Civil and Environmental Research www.iiste.org
ISSN 2224-5790 (Paper) ISSN 2225-0514 (Online)
Vol.15, No.1, 2023

Short-term Deformation Model based on Surrounding Relative Humidity of Concrete Plate under Humid Tropical Weather

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Abstract

This paper presents the deformation model based on surrounding relative humidity on one full scale concrete plate with compressive strength of 60MPa in which the concrete plate was placed on several pedestals. This research was conducted in Indonesia, a country with humid tropical weather with dry-wet conditions. A plate specimen measuring 3.00m × 1.60m × 0.15m was used for the experiment. The load was applied at the age of 14 days. The concrete plate behaviour was obtained by using four embedded vibrating wire strain gauges. The specimen was observed between 7 to 97 days of period. As a result, deformation model is similar to surrounding relative humidity reflection model. The result of Omar et al., 2008 research in Malaysia also shows a resemblance to the reflection of surrounding relative humidity (SRH) model. The deformation or shrinkage model for high performance concrete plate is $\varepsilon_t = -SRH_t.10^{-5} + SRH_{initial}.10^{-5}.\ f + C$. "f" is a factor of initial surrounding relative humidity, C is the factor related to the position, and surface area. Meanwhile, the average error in maximum deformation position is about 26.8%. A large difference indicates that the level of difficulty for humidity enter the pore network.

Keyword: Concrete, Deformation, Humidity, Plate, Shrinkage

DOI: 10.7176/CER/15-1-04
Publication date: February 28th 2023

1. Introduction

Concrete behavior (shrinkage and expansions) is an important factor in designing of building. Shrinkage in concrete is influenced by several factors such as temperature, humidity, time, mix design, material characteristics, curing processes, and specimen geometry (Dey et al., 2021; Pecker, 2020). Wet curing also allows a total elimination of the shrinkage in the first 28 days (Szlachetka et al., 2021). Moisture migration causes drying-shrinkage is a major concern in cementitious materials and can lead to a high probability of cracking, resulting in a deterioration in long-term performance and serviceability (Tran et al., 2021). Concrete behavior towards absolute volume change is still faced with uncertainties in terms of chemical and physical reaction at different stages of its life span, starting from the early time of hydration process, which depends on various factors including surrounding environmental conditions (Elzokra et al., 2020; Lentzkow, 2018). Higher temperature, wind speed, and lower humidity affected interlayer properties of concrete negatively (Niu et al., 2020). Degradation of material due to moisture content and temperature was obtained (Latief, 2019). Shrinkage and creep will decrease as the ambient humidity increases, and the relative humidity will have a greater impact on the early creep (Li et al., 2019). Over the past 30 years, several models have been proposed for the prediction of drying shrinkage, creep, and total strains under load. The best method to modelled concrete deformation is by involving the interaction process between its material elements and environment. Relative humidity plays a critical role in concrete creep. When cement is added to fly ash, the processes that occur are hydration processes and pozzolanic reactions, both of which are influenced by the surrounding relative humidity (SRH). SRH always changes and in areas with humid tropical weather changes in SRH are a daily dry-wet cycle. This adds to the difficulty in modeling the deformation. A model is chosen as the compromise between accuracy and ease of use.

Concrete is a porous material, as a consequence, it is easy for ambient moisture to enter it; thus, surrounding relative humidity influences concrete behavior from casting, before and during load is applied and its quality.

Indonesia, is a country with high relative humidity and high fluctuation of it over the year (Figure 1). Figure 1a and 1b were obtained by investigating temperature and humidity in the morning and in the afternoon which describes the dry-wet humidity cycle per day. The research was held from November 2009 to December 2011, at the University of Indonesia, Jakarta, Indonesia (humid tropical climate).

A. Jakarta B. New York

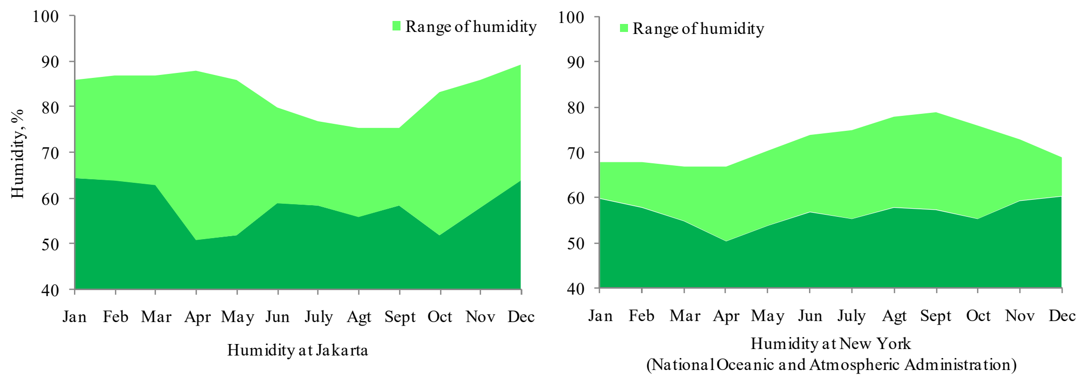


Figure 1. Relative humidity at Indonesia and New York.

A. Jakarta B. New York

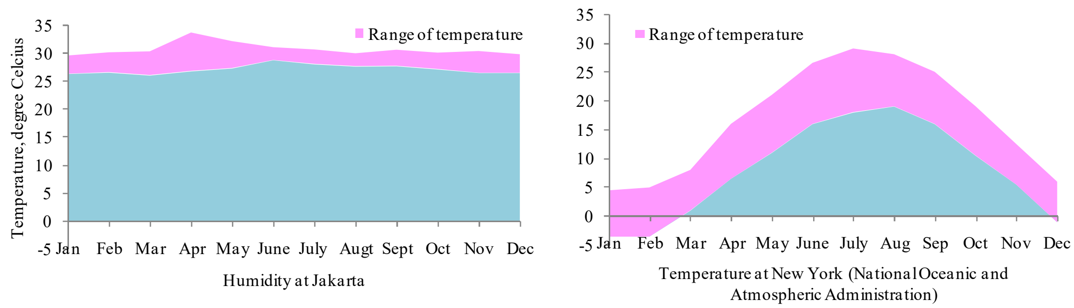


Figure 2. Temperatures in Indonesia and New York.

The irreversible shrinkage strain was developed when the specimen was dried up to less than 80% relative humidity (RH), while other previous experiments in literatures showed that the shrinkage strain between 40% RH and 11% RH is reversible (Maruyama et al., 2021). Indonesia does not reach 80% relative humidity for only 3 months of the year (Figure 1a). It means that for 9 months in Indonesia there has been reversible shrinkage. Relative humidity equal or lower than 55% could lead to relatively large damage index and high cracking risk in concrete (Gao et al., 2020). Figure 1 shows that Indonesia experienced the lowest humidity of less than 55% for ±4 months. This causes unstable deformation properties and the risk of cracking also needs to be watched out for.

Both the creep strain and the deflection of specimens under cyclic humidity conditions exhibit approximately linear tendencies that are obviously less than those of specimens exposed only to natural air. During certain wetting cycles, the deformation rate became slower and the creep strain even recovered with an increase in the humidity, especially for shorter wetting-drying cycles. The findings included rather large errors between the predicted results and experimental data when the average relative humidity was adopted in the analytical models (Li & He, 2018).

Relative humidity, concrete temperature and wind velocity determines rate of evaporation (Lentzkow, 2018). This evaporation results in a change in volume or shrinkage (Namita, 2020). The difference in humidity between the top, middle and bottom layers of the slab, can cause humidity warping stress of the pavement slab. To suppress this moisture bending stress, internal curing with super absorbent polymer has been investigated on the pavement plate (Yu et al., 2020; Yang et al., 2019). Total long-term deformation or movement in concrete is highly dependent on time, humidity and temperature (Mohammad, 2018). Relative-humidity effect is considered to be more important in volume change than temperature (ACI 209R, 1992).

The relationship between shrinkage and relative humidity has been studied by Zhang et al., 2012 (Figure 2). Changes in relative humidity are made by wetting and drying. The samples used were 60 x 100 x 350 mm for concrete quality of 30 and 50 MPa and 40 x 100 x 350mm for concrete quality of 80 MPa.

The shrinkage in the wet and dry cycle conditions is a reflection of the relative humidity cycle. The range of the humidity is 70-90%, thus; it can be said that the specimen is in a humid environment (Figure 2). From this research, it can be said that there is an approximately relationship between the surrounding relative humidity and deformation.

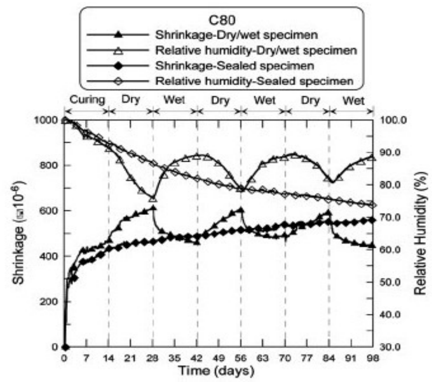


Figure 2. Relationship between shrinkage and relative humidity (Zhang et al, 2012)

In view of engineering applications, such a correlation is critical in prediction and prevention of shrinkage-induced cracking in concrete structures under drying and wetting alternating environments. Very few references are found in the literature on the study of the shrinkage performance of concrete during dry–wet cycles (Zhang et al, 2012).

The purpose of this study was to find the relationship between concrete deformation and surrounding relative humidity (SRH) in actual conditions or dry-wet conditions.

2. Materials and Methods

This research was conducted in Jakarta, Indonesia, with humid tropical weather. It was performed experimentally using one specimen with a dimension of 3.00m × 1.60m × 0.15m placed on several concrete cylinders in horizontal position. Four embedded vibrating wire strain gauges (SG) as shown in Figure 3 were installed. SRH and temperature are monitored with a thermo-higrometer.

Concrete with a target compressive strength of 60 MPa and a slump flow diameter of 35±2 cm was applied (Figure 3). The plate was casted at 10.10 pm local time with an ambient temperature of 25.4 Celsius degree and SRH of 94%. The plate was placed on several pedestals of a 0.15 m diameter concrete cylinder with horizontal position at a distance of 0.30m.

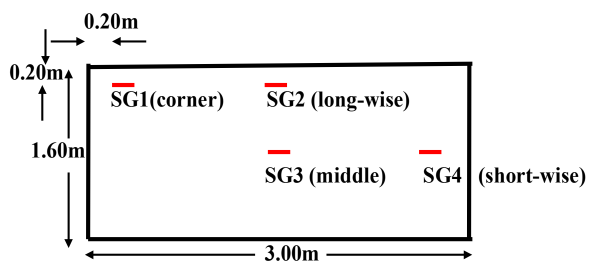


Figure 3. The scheme of plate and the placement of vibrating wire embedded strain gauges (SG)

2.1. Materials

The mix design was conducted with a limit of 500 kg/m^3 cement content to meet the shrinkage material factor closest to 1 (ACI 209R, 1992). Ordinary Portland Cement (OPC) produced by Indocement Ltd was used. The condition of the aggregate was SSD. The mix composition is OPC 500kg/m^3, silica fume 40kg/m^3, water 142.6kg/m^3, sand 800kg/m^3, coarse aggregate 935kg/m^3, and HRWR 7.6kg/m^3.

2.2. Methods

Shrinkage was measured as strain change against time by installing four embedded vibrating wire strain gauges (SG) in the specimen (Figure 3). The observation was ended when the concrete was in 97 days. The specimen was cured after the mold of concrete was removed (one day after casting) by covering wet sacks over the specimen to the age of 7 days. After this treatment, the specimen was left in direct contact with surrounding relative humidity and temperature but with protection against raindrops.

The observation was performed right after pouring using a readout as follows: days 7 - 10, every 2 hours; days 10 - 14, one time a day. Two beams of 3.00m × 1.60m × 0.20m of dimension were cast on the plate at the age of 14 days. Creep then occurred on the plate. Fourteen days were closest approach to the real load application on a rigid pavement in Indonesia. The observation was performed right after the applied load as follows: specimen age days 14 - 16 every 15 minutes; days 16 - 17, every 60 minutes and days 17 - 22, every 2 hours; days 22 - 97, every ± 35 hours. Surrounding relative-humidity and temperature are recorded at the same time.

2.3. Data Analysis

Data from each SG is processed separately because SRH penetration mechanism at each position in the plate is different (Niken et al., 2018), therefore; the four deformation values are not taken as a statistical value. Although based on one data at each position, this value is reliable because it is taken from a full-scale sample with a calibrated tool.

SRH data is taken once during the day and once in the afternoon which shows a cycle. This humidity data was checked for correctness by checking the presence of humidity in the range according to Figure 1 which was obtained based on observations for 2 years at the same location. The SRH value and time are taken in the middle of two consecutive observations although this choice resulted in a large error (Yu et al., 2020). This was chosen because the reversible deformation at the highest SRH was very different from the lowest SRH.

The SRH pattern is compared with the four patterns of the four SGs. The relationship of deformation in each strain gauge to the SRH graph was estimated base on assumption as mentioned above and a mathematical model was made using an excel program. The required parameters are obtained by trial and error and the smallest deviation is chosen. It is reasonable because this parameter depends on the position and pore network of the capillaries at the site.

The result was compared to creep research in Malaysia by Omar *et al*., 2008. The creep observation used 6 cylinders 100 mm Ø ×300 mm high of dimension. The specimens were moist cured and tested in ambient (humid tropical weather) with compressive strength of 65 MPa.

3. Result and Discussion

3.1. Result

The observation result of surrounding relative humidity, surrounding relative humidity model and deformation model is displayed in Figure 4.

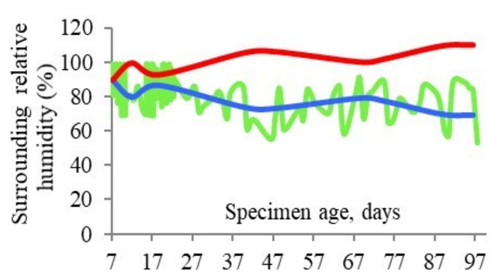


Figure 4. Surrounding relative humidity (SRH) (green), SRH model (blue), SRH reflection model (red)

The deformation model based on SRH was shown in Equation 1.

$$\varepsilon_t = SRH_{initial}.10^{-5}.\ f - SRH_t.10^{-5} + C \quad (1)$$

Where:

ε_t : plate strain at t

t : selected concrete age, days

SRH_t : SRH at time t, %

$SRH_{initial}$: initial SRH at the time- frame, %

f : correction factor of $SRH_{initial}$ by trial

C : material constant by trial

Figure 4 shows the deformation model as the reflection of the SRH model.

To determine the correction factor "f" and "C", the deformation data in peak and valley were chosen. The observation times are 7, 12.1, 18.5, 48.1, 69, 75, 89, and 96.7 (days) as shown in Figure 5. $SRH_{initial}$ was taken from the SRH pattern at 7 days. Correction factor "f" and "C", are shown in Table 1.

Tabel 1. Correction factor "f" and material constant "C"

Strain gauge		f	C
No	Position		
1	Corner	0.975	0.000075
2	Long-wise	0.25	0.00064
3	Middle	0.273	0.000595
4	Short-wise	0.26	0.0006

Application Equation 1 for all positions in plate are displayed in Figure 5

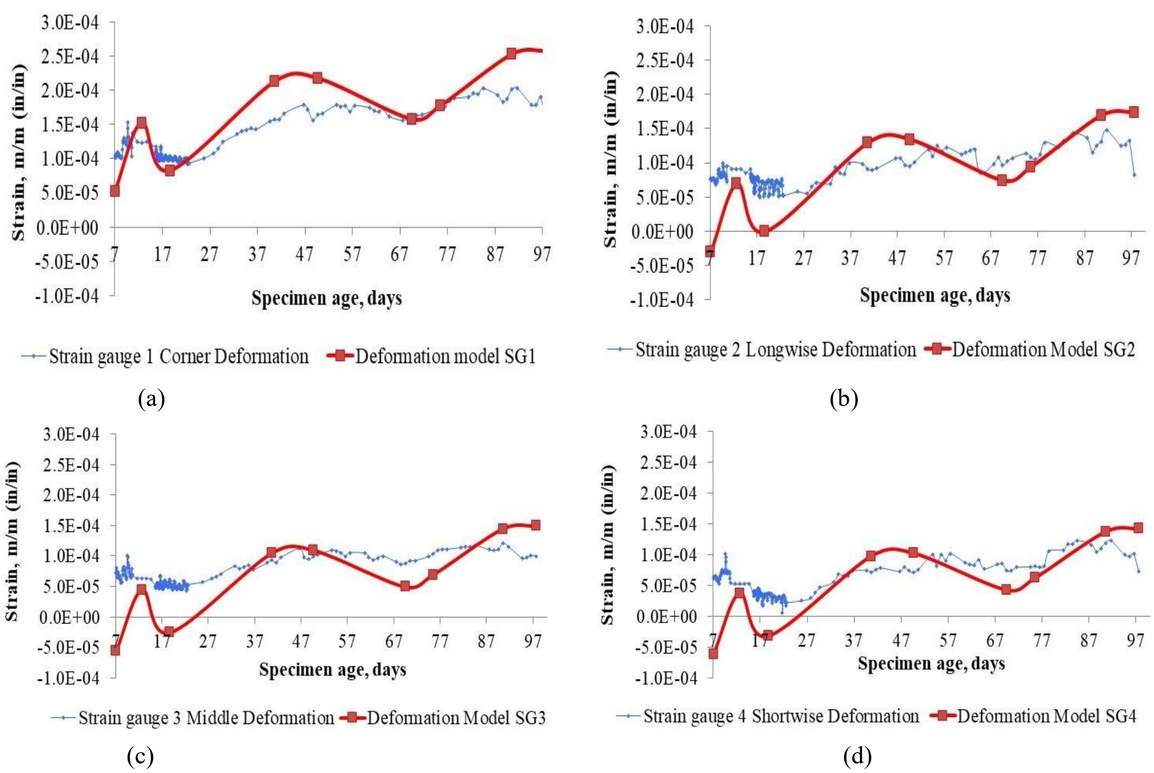


Figure 5. Deformation and its model: (a) SG 1 (corner); (b) SG2 (long-wise); (c) SG 3 (middle); (d) SG4 (short-wise)

The difference between model and observations (error) was displayed in Figure 6.

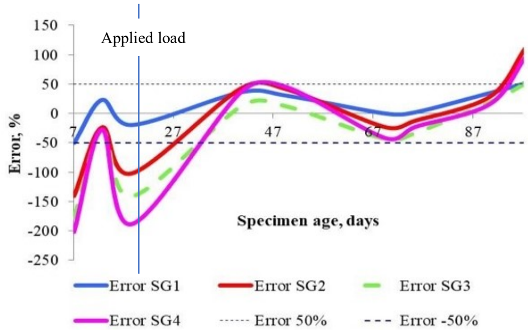


Figure 6. Error between observation and model.

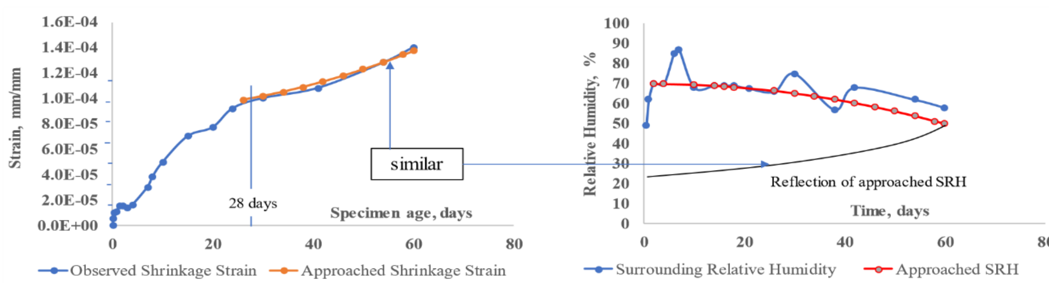
3.2. Discussion

3.2.1. SRH reflection model

Deformation in dry-wet cycles and sealed conditions as shown in Figure 2 is a reflection of the relative humidity of the surroundings (Zhang et al, 2012). Relative humidity during wet to dry conditions can drop in the range of 15-35% (Figure 1). A drop of humidity lead counteracts concrete shrinkage by hydrating cement (Aghdam et al, 2019). High fluctuations of SRH will influence the inner water movement.

SRH model as shown in Figure 4 was obtained from the mid-point of SRH. It does not depend on high and low SRH fluctuation. In low SRH fluctuations, it is possible to have the same pattern with areas of high SRH fluctuation. Taking 1 SRH value for 1 cycle with a wide range of values contains a weakness, namely simplifying the difference mechanism in deformation when SRH is high and SRH is low.

As found by Zhang et al, 2012 in Figure 2, the deformation model was also a reflection of SRH model (Figures 4 and 5). This SRH model also conforms to Omar *et al*, 2008 research (Figure 7a and 7b).



(a) (b)

Figure 7.a: Shrinkage of HSC in Malaysia (Omar *et al*, 2008) approached shrinkage model by Author;

b: SRH (ambient) in Malaysia (Omar et al, 2008) approached SRH model by Author

Size and observation intensity of SRH. Cylinder specimen (Omar *et al*, 2008) has less surface area than a plate. For 7 to 60 days, number observation in this research is 246 (Figure 4) whereas Omar *et al*, 2008 is 12 (Figure 7b).

Figure 4, 5, 7 and deformation model in Equation 1 and Figure 2 shows how strong the relationship between deformation and SRH was; so; the discussion will be emphasized on the change of concrete inner humidity (IH).

3.2.2. Basic concept

Concrete pores become the entrance of water contained in the surrounding air. There are about 500 m^2/cm^3 pores in concrete (Bažant & Wittmann, 1982). The cement paste pore content can reach ± 30% as shown in Figure 8 (Holzer et al, 2006).

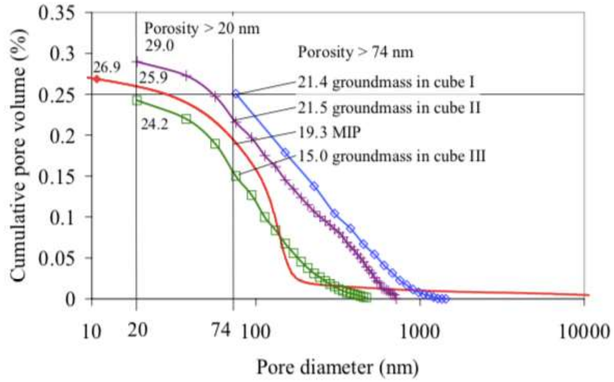


Figure 8. Pore size distribution (PSD) of 28 days old cement paste (Holzer et al, 2006)

This condition makes the surrounding air containing water easily enters the concrete entering the capillary pore and move to all parts of the concrete. This phenomenon occurs because all capillary pores are connected and down to several phaenograins as schematic illustration shown in Figure 9 (Holzer et al, 2006). SRH's touch of un-hydrated cement through phaenograins triggers the hydration process.

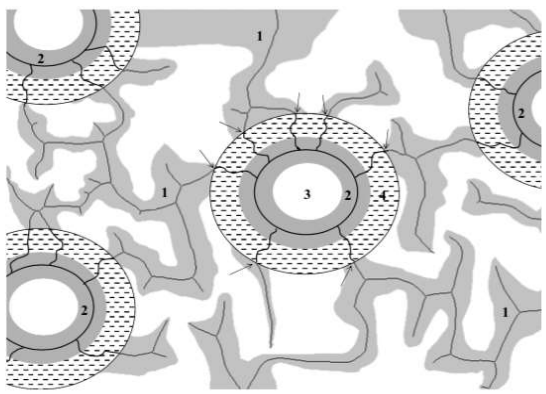


Figure 9. Schematic illustration
(Holzer et al, 2006)

Notes:

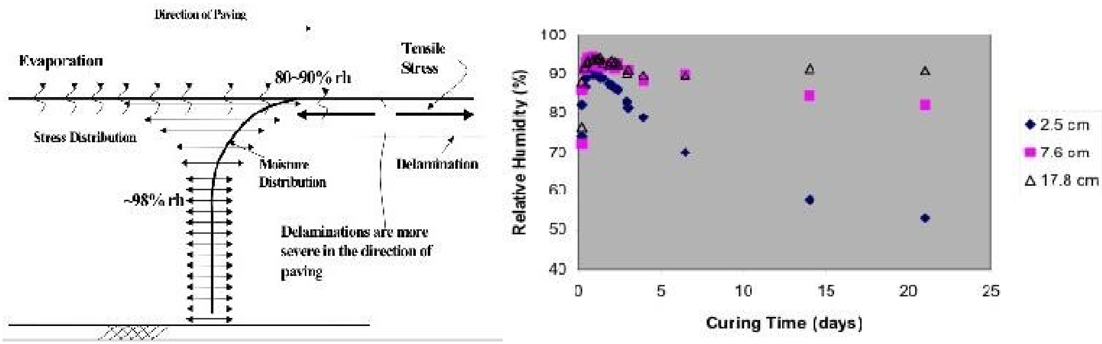
1: the capillary pore in the groundmass, 2: the phaenograins with porous zone, 3: unhydrated clinker, 4: dense hydration layer

High humidity over the year makes concrete conditions always like moisture curing. Curing will increase silica growth, determines CSH morphology, and form stable binders in large numbers (Termkajornkit & Nawa, 2006). The increase in the number of stable binders occurs in harmony with SRH penetration. This hydration process will change inner stress by product hydration growth, and capillary tension. This phenomenon gives rise to deformation. This process occurs until the un-hydrated clinker no longer exists.

This phenomenon occurs in humid tropical weather areas. In non-humid weather, this mechanism does'n not occur, thus, the mechanism for shrinkage is different.

3.2.3. Inner humidity, expansion and contraction

SRH enters to the concrete were distributed and changes IH. Figure 10 shows two studies of inner concrete moisture distributions (Mukhopadhyay et al, 2006; Wang & Zollinger, 2000). IH near the top surface of the specimen decreased substantially for 21 days of measurement due to the high level of evaporation attracted especially to a depth of ± 2.5 cm from the surface as shown in Figures 10a and b. This situation causes high tensile stress that can trigger delamination (Figure 10a). At a depth of more than 2.5 cm, the pore evaporation experienced significant obstacles due to passes through several phaenograins.



(a) (b)

Figure 10. Moisture distribution: (a) formation of horizontal delamination (Wang & Zollinger, 2000); (b) Moisture distribution and curing time (Mukhopadhyay et al, 2006)

The distribution change IH which was affected by curing time (Figure 10b). By assuming the material and curing method between this research and Mukhopadhyay et al, 2006 are similar, IH of the slab is about 80% in 7.5 cm depth at 7 days (Figure 10b). With high SRH over the year, IH can be assumed always ± 80% in the middle of the slab. This condition leads to silica bridges as a binder of product hydration, growth optimally (Termkhajornkit & Nawa, 2006). High IH leads a lot of attractive interactions between two surface water film. More water film thickness, more disjoining pressure (Derjaguin & Churaev, 1978). Water film thickness always changes according to IH; therefore, deformation was also by product hydration growth and disjoining pressure change.

Loss of water by evaporation (Figure 10a) from hardening concrete is referred to as drying shrinkage. Concrete exposed to ambient conditions undergoes drying shrinkage where some of it not reversible caused partly by the high fluctuation. This causes surface tension which results in deformation.

The shrinkage of the hardened cement paste is a direct result of its desorption isotherm. The relationship between the desorption isotherm and the relative humidity in the hydrating cement paste is primarily controlled by the pore size distribution (nanopores to micropores).

There are several hydration models to describe the microstructure of cement paste, but desorption and self-drying isotherms are not direct outputs of these models as they are usually given as constitutive inputs (Mazaheripour, 2021).

3.2.4. Deformation model

Visually the deformation model is similar to the reflection of the SRH pattern. The mathematical model as shown in Equation 4 was made based on it. The deformation model needs a point to start. The point to start was correlated to the activation energy which is depended on w/c. Initial shrinkage as a manifestation of activation energy is considered to be shrinking at the age of 7 days because it is time in direct contact with SRH.

Initial shrinkage is approximated as $SRH_{initial}$ with the correction factor "f". $SRH_{initial}$ is the same for all positions. The correction factor "f" is added as an adjustment to the absorption of SRH. Correction factor "f" was obtained by trial that gives the smallest error. The value of correction factor "f" of Equation 4 is similar for middle, short-wise and long-wise are about 0.26 as shown in Table 1 but in the corner position the "f" value is 0.975. That means in the corner, the energy associated with SRH is the greatest and leads CSH grows optimally. The corner position shows the smallest error (Figure 7).

Constanta "C" was included to accommodate other factors besides SRH. Constanta "C" in the corner is also the smallest (0.000075); whereas, in another position, the C value is about 0.0006 (Table 1). Without "C" value, concrete deformation is only dependent on SRH. The smaller C value is a greater correlation between SRH and deformation.

3.2.4. Difference between observation and model

IH in each place is different, which causes the hydration process that occurs is also different. Thus, the wider a specimen, the more varied the deformation values that occur. Unlike other types of data values, this deformation data has a close relationship between the data and local conditions that influence each other. Because the SRH condition taken is the average value in 1 cycle, it does not reflect the mechanism that occurs in each position. This results in a considerable deviation between the model and the observations. The weakness of this model is that it is unable to adapt to the deformation due to the difference in height of fluctuations.

Large errors (more 50%) may occur at the age of 15 - 35 days or 21 days after the load is applied. The large difference between the model and the observations that occurred in this study was stated above by Li & He, 2018 when the average relative humidity was adopted in the analytical models (Li & He, 2018). The difference (error) in corner position (SG1) is similar at the range of 7 – 97 days in the range of 0-50% (Figure 6). This means, corner position has the closest relationship between deformation and SRH. Plate deformation in the corner shows the greatest value compared to other locations. This error is met by other positions at the age of 40-97 days. The average error in the age range of 40 – 97 days is ± 26.8%.

The application of the model on the reset results of Omar *et al*, 2008 shows that the differences in the model and data are smaller than this plate specimen (Figure 6 and 7). This is because Omar's specimens are cylindrical so that the SRH penetration does not reflect the difference in position. Observations of humidity in the study of Omar *et al*, 2008, did not show a cycle of relative humidity in every day.

4. Conclusion

Relative humidity in Indonesia (humid tropical weather) is a dry-wet cycle every day. The relationship between deformation and SRH has been investigated under conditions of relative humidity with the actual dry-wet cycle. Concrete contains many extraordinary pores. This makes humidity all around easy to enter it. Continuous penetration of SRH throughout the year occurs in the humid tropical weather area make concrete under curing condition over year.

Penetration of SRH into the specimen continuously causes the inner humidity in the specimen to continuously change and differ in every vertical and horizontal position.

The depth and distribution of SRH penetration depends on the amount, position, pore network of the concrete and the value of SRH itself which is always changing. The difference in surface area in contact with the surroundings causes differences in SRH penetration at each position, especially for large contact areas such as plates. This makes the deformation model based on SRH on the plate has a large difference in several positions.

If the penetration of SRH touches the unhydrated cement, a hydration reaction occurs and forms hydration products. This hydration product will change the pore network, pore water tension, disjoining pressure and change further SRH penetration.

Deformation occurs due to the growth of hydration products, pore water stress and disjoining pressure, all of which are related to SRH. Thus; there is a mighty relationship between SRH and deformation. This process continues until the unhydrated cement is used up.

The relationship is expressed in a model which is a reflection linear function of SRH. The relationship in the form of reflection was also shown in the research of Zhang *et al*, 2012 on beam specimens with an environment conditioned to have a dry-wet relative humidity cycle (Figure 2).

This model is suitable for predicting the largest shrinkage that occurs at the corner of the plate with the difference between the model and observations (error) ± 26.8%. For other positions, this model has an error > 50%. Because it is suitable for the largest deformation of the plate, this model can be used as a reference in designing plate deformation. The model is also in line with Omar *et al*, 2008 research using cylindrical specimens (Figure 7).

For future research, the relationship between ambient humidity in humid non-tropical areas can be sought.

5. Acknowledgements

We would like to thank the University of Lampung and Universitas Indonesia for the full support of this research. Our endless gratitude is for Dr. Eng. Josia Irwan Rastandi and Mr. Apri for his infinite support. Our deep gratitude to Indocement Ltd and Sika Ltd for their materials support.

6. Author's note

The author declares that there is no conflict of interest regarding the publication of this article. Authors confirmed that the data and the paper are free of plagiarism.

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