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Short-Term Deformation Model of High-Performance Concrete Plate Based on Surrounding Temperature

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Abstract: The relationship between surrounding temperature and deformation behaviour of one full scale concrete plate with compressive strength of 60 MPa was presented in this paper. This research was done in Indonesia. Indonesia presents humid tropical weather. A specimen measuring 3.00m × 1.60m × 0.15m was used. Deformation was obtained by using four embedded vibrating wire strain gauges. The range observation is held between 7 to 28 days. The peaks of deformation follow peaks of surrounding temperature. Some deformation peaks time occur after surrounding temperature peak time, it is called as delay time. As a result, there is a linear relationship between temperature and deformation. The relationship was influenced by a factor which presented its position and delay time. The average error of this model is less than 15% at the age range of 7 until 14 days, and less than 50% at the age range of 15 - 28 days.

Keywords: Concrete; Deformation; Humid; Plate; Tropical

1. Introduction

Weather is never constant over the year. Surrounding temperature and relative humidity (RH) has ability to enter the concrete through the pores. Combination between RH, temperature, and their fluctuation make concrete properties change, slowly but surely. High temperature changes the chemical & physical characterization, kinetic reaction, thermodynamic properties and equilibrium system. Weather will influence hydration process and every chemical process always correlates with the change of heat. The heat leads concrete particles move and change of volume. Research on temperature and creep in 1959-2020, in which the temperatures imposed on the specimens are 20°C, 40, 50, 80, 94°C and some reach 900°C has been summarized [1]. This does not reflect the temperature on earth even in the tropics. The role of ambient temperature variation on drying shrinkage has been studied [2]. Environment-dependent creep tends to compensate for an increase in temperature strain [3]. Atmospheric temperature is an important factor in shrinkage strain [4]. High temperature increases its influence, even since mixing. Temperature can accelerate moisture evaporation. There are many problems associated with moisture and water demand, such as rate of slump loss, rate of setting, difficulty of handling, placing, consolidating, finishing and risk of cold joints. The rapid evaporation always occurs in hot weather condition. Because in this condition there is a combination of high ambient temperature, high concrete temperature, low RH, wind speed and solar radiation [5]. Rapid evaporation was also determined by humidity level; therefore, deformation in humid tropical weather is different to another weathers. Rapid evaporation causes plastic shrinkage cracks. The cracks occur in plastic phase or young concrete. In young concrete there are many pores and, surrounding temperature easy to enter. Thus, the influence of temperature on deformation of the concrete needs attention.

Reinforced concrete structure exposed to environments that are prone to concrete carbonation or chloride attack couple with high temperature and RH suffer from accelerated corrosion of reinforcing material [6]. The combination between temperature uprise and longer holding time cause cracking delay on ceramic shell and contribute significantly to the length of the crack [7]. The effect of temperature on frictional properties of concrete pavements containing crushed glass has been investigated [8]. Concrete temperature between cold and hot weather condition in extremely hot and arid climate

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in Riyadh city has been studied. In Riyadh city the difference of cold and hot weather is about 16°C. This result shown an increase of the ambient temperature about 5°C would increase the concrete temperature by 2.2°C [9]. Although there is only a little volume (0.1%), ZnO is available in ordinary Portland cement (OPC). ZnO changes their morphology because of the ultrasonic irradiation and the atmospheric environment [10].

The influence of surrounding temperature is dominant on elements with large surfaces that are directly related to surrounding weather such as bridge, concrete roof and concrete pavement. Roof defect was also mentioned as an effect of hot weather [11]. In the last decade, concrete pavement is chosen because of the strength and has more resistance to the weather than flexible pavement. The studies of the influence of surrounding temperature to rigid pavement were done [12–14]. The effect of temperature and moisture gradient on slab deformation for jointed plain concrete pavements at Pennsylvania America have been studied [15]. Pennsilvania is 3 km from New York, the weather at Pennsilvania can be assumed similar to New York. In New York, the temperature is about 30°C with the high RH (over 72%) occurs in 3 months [16].

Load also caused change deformation behaviour. Deformation under constant load (creep) has been analyzed based on the standard non-linear theory at a normal and time analogy temperature [17]. Average creep deformation at 50°C is about twice the creep at 20°C [18,19].

To serve high load, high load intensity, or special building, high strength concrete (HSC) or high-performance concrete (HPC) was needed. HPC is defined commonly as concrete with a minimum compressive strength of 60 MPa with good durability [20]. HSC and HPC needs limited water and more cement; so, hydration process, pores evolution, and deformation behaviour such as shrinkage and creep, especially in relation with surrounding temperature becomes different to normal concrete. The influence of surrounding temperature to deformation of HPC was studied experimentally. Shrinkage in Malaysia (humid tropical weather) using cylinder specimens has been observed [21].

According to [22], the shrinkage and creep properties are determined under ideal air temperature between 20 - 22°C and RH 40 - 60%. In humid tropical weather, high temperature and high relative humidity occur over the year; with average temperature in Jakarta is 27°C and the RH is 72% [16]. Based on the explanation above, a study of deformation in humid tropical weather is worth of attention.

2. Experimental Program

The research was conducted in Jakarta, Indonesia, with humid tropical weather. This research was performed experimentally using one specimen of 3.00m× 1.60m × 0.15m, with four embedded vibrating wire strain gauges (SG) as shown in Fig. 1.

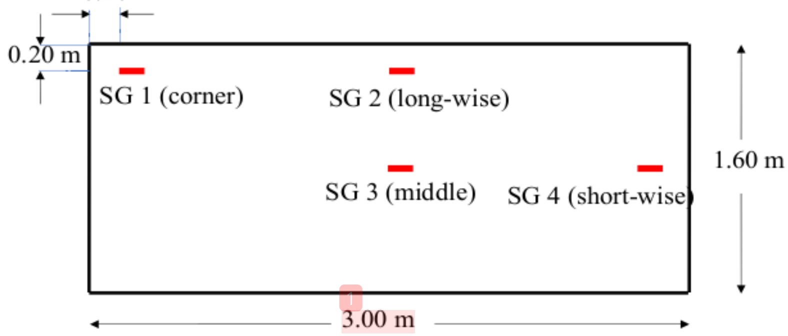


Fig. 1 – The Scheme of Plate and the Placement of Vibrating Wire Strain Gauges (SG)

2.1 Materials

The mix design to make concrete with compressive strength 60 MPa was conducted in compliance with [23] with a limit of 500 kg/m^3 cement content to meet the shrinkage factor closest to 1 [22]. The mix compositions are shown in Table 1.

A tilting drum mixture of 0.3 m^3 capacity was used. The mixing started with all cementitious material in dry condition, followed with 50% fine aggregate. Subsequently, 50% water was added to the revolving mixture. Then these materials were mixed for approximately 1.5 minutes. Next, 50% water was slowly poured in, which was mixed with HRWR homogenously. Thereafter, 100% coarse and 50% fine aggregate were added. With all the materials placed according to its order into the mixer, the concrete was mixed for approximately 3 minutes. The slump flow of the mixture was measured before pouring by using Abram's cone upside down. The average water penetration depth in the permeability test is 1.2 cm.

Table 1 – Mix composition

Materials	Quantity, Kg/m^3	Source	Description		
OPC	500	Indocement, Ltd	Fresh from silo, one time burning, electrical scale		
Silica fume	40	Sika Indonesia Ltd	8% cement weight, electrical scale		
Water	142.6	Universitas Indonesia	electrical scale		
Sand	800	River, Bangka, Sumatra	Saturated surface dry (SSD)		
Coarse aggregate	935	Volcanic rock, Banten	SSD		
			Size	70%	13-19mm
			Size	30%	6-12mm
			specific gravity	2.563	2.636
			absorption	1.543%	2.26%
HRWR	7.6	Sika Indonesia Ltd	Polycarboxylic superplasticizer, Visco Crete 10, 1.4% cement weight, electrical scale		

3. Methods

Shrinkage was measured as strain change against time by installing four SGs in the specimen (Fig. 1). The SG has abilities to detect the strain up to 3000 με with accuracy of about 0.025% and concrete temperature between -80°C and 60°C with about 0.5% accuracy. Surrounding relative humidity (SRH) and temperature were obtained by using room humidity and thermometer.

Right after casting specimens were covered with plastic membrane to eliminate water evaporation. The specimens were cured after remove the mold (one day after casting) by covering wet sacks over the specimens to the age of 7 days. After this treatment, specimen was allowed to intersect with SRH and temperature but with protection against raindrops. Observation was performed right after pouring as follows: 0 - 24 hours, every 15 minutes; 24 - 48 hours, every 60 minutes; days 3 - 10, every 2 hours; days 10 - 14, one time a day using a read out. Two beams of 3.00 m × 0.60m × 0.20 m were cast on the plate at the plate age of 14 days; therefore, on the plate occurs creep (Fig.2). Fifteen days is selected because load generally applied on the rigid pavement or slab. Observation was performed right after applied load as follows: days (specimen age) 14 - 16, every 15 minutes; days 16 - 17, every 60 minutes, days 17 - 23, every 2 hours and days 24 - 28 every 2 days.

Data analysis was done in the age range of 7 until 28 days. Every peak of temperature for four SGs were observed and related to deformation. Based on the relationship, mathematical model was created.

The result was compared to shrinkage research in Malaysia by [24]. The shrinkage observation used 6 cylinders 150 mm diameter and 300 mm high of dimension. The specimens were moist cured and tested in Malaysia's natural ambient (humid tropical weather) with compressive strength of 65 MPa [24].

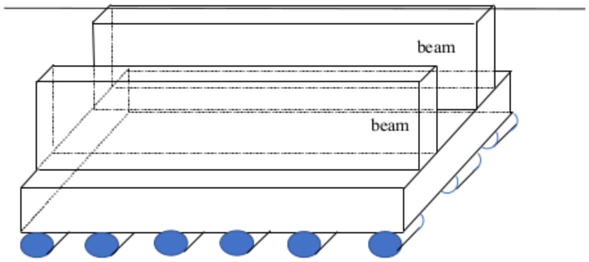


Fig. 2 – Plate with beam as load

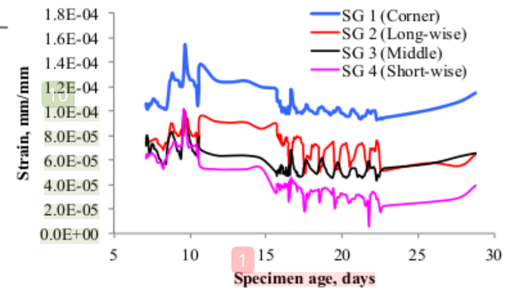


Fig. 3 – Plate deformation in all strain gauges (SG)

4. Result and Discussion

Result of the experimental data and discussion were supported by data analysis.

4.1 Result of the Experimental Data and Data Analysis

Result of the experimental data and data analysis are described as follow.

4.1.1. Result of the Experimental Data

Relationship between temperature and plate deformation can be mentioned by mathematical model as shown below:

$$\varepsilon = ST_{t-td}. \times f \times 10^{-5} + C \quad (1)$$

Where, ε: plate strain (plate deformation); ST: peak of surrounding temperature at t, °C; t: specimen age, days; t_d: delay time between the peak of deformation and surrounding temperature, days (depend on; network of pores, number and size of open pores); f: constant (depend on material maturity); C: constant (depend on material quality, material composition, position)

In this research, the value of C is zero. The model only is valid for specimen age range of 7 until 14 days, with less than 15% error, and until 28 days with less than 50% error. The observation results of deformation of all SG were shown in Fig. 3.

4.1.2. Data Analysis

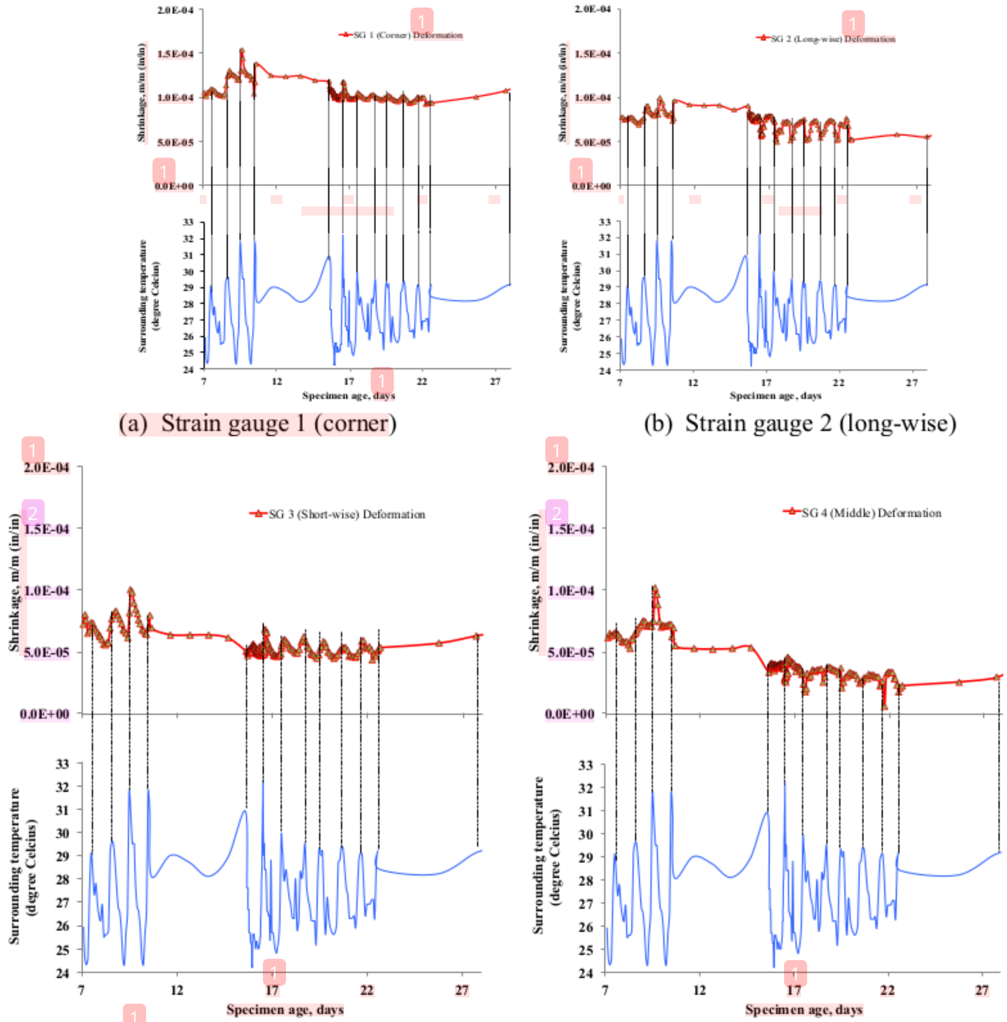
Relationship between surrounding temperature and deformation was done until specimen age of 28 days. The relation ship was shown in Fig. 4.

Surrounding temperature and humidity enter the concrete through the pores. There are distinctions times (delay time or t_d) to reach peak of deformation from peak of surrounding temperature (Fig. 4). Delay time is depending on pores network. The delay time range of all SG was shown in Table 2.

Table 2 – Range of delay time

Position	Range of delay time, days		Position	Range of delay time, days	
	7 – 15 days	15 – 28 days		7 - 15 days	15 - 28 days
SG 1	0 – 0.25	0 – 0.25	SG 3	0 – 0.25	0 – 0.25
SG 2	0.08 – 0.29	0 – 0.25	SG 4	0 – 0.33	0 – 0.17

Determination of t_d value for making this model is done by trial and error until minimal error was occurred. The values of t_d were obtained 0.153, 0.25, and 0.08 days (Table 3). t_d was affected by network of pores, number and size of open pores. Network of pores, number and size of open pores also affect the infiltration of the SRH. The magnitude of the error at each position and time can be seen in Figure 6.



(a) Strain gauge 1 (corner) (b) Strain gauge 2 (long-wise)

(c) Strain gauge 3 (middle) (d) Strain gauge 4 (short-wise)

Fig. 4 – Relationship between concrete deformation-surrounding temperature, (7 – 28) days:

High inner humidity triggers silica bridge to grow optimally. If the growth of silica bonds is faster, the concrete will mature rapidly. The value of f in Equation 1 indicates the maturity of the concrete. Factor f also obtained by trial and error. From this description it is known that there is a relationship between t_d and f (Table 3). A large f value indicates a close relationship between ambient temperature and deformation, the number of pores connected to the surroundings is quite large, meaning that the silica bond that blocks the entry of temperature is not much, which means that the concrete in the area is immature. The growth of silica bonds depends on the ability of the ambient humidity to enter the concrete. In the corner, there is a collision of humidity forces that enter from 3 sides (top, 2 angled sides), as a result the silica bonds that are not strong will break and pores will occur again. In short-wise the impact is not as much as the corners, so the humidity around is easy to enter and the concrete is more mature. In many concrete slabs in the field, cracks or broken are common at the corners.

The factor f and t_d for minimum error can be seen in Table 3.

Table 3 – Material maturity level factor (f) and delay time (t_d)

Specimen age	f & t_d for minimum error			
	SG 1 corner	SG 2 long-wise	SG 3 middle	SG 4 short-wise
7 - 15 days	0.004 & 0.153	0.00308 & 0.153	0.00286 & 0.153	0.0025 & 0.153
15 - 28 days	0.00383 & 0.153	0.00222 & 0.25	0.00208 & 0.25	0.000909 & 0.25

Constanta f ranging from 0.0025-0.004 has a t_d value of 0.153; while the f value < 0.0025 the t_d value is 0.25 (Table 3). From these data, it can be concluded that there is a relationship between the maturity of concrete and the network of pores, the number and size of open pores or the more mature the concrete, the factors are related to the network of pores, number and size of open pores are lower. Factor C also obtained by similar way. C presents material quality, material composition, and position.

4.1.3. Research of Omar et al, 2008 [24]

Shrinkage temperature and RH of test condition in natural ambient using 6 cylinders specimens with 65 MPa has been observed [24]. Equation 1 only in line with research of [24] for 7 - 14 days age (Figure 5A) but not in line for age range of 15 – 28 days age (Figure 5B). In the range of 7 – 14 days, [24] have 6 data (Figure 5A), whereas this research have 49 data (Figure 4A, B, C, D). For research Omar et al [24], f value in Equation 1 is in the form of linear equation with time (t) as a function. The linear equation of f is:

$$f = 0.015226 \times t \quad (2)$$

where: t is specimen age (days). C value is equal to 8 E-06, obtained by trial and error.

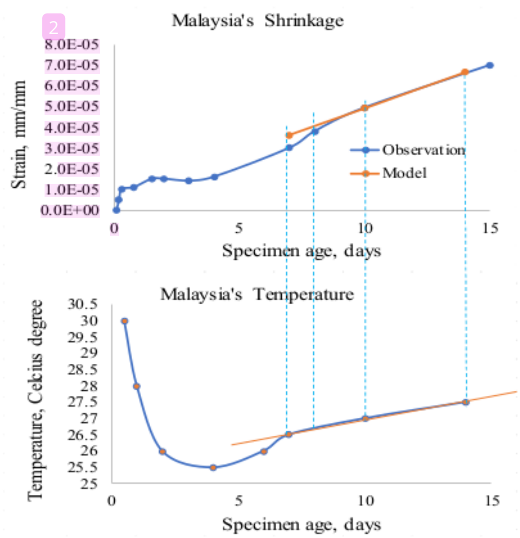


Fig. 5 – Shrinkage and Temperature in Malaysia [24] and Niken Model in this research:
(A). Range time of 7 – 14 days (B). Range time of 15 – 28 days

4.1.4. Error

Comparison between Equation 1 as a model of Niken in this research, and real deformation was displayed in Fig. 6.

The difference between the both (error) was also shown in Fig. 6, and large error was displayed in Table 4.

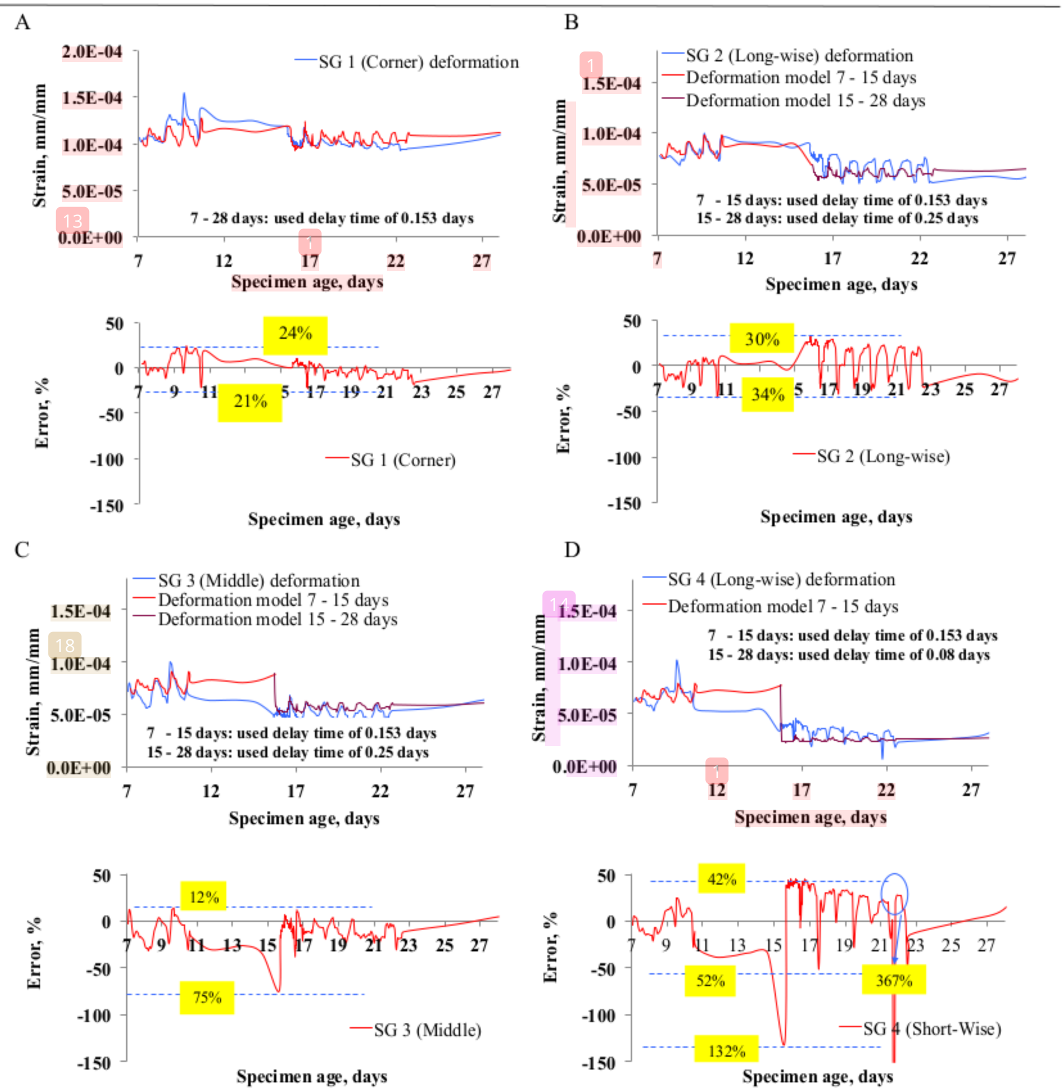


Fig. 6 – Real deformation, deformation model, and error:
(A). Strain gauge 1 (corner) (B). Strain gauge 2 (long-wise)
(C). Strain gauge 3 (middle) (D). Strain gauge 4 (short-wise)

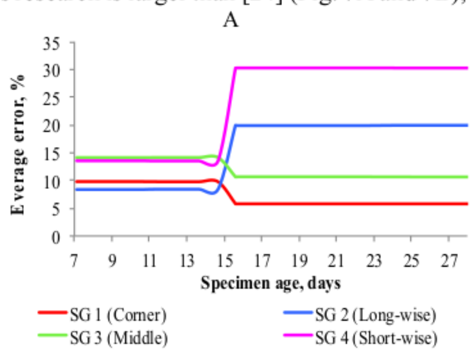
Table 4 – Large difference (error) between model and real deformation

Strain gauge	Specimen age		Error in another specimen age
	Days	Large error, %	
SG 1 - corner	16.5	19.9	< 24%
SG 2 – long-wise	17	27.2	< 34 %
SG 3 - middle	15.6	75.5	< 36 %
SG 4 – short-wise	15.6 21.7	132 367	< 50 %

Deformation data associated with the temperature amounted to 52 pieces. There is one point data in the middle (SG3) at the age of 15.6 days and two points data in short-wise (SG4) at the age of 15.6 and 21.7 (blue circle and blue arrow in Figure 6) shown a huge error (Table 4). When the data with large error is ignored, in the other hand the data received amounted to 49 pieces or 94%. This amount is considered sufficient to accept the above model with error less than 50% (Table 4). By ignoring two points data in short-wise because of its very large error, average error shown in Fig. 7A.

The error of the used of Equation 1 and 2 for Omar et al research [24] was shown in Figure 7B.

Difference between observation and model (error) of this research is larger than [24] (Fig. 7A and 7B), but the model can be used for the age range of 15 – 28 days on Niken observation (Fig. 7A) whereas for Omar et al [24], the model cannot be used because of limited observation on Omar et al research [24] (Fig. 5B).



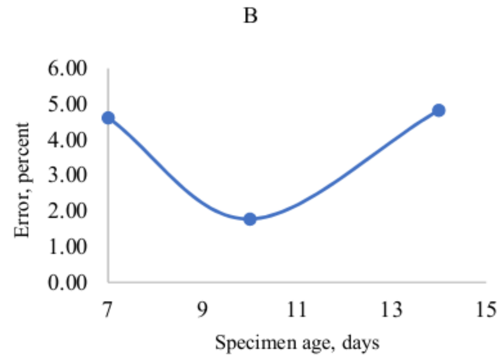


Fig. 7 – Difference between observation and model (error), (A). Niken, (B) Omar et al

4.2 Discussion

Temperatures in Jakarta (tropical weather) are more than 24°C and occur over the year with highest temperature of 32.2°C [16], while normal range temperature according to [22] is 19-24°C. In temperature of 50°C, creep strain can reach 2 - 3 times creep strain in normal temperature [22]. It can be meant, creep in tropical weather is 1 - 1.2 times than creep strain in the normal temperature, thus, deformation in tropical weather need an attention. Age 7 - 28 days, is the formation time of product hydration such as ettringite, C-S-H, C-H, C-A-F-H, monosulfat, evolution number and size of pores. In humid tropical weather, the both processes occur under the influence of high SRH and high temperature. By observing the peaks deformation and peaks of surrounding temperature in Fig. 4, the time for achievement the both peaks is almost similar; although there are some delay times. Therefore, at the time range of 7 - 28 age, deformation and surrounding temperature have a linear correlation as shown in Eq.1. The direction number of its equation, were obtained by trial. The direction numbers were called maturity material level as displayed in Table 3. Linear shape also described correlation between average slab curvature based on SG measurements and equivalent linear temperature gradient for restrained and unrestrained slabs in non-humid tropical weather [15].

The direct correlation was caused by the ease of penetration of surrounding temperature to the concrete. The air in high temperature moves more rapidly than the air in low temperature. So that, the air particles enter to the concrete through concrete pores quickly. Temperature enters to the concrete will change concrete temperature. The high temperature makes concrete particles and inner water molecules move rapidly and deformation happened.

The ease of penetration in young concrete is also affected by a lot of pores, a least and a weak of bonds which were formed; thus, error at the age of 7 - 14 days are small (Fig. 7A). The phenomenon also causes the temperature barrier still can impenetrable it by the heat energy. The high heat energy occurs together with high SRH. High heat energy makes the particles move rapidly, and high SRH leads product hydration growth rapidly. The fast growth was caused by the optimum growth of silica bridges with a lot of stable bond under the high surrounding humidity [25]. The product hydration together with inner water becomes barrier for temperature to influence particles to move, and delay time or large error happen. The more strength barriers, the more difficult for temperature to penetrate. Generally, the more difficult for surrounding temperature to penetrate, the larger error happens. Delay time was influenced by material quality, material composition, mix design, concrete maturity, wind and position in plate. The particles movement meet strong barrier at the age of 14 days because inner C-S-H were formed [26]. The consequence is, the model has a large error at the age of about 14 days, there is at the range age of 15.6 – 21 days (Table 4).

Barrier for temperature was shown larger in short-wise and long-wise at the age of 15 - 28 days. This circumstance was shown by the increase of error at the age of 15 - 28 days (Fig. 6B and 6D). Based on this discussion, the influence of temperature to concrete deformation is being dominant at early age but it is only for a shorter time range than in non-humid tropical weather.

5. Conclusion

Surrounding temperature and surrounding relative humidity (SRH) enters the pores of the concrete. Surrounding temperature has a direct correlation with concrete plate deformation. Relationship between temperature and plate deformation in humid tropical weather can be mentioned by mathematical model as shown below:

$$\varepsilon = ST_{t-td} \times f \times 10^{-5} + C \qquad (2)$$

Where: ε: plate strain (plate deformation); ST: peak of surrounding temperature at t days of specimen age, °C; t: specimen age, days; t_d: delay time between the peak of surrounding temperature and deformation (depend on network of pores, number and size of open pores); f: constant (depend on material maturity); C: constant (depend on material quality, material composition, position).

Infiltration of the SRH affects the growth of silica bridges. The stronger the silica bridge is formed, the more mature the concrete. The degree of maturity of the concrete on the slab depends on its position. The lowest level of maturity is located in the corner. The corner position has the highest *f* value (0.004) and the lowest t_d value (0.153), because of this, the edge of the plate is easy to splinter.

The model is valid for concrete plate age of 7 - 14 days with the error less than 15%, and for the age of 15 - 28 days the error less than 50%. The application of the model in the research of shrinkage in Malaysia [24] showed conformity at the age of 7-14 days with an error of 5%. The influence of temperature to concrete deformation is being dominant at early age but it is only for a shorter time range than in non-humid tropical weather.

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