.73	1	1.21	
Portland cement type III	Uncrushed stone	0.55	0.74	1	1.16	Cylinder
	Crushed stone	0.57	0.75	1	1.09	

Maturity method has been used for several years to predict the compressive strength development. For instance, V. Waller utilized a numerical tool such as finite element to extend the maturity method. This approach can correctly characterize the concrete properties (Young's modulus, tensile strength and thermal coefficient) in order to predict the risk of thermal cracking and describe properly the construction method [8]. Y.A. Adel-Jawad carried out study on maturity method based on ASTM C 1074-98, and have been made two modifications for the Nurse-Saul maturity function to improve the estimation of concrete compressive strength cured at different temperatures [9]. Kim, T., et.al conducted a study based on procedure outlined in ASTM C 1074 and developed a modified equivalent age. The modified methods add two factors: The influences of the water diffusion through layers of hydrates and influence of the nucleation process and its growth in forming new hydrates due to the combination of anhydrate's cement with free water [10]. B.W. Langan, et.al studied the influence of silica fume and fly ash on heat of hydration of portland cement type-1 (ordinary Portland cement, OPC) based mixtures at early ages [11].

Basically, there were two stages in the production of compressive strength using the maturity method. The first, develop the maturity curve. Maturity curve was a curve, which represents the relationship between time-temperature factor and concrete compressive strength. Using maturity curve could be determined a maturity function. Second, predict the concrete compressive strength at particular ages of concrete using maturity function [12].

This research aims to study the accuracy of the maturity method to predict the compressive strength development of concrete composed of Portland composite cement, marine sand, and sea water under closed room curing that is kept at a constant temperature and the fixed humidity. Compressive strength of concrete to be predicted is at the age of 28 and 90 days (referred to as the target age predictions). While the initial age data is used as the basis data for predicting the compressive strength of concrete is the age at 1 and 2 days (referred to as early age). This paper introduces a simple mathematical model to predict the compressive strength for a specified concrete mix at any age with the help of two fixed constants indicating of mix.

BASIC THEORY

The compressive strength of concrete is a complicated property that depends not only upon the intrinsic makeup and workmanship of the concrete, but also varies with its age and the temperature at which it hardens. For many years it has been proposed that the strength of concrete can be related to simple mathematical function of time and temperature so that strength could be assessed by calculating without mechanical testing [13]. Such as function is used to compute what is called the "maturity" of concrete, and the computed value is believed to bear a correlation with the strength of concrete.

There are two standards of ASTM discuss the maturity method: ASTM C 918-02 "Standard Test Method for Measuring Early-Age Compressive Strength and Projecting Later-Age Strength", and ASTM C 1074-98 "Standard Practice for Estimating Concrete Strength by the Maturity Method". The maturity function in ASTM C 1074-98 is used to compute the temperature-time factor as follows:

$$M(t) = \sum (T_a - T_o).\Delta t \text{ .... } (1)$$

where:

$M(t)$ = the temperature-time factor at age t, degree-days or degree-hours,
Δt = a time interval, days or hours,
T_a = average concrete temperature during time interval, Δt, °C and
T_o = datum temperature, °C.

Figure 1 is used to predict the concrete strength based on an early-age concrete as provided in ASTM C 918-02 [14] as a guideline. The relationship between cumulative temperature-time factor (the x axis is in logarithmic scale) and concrete strength to determine the equation (2).

$$S_M = S_m + b\ (\log M - \log m) \text{ .... } (2)$$

where:

S_M = projected strength at maturity index M,
S_m = measured compressive strength at maturity index m,
b = slope of the line,
M = maturity index under standard curing conditions, and
m = maturity index of the specimen tested at early age.

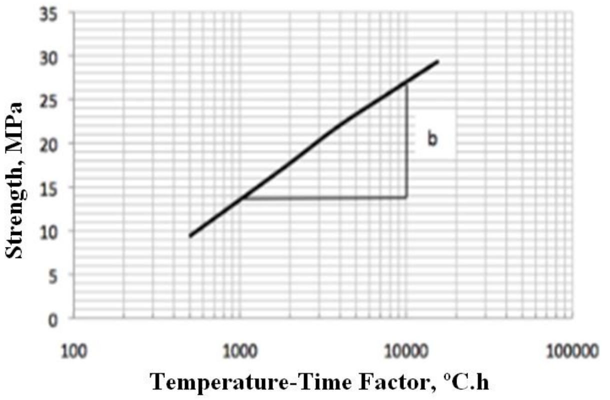

Figure 1. Cumulative temperature-time *vs* concrete strength

MATERIALS AND TESTING METHODS

As a substitute for fine aggregate, marine sand was taken directly from a beach then tested in the laboratory. The marine sand with fineness modulus of 1.9, passing through sieve size of 4.75 mm; specific gravity at the saturated surface-dry and water absorption are 2.56 and 2.46 % respectively, was used as fine aggregate. The marine sand was used in natural state (unwashed).The coarse aggregate has been processed from crushed river stone with maximum size of 20 mm, specific gravity of 2.82 and water absorption of 2.57 % was used in this research work. Coarse aggregate was soaked in the sea water for 24 hours, and used in surface saturated dry. Sea water originating from the beach with taken directly by a container for use in concrete laboratories as mixing water. Table 4 shows some the physical properties and chemical compound of sea water.

The material used in this research was Portland composite cement (PCC) obtained from a national cement factory. Some of chemical compositions and physical properties of the PCC are shown in the Table 2 and Table 3, respectively. The component oxides and physical properties meet the requirement of SNI 15-7064-2004 (Indonesia Standard for Portland Composite Cement) [15].

Table 2. Component oxides of PCC

Oxide	Unit	SNI 15-7064-2004	PCC
MgO	%	6.0 (max)	0.97
SO_3	%	4.0 (max)	2.16
Loss of Ignition	%	5.0 (max)	1.98

Table 3. Physical properties of PCC

Physical properties	**SNI 15-7064-2004**	**Unit**	**Cement used (PCC)**
Air content of mortar	12 max.	%	11.5
Fineness/Blaine meter	280 min.	$m^2.kg^{-1}$	382
Expansion	0.8 max.	%	-
Compressive strength			
a. 3 days age	125 min.	$kg.cm^{-2}$	185
b. 7 days age	200 min.	$kg.cm^{-2}$	263
c. 28 days age	250 min.	$Kg.cm^{-2}$	410
Time of setting (vicat test)			
a. Initial set	45 min.	minutes	132.5
b. Final set	375 max.	minutes	198
False setting time	50 min.	minutes	-
Heat of hydration 7 days	-	$cal.g^{-1}$	65
Normally consistency	-	%	24.2
Specific gravity, SG	-	-	3.13

Table 4. Physical properties and chemical compound of sea water

Specific gravity ($g.cm^{-3}$)	pH	Salinity (%)	Chemical compound ($mg.l^{-1}$)					
			Na	Ca	Mg	Cl^-	SO_4	CO_3
1.03	8.5	18.0	2085	348.4	1974	5304	134	576.6

Table 5 shows the composition of the concrete mixture, it was designed based on SNI 03-2834-2000 with water cement ratio of 0.4 and slump of 6.0 cm, respectively [7].

Table 5. Mixture design of concrete in 1 m^3

Sea Water (w), kg	Cement (c), kg	Marine sand, kg	Crushed stone, kg	Admixture, kg
210.0	543.8	631.5	947.3	7.5

Fresh concrete was poured into the molds cylinder molds with 10 cm diameter and 20 cm height to produce the temperature recording specimen and compressive strength specimen. After 24 hours, compressive strength specimens were taken from the molds and cured in the air until testing day.

The method of temperature recording provided by ASTM C 918-02 [13] was used in this investigation. Embed a temperature sensor into the center of the specimen concrete. Thermocouple was inserted into the center of each cylinder to obtain temperature readings when molding the fresh concrete into the cylinders, all specimens were cured in the air. Equipment for temperature recording is shown in Figure 2. All specimens were cured in the air. Monitor and record the temperature of a test specimen as a function of time beginning 30 minute after molding. A device includes thermocouples connected to continuous digital data recorders. The temperature recorded in 15 minute intervals for the first 48 hours in an accurate 0.1°C.

Figure 2. Equipment for temperature recording

RESULTS AND DISCUSSION

Temperature record of concrete

Figure 3 shows the temperature recordings obtained at mid-concrete depth during the hydration process until the concrete mixture is observed. The result describes the temperature of the concrete mix higher than the room temperature due to the effect of mixing. In Stage 1, concrete temperature at casting decreases during the first 3 hour period. Stage 2 for a period of 3 hours to 6 hours increased temperature. Stage 3, from 6 hours to 24 hours the temperature decreased rapidly, then Stage 4 slowly decreased from 24 to 48 hours.

The history of concrete temperatures shows a temperature trend movement that can be divided into four stages as shown in Figure 3.

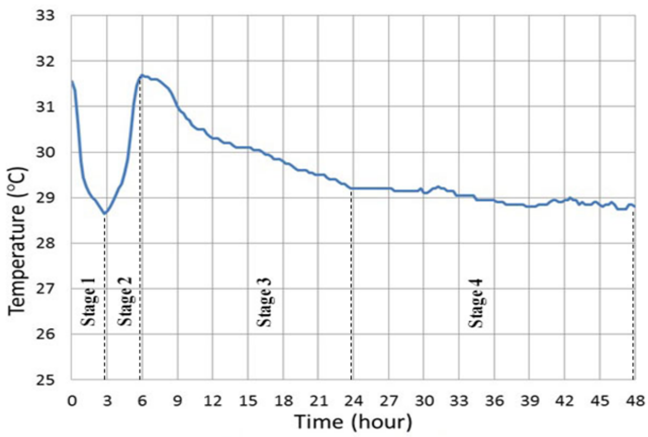

Figure 3. Temperature of the concrete in four stages

Stage-1, concrete mixture temperature drastically decreased adjusts relatively lower curing temperatures (25°C). The cement in the concrete mixture at this early stage has not shown the effect of hydration so that the temperature of the concrete decrease to adjust to the curing temperature. The temperature of the concrete mixture is relatively higher than the curing temperature due to the effect of aggregate friction and mixer when mixing is done on Pan Mixer.

Stage-2, the concrete temperature increase is drastically affected by the presence of cement hydration that begins after the end of the initial setting to the final setting of portland cement.

Stage-3, slowly decrease the concrete after the final setting of cement ends on stage 2, the temperature decrease of the concrete occurs due to adjustment to the curing temperature. At this stage the concrete temperature does not drastically decrease as there is still cement hydration.

Stage-4, the concrete is still experiencing a temperature decrease due to adjustment of curing temperature and the cement hydration that occurs on this stage is relatively smaller than the hydration of cement in stage three.

The time-temperature record is shown in Table 6. It can be observed that during the early stage the decrease trend and an increase in temperature were occurred as shown in the Figure 3. Concrete temperature at casting was 31.6°C and then decreased to a lowest temperature of 28.7°C. The peak temperature of 31.8°C occurred at age of 6 hours after molding as shown in Table 6.

Table 6. Temperature and time history of concrete

Concrete properties	Unit	Temperature
Concrete temperature at casting	°C	31.6
Lowest temperature	°C	28.7
Peak temperature	°C	31.8
In 24 hour temperature	°C	29.2
In 48 hour temperature	°C	28.8
Time since in casting to peak temperature	hour	6.0

Cumulative-TTF and the compressive strength

Table 7 shows the results of the cumulative-TTF test and compressive strength test for 25 cylinders of concrete at ages 1, 2, 3, 7, 28 and 90 days. At the 24 hour or 1 day test age, the compressive strength of concrete averaged 18.7 MPa based on the 5-cylinder compressive strength test of 19.2, 18.7, 17.8, 19.0, and 18.8 MPa, respectively. The test age was 48 hour or 2 days, the average compressive strength of concrete rose to 23.5 MPa based on the 5 cylinder compressive strength test of 21.9, 24.2, 25.2, 24.4, and 21.8 MPa, respectively. 3-day test age, compressive strength of 25.4 MPa concrete based on four cylinders compressive strength test of 25.1, 24.8, 25.4, and 26.3 MPa, respectively. Age of 7 day test, compressive strength of concrete averaging 30.5 MPa based on test results of compressive strength 4 cylinder respectively 30.5, 30.1, 31.2, and 30.1 MPa. Age of 28 days test, compressive strength of concrete averaging 38.7 MPa based on four cylinders compressive strength test each 38.2, 40.3, 38.1, and 38.0 MPa. At the 90 days test age, the compressive strength of the concrete is 45.9 MPa based on the compressive strength test of 3 cylinders each 45.6, 46.4, and 45.7 MPa. Based on the compressive strength test of 25 concrete cylinders, shows the compressive strength of concrete has increased along with the age of concrete.

Using equation 1, the cumulative-TTF at each age can be calculated. The cumulative-TTF values as shown in Table 7 at ages 1, 2, 3, 7, 28 and 90 days are worth 722, 1.423, 2.124, 4.927, 19.644 and 63.093ºC.hour respectively.

Table 7. The compressive strength and cumulative-TTF of concrete at the age of 1, 2, 3, 7, 28 and 90 days

Concrete ages (day)	(hour)	Cumulative-TTF (ºC. hour)	Compressive strength (MPa)
1	24	722	19.2 18.7 17.8 19.0 18.8
2	48	1,423	21.9 24.2 25.2 24.4 21.8
3	72	2,124	25.1 24.8 25.4 26.3
7	168	4,927	30.5 30.1 31.2 30.1
28	672	19,644	38.2 40.3 38.1 38.0
90	2,160	63,093	45.6 46.4 45.7

Data at early-age of 24, 48, 72, and 168 hours on Table 8, were used to build the prediction equation as shown in Figure 4. The test results data of age 28 and 90 days is the actual compressive strength used to validate concrete compressive data based on calculation by using prediction equation function.

Figure 4 shows the relationship between compressive strength vs cumulative-TTF. The function $y = 6.110 \times ln(x) - 21.27$ is the concrete compressive strength trend line on the Cumulative-TTF. A similar function has been reported by C. Irawan et.al. [13] studied the using fly ash-concrete strength under steam curing 70°C with maturity method obtained the equation $y = 7.969 \times ln(x) - 35.53$. The two functions of equation (y) each give a positive value only when the value of $ln(x)$ at a certain age, this means the compressive strength of new concrete formed at the age of adequate maturity. An overview at an early age, where the variable $ln(x)$ is 0 then the y function is negative, indicating that the concrete has no strength. The compressive strength of the concrete at an early age is formed after the equation is positive (> 0).

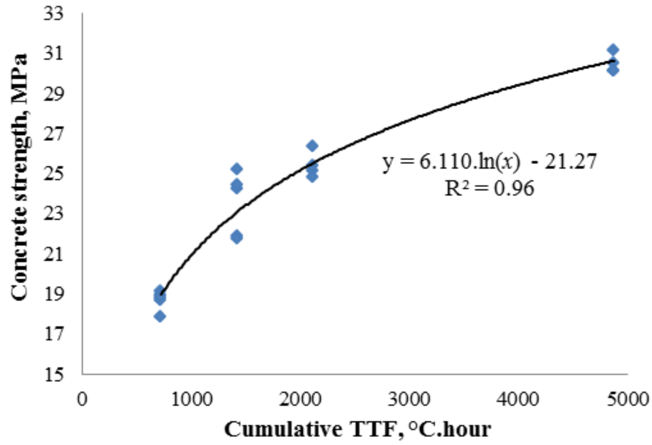

Figure 4. The cumulative-TTF *vs* concrete strength

The *f (M)* and *f (m)* can be calculated based on the equation $f(x) = 6.110 \times ln(x) - 21.27$. The value b is the slope of prediction equation, for this study b = 14.07 MPa, which is the difference between the value of the cumulative time-temperature = 10000°C.hour and the cumulative time-temperature = 1000°C.hour as shown in Figure 5.

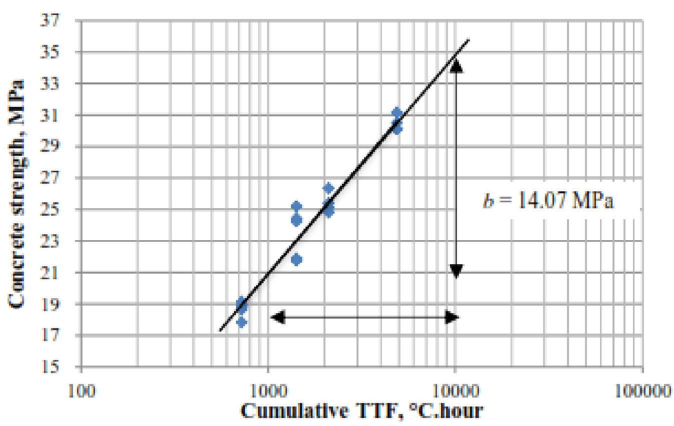

Figure 5. Value of slope line (b)

Figure 5 shown straight lines were obtained by logarithmic regression analysis of relationship between strength and the Cumulative time-temperature at the early age 1, 2, 3 and 7 days. For this research, b = 14.07 MPa is the slope of the prediction equation and is the vertical distance, which represents the strength increase for a tenfold increase in the temperature-time factor.

Cumulative-TTF at an early age 1 and 2 days (*m*) is 722 and 1,423°C.hour, respectively. From the experimental data of Table 7, the *M* values based on the predicted age of 1 and 2 days at the target age of 28 and 90 days are shown in Table 8, respectively.

Table 8. The Cumulative-TTF at target age 28 and 90 days

Early-ages, days	Cumulative TTF at target ages (*M*)	
	28 days	90 days
1	19,644	63,093
2	19,389	62,243

Prediction coefficient vs concrete age

Actual strength of concrete was obtained based on cylinder compressive strength test at age 28 and 90 days as many as 4 and 3 cylinders as shown in Table 7. The average compressive strength at age 28 and 90 days were 38.7 MPa and 45.9 MPa. Table 9 shows the difference values (in %) between the compressive strength of the predicted results and the actual compressive strength of the concrete tested at 28 and 90 days.

Table 9. Concrete strength prediction and difference

Early ages, day	Compressive strength at early age (S_m), MPa	Compressive strength prediction at target age (S_M), MPa		Difference, %	
		28 day	90 day	28 day	90 day
1	19.2	39.3	46.5	1.8	1.2
	18.7	38.8	46.0	0.5	0.1
	17.8	38.0	45.2	1.6	1.7
	19.0	39.2	46.3	1.3	0.8
	18.8	39.0	46.2	1.0	0.5
	Average	*38.9*	*46.0*	*0.6*	*0.2*
2	21.9	37.9	45.0	2.0	2.0
	24.2	40.2	47.4	4.1	3.1
	25.2	41.2	48.3	6.5	5.2
	24.4	40.4	47.5	4.6	3.5
	21.8	37.8	44.9	2.3	2.3
	Average	*39.5*	*46.6*	*2.2*	*1.5*

The difference between the actual compressive strength and the predicted compressive strength at 28 and 90 days for prediction based on early age 1 day compressive strength were 0.6 and 0.2 %, respectively. At prediction based on early age 2 days compressive strength, the difference between the actual compressive strength and the predicted compressive strength at 28 and 90 days were 2.2 and 1.5%, respectively.

The equation $f(x) = 6.110 \times ln(x) - 21.27$ was composed by using cumulative time-temperature and *b* with based on early-age of 1 day. Prediction equations developed into the equation (3).

$$S_M = 14.07 \times \log(M) - 21.52 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

where:

S_M = Projected compressive strength at maturity index *M*,

M = Maturity index based on 1 day age and under experiment curing condition.

When the maturity index is measured at 1 day concrete age then *M* from Table 7 is 722ºC.hour, the S_M value becomes 18.7 MPa. The result of the compressive strength prediction using equation (3) corresponds to the average strength value of 5 cylinder compression test results at the age of 1 day as shown in Table 7. The value of 21.52 equations (3) indicates concrete compressive strength (S_M) will have zero value after the maturity index (*M*) is worth 33.3°C.hour, this maturity value occurs when the concrete is 1 hour at 30°C.

Equation (3) is derived to predict the compressive strength development of concrete at the ages of 3, 7, 14, 21, 28, 90 and 365 days and to obtain the value of the prediction coefficient as shown in Table 10.

Table 10. Compressive strength development and prediction coefficient according ages

Properties	Ages (day)						
	3	7	14	21	28	90	365
Maturity index (ºC.hour)	2,124	4,927	9,832	14,738	19,644	63,093	255,813
Compressive strength (MPa)	25.3	30.4	34.6	37.0	38.8	45.9	54.4
Prediction coefficient	0.65	0.78	0.89	0.95	1.0	1.18	1.40

The relationship between of concrete compressive strength prediction (*y*) and concrete age can be obtained by using logarithmic regression. The trend line can be described by an equation $y = 0.16\ ln(x) + 0.48$ as shown in Figure 6. The coefficient of 0.48 in equation means that the concrete reaches the age of one day; the concrete has strength of 48 % against the compressive strength of concrete at 28 days age.

This mathematical model is base to calculate the prediction coefficient of concrete strength, method to estimate the compressive strength of the concrete before reaching the age of 28 days.

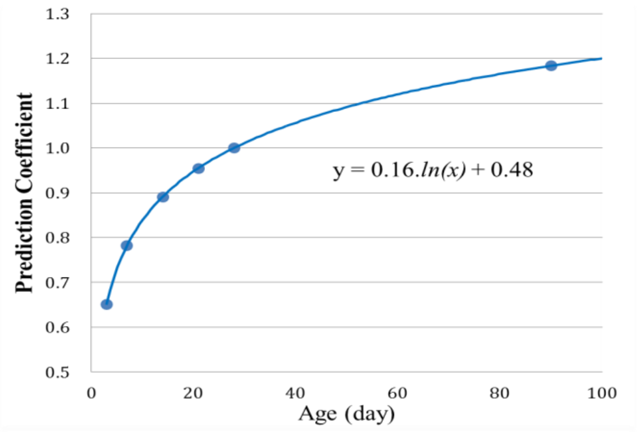

Figure 6. Prediction coefficient *vs* concrete age

CONCLUSIONS

Maturity method can be used as an effective method to predict the 28 and 90 days of compressive strength of concrete consists of Portland composite cement, marine sand, and sea water under closed room curing condition that kept at a constant temperature of 25 °C and the humidity of 70±1 % respectively. At prediction based on early age 1 day compressive strength, the actual compressive strength has difference value of 0.6 % and 0.2 %, compared to the predicted compressive strength at 28 and 90 days, respectively. At Prediction based on early age 2 days compressive strength, the actual compressive strength has difference value of 2.2 % and 1.5 %, compared to the predicted compressive strength at 28 and 90 days, respectively.

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