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One day high-performance concrete mechanism of plate, beam, and column

C Niken¹

¹ Civil Engineering Department, Faculty of Technology, Lampung University, Bandar Lampung, Indonesia

chatarinaniken@yahoo.com

Abstract. Plate, beam, and column have a different mechanical characteristic. Understanding the one-day mechanism of the three concrete structural elements is the objective of this study. The quality of the concrete used is f_c' of 60 MPa. Observation of concrete strain was done during 24 hours. Five small specimens measuring of 150 mm × 150 mm × 600 mm with one strain gauges (EVWSG) for each specimen, three specimens in horizontal position as a beam and two specimens in vertical positions as a column; one full-scale beam specimen measuring of 200 mm × 600 mm × 3000 mm (four EVWSG), and one plate specimen measuring of 3000 mm × 1600 mm × 150 mm (four EVWSG) were used. All specimens were covered with styrofoam. One-day behavior was found by computing the average strain change from a small beam and column specimens, and average strain change of the fourth EVWSG in the plate/full-scale beam. As a result, there is a similar type between concrete temperature and the behavior of plate, beam, and column. The behavior of the beam is identically to the plate behavior. Column behavior is more fluctuating than beam and plate. High rate shrinkage is significant in beam and plate, but in the column, expansion was dominated.

1. Introduction

The column is a significant element structure in a building. Design of reinforced concrete for construction should be based on the strong column and weak beam. Lampropoulos and Dritsos [1] has stated that biaxial stress will reduce the strength of the column. Axial load and shrinkage reduce stiffness, and column strength. Dimensions and presence of reinforcement were affected the shrinkage. Nevertheless, the standard specimen for shrinkage test is beam (ASTM C157/C157M-17) [2]. The difference between beam and column behaviour was determined by the both early age behavior. Because at the early age expansion dominates column behavior, in long-term period shrinkage in column become smaller than in beam [3]. Based on beam specimen, Yahia [3] mentioned that early age cracking does not depend on compressive strength of concrete (f_c'). These cracks will reduce long-term performance.

Plate and rigid pavement have a largest surface than another element structure. Plate behaviors is the most influenced by surrounding. The factors that influence early-age shrinkage are hydration, relative humidity, self-desiccation, environment factor, water to cement ratio, curing methods, and admixture [5].

In the first one day, the behavior of specimens with covering plastic or styrofoam does not influenced by environment. Water in the air can't penetrate to the concrete. Water is the main factor in hydration process and shrinkage mechanism. The amount of water was calculated carefully in concrete mix design. Some countries have concrete mix design procedures and calculations such as Bureau of



Indian Standards-I.S.10262-2009, American (ACI) method, and Indonesian standard SNI 7656-2012 [6-10]. To maintain the amount of water for the hydration process in accordance with the mix design, it is appropriate to cover the concrete immediately after pouring. Consequence of it, autogenous deformation occurs in the specimen, because autogenous deformation is a shrinkage or expansion without external influences. Right after cement meet with water, chemical reaction occurs. Temperature which appear by this reaction creates physical mechanism. Therefore, in one day age chemical, physical and autogenous shrinkage occur. It is challenging to separate chemical, physical and autogenous shrinkage because they are happened simultaneously.

The first behaviour is expansion and shrinks in macro volume. If the hydration process occurs under lack of water, many pores become empty and change concrete microstructure, such as decreasing space for hydration. The influence of the empty capillary pore is the reduction of internal relative humidity (70% for w/c less than 0.3). The reducing relative humidity process will increase capillary pore water pressure (σ capillary). The pores solution and its radius meniscus influence the magnitude of the pressure. The quality of matrix to be decrease. The consequence is aggregate restrains autogenous shrinkage which occurred in cement paste [11]. High-performance concrete (HPC) is concrete with high strength and durability. HPC makes the element structure becomes smaller than normal concrete, while column need great stiffness. Therefore, the use of HPC to be a crucial of tall building. HPC can only be made with a limited amount of water generally equal or smaller than 0.36; so, not all cement is hydrated; and the matrix does not contribute to the modulus of elasticity. Modulus of elasticity is more influenced by aggregates. Based on this reason, autogenous shrinkage is the major behavior in HPC, while in normal concrete drying shrinkage is a major deformation [3]. In high-strength concrete autogenous shrinkage almost similar to drying shrinkage [12]. In the fact, beside shrinkage, there is expansion in the concrete. The young concrete should be able to handle the two types of deformation which happen alternately to avoid early cracking.

The limited water for hydration and cementitious material influences inner humidity, micro prestresses, degree of hydration and interface structure; therefore, fluctuation of expansion and shrinkage was also affected. Wu et al. and Yahia [4,13] were also studied the influences of limited water and cementitious materials. Chemical and autogenous shrinkage causes self-desiccation because delayed ettringite formation [4]. Due to the limited water-to-cement ratio, HPC develops higher early-age shrinkage which lead initial crack. The initial cracks are easily growth because of self-desiccation. To reduce the risk of random cracking and joint raveling, saw-cutting should be done in rigid pavement in rigid pavement at early age [14].

Aly and Sanjayan [15] was observed the mechanism of early age shrinkage of concrete based on the reason phenomenon that shrinkage at early ages are found to increase with increased curing. Mechanism behavior in one-day age of plate, beam, and column which was has varies size need to study. Size determines of the drying rate. Characteristic of concrete is a strong non-statistical size effect on both the structural strength and on the rate of creep and shrinkage. The size effect is now widely acknowledged to be a serious issue even in the ACI code-making committees, ACI 318 and 445 [16]. Safety factors for quasi-brittle structures should significantly increase with structure size [17].

Understanding of one-day mechanism in column, beam, and plate with laboratory and full-scale specimens give a useful contribution in treating and designing concrete correctly to meet excellent performance and structure safety. Treatment delay time can make raveling, spalling, and random cracking in the concrete surface. The treatment determines the quality and resistance of structural elements to weather and loads throughout service life. Proper treatment can only be done if the behavior of each type of structural element is well understood.

2. Experimental program

The research was conducted in Jakarta, Indonesia, with humid tropical weather.

2.1. Specimens

This research was performed experimentally using one specimen of 3000 mm × 1600 mm × 150 mm as a plate (Fig. 1a), three specimens of 150 mm × 150 mm × 600 mm as a laboratory-scale specimen with one embedded vibrating wire strain gauge (EVWSG) per specimen (Fig. 1b); two specimens of 150 mm × 150 mm × 600 mm in vertical position as a column with one EVWSG per specimen (Fig. 1c), and one full-scale specimen of 200 mm × 600 mm × 3000 mm as plate (Fig. 1d). The shrinkage in the beam center was affected by the maximum deflection. Based on this study, the position of the EVWSG was at the end of the beam, 5 cm for laboratory-size of beam and column (Figure 1a) and 70 cm for the full-scale specimen (Figure 1b). HPC with a target compressive strength of 60 MPa and slump flow diameter of 35 ± 2 cm were used.

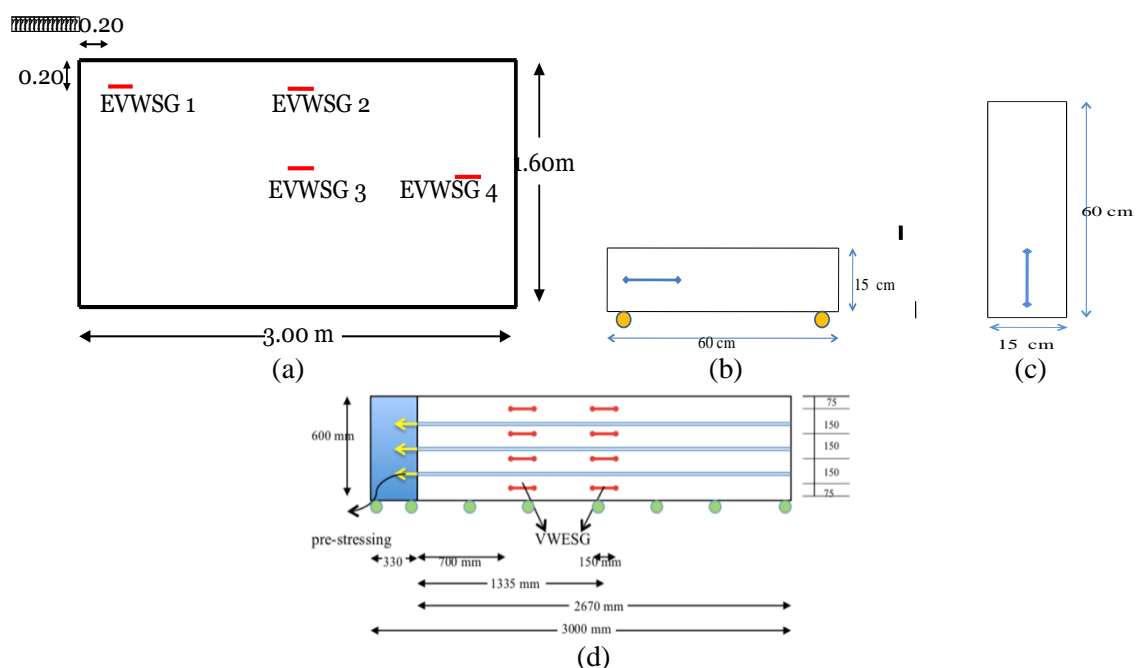


Figure 1. Specimens and placement of EVWSG: (a) Plate, (b) Laboratory-scale beam specimen, (c) Laboratory-scale column specimen, (d) Full-scale beam specimen

2.2. Materials

The mix design was conducted in compliance with ACI 211.4R (1993) with a limit of 500 kg/m³ cement content to meet the shrinkage factor closest to 1 (ACI 209R, 1992). Ordinary Portland Cement (OPC) produced by Indocement Ltd was used. The condition of the aggregate was saturated surface dry (SSD). Fine aggregate in the form of river sand was brought from Sungai Liat (Bangka, Sumatra, Indonesia), specific gravity (SSD) was 2.605, and absorption was 0.4%. The sand had been filtered and cleaned using a mixture of standard graphs obtained from the mid-gradation. Fine aggregate shall be free of the injurious amount of organic impurities (American Society for Testing and Materials International, 2002). Coarse aggregate in the form of volcanic rock fragments was obtained from Banten, West Java, Indonesia. The composition of the coarse aggregate used was 70% sized 13 - 19mm, specific gravity (SSD) of 2.563, absorption of 1.543%, and 30% sized 6 - 12mm, a specific gravity of 2.636, and absorption of 2.26%.

The added material used was silica fume of 8% cement weight, produced by Sika Indonesia Ltd. To achieve the inclination high strength with a low ratio of water to cementitious material and excellent workability, polycarboxylic super plasticizer under the commercial name Visco Crete 10 from Sika

Indonesia Ltd was added to the concrete mix at the high range water reducer (HRWR). A dose of HRWR of 1.4% cement weight was added according to that generally used in Indonesia. The local water was supplied by the Structure and Material Laboratory of Universitas Indonesia. An electrical scale was used for cementitious material and water to obtain the accurate ratio of water to cementitious material.

The mix composition was 500 kg/m³ of OPC, 40 kg/m³ of silica fume, 142.6 kg/m³ of water, 800 kg/m³ of sand, 935 kg/m³ of coarse aggregate, and 7.6 kg/m³ of HRWR. During the concrete mix design stage, all of the aggregates were assumed to be an under SSD condition. A tilting drum mixture with a 0.3 m³ capacity was used. The mixing started with all cementitious material in a dry state, followed with 50% fine aggregate. Subsequently, 50% of water was added to the revolving mixture. Then, these materials were mixed for approximately 1½ minutes. Next, 50% of water was slowly poured in, which was homogenously mixed with HRWR. After that, 100% coarse and 50% fine aggregate were added. With all the materials placed according to their order into the mixer, the concrete was mixed for approximately 3 minutes. The slump flow of the mixture was measured before pouring by using an Abrams cone upside down.

2.3. Methods

In this research, shrinkage was measured as strain change against time by installing one EVWSG in each beam and column specimen, and four EVWSGs in a full-scale specimen and plate (Figures 1a and 1b). The EVWSG was able to detect the strain up to 3000 µε with an accuracy of about .025% and concrete temperature between -80oC and 60oC with about .5% accuracy. Right after casting, specimens were covered with styrofoam to eliminate water evaporation (Figure 2). The observation was performed right after pouring every 15 minutes until 24 hours using a readout.



Figure 2. Styrofoam covers the specimens for one day

Data of the three beam laboratory size specimens were analyzed using Dixon's criteria as the standard practice for dealing with outlying observation. ASTM E 178-02 [18] has mentioned that Dixon criteria, based entirely on ratios of differences between the observations may be used in cases where it is desirable to avoid calculation of standard deviation or where quick judgment is called for. For a Dixon test, the sample criterion or statistic changes with sample size. The equations of the Dixon criteria for 3 to 7 samples with $x_1 \leq x_2 \leq \dots \leq x_n$ are as follows:

- If smallest value is suspected:

$$r_{10} = (x_2 - x_1) / (x_n - x_1) \quad (1)$$

- If the largest value is suspected:

$$r_{10} = (x_n - x_{n-1}) / (x_n - x_1) \quad (2)$$

Using Equations 1 and 2 for data at ages with a significant difference of shrinkage from the three specimens were computed. Shrinkage of laboratory-size specimens was found by using an average of accepted data. Shrinkage of the full-scale specimen was observed by using the average value of all

EVWSG. The largest of all beam specimens was preferred to reach high safety although Dixon's criteria were used. Column behavior was taken from the average strain changes that occurred in the two specimens. Plate and full-scale beam behavior were made from the average strain changes that happened in all EVWSG in the specimen.

Beam temperature was preferred from the full-scale beam. The temperature in the full-scale beam and plate were taken from the average temperature that occurred in all EVWSG in the specimen. The column temperature was taken from the average temperature that occurred in the two specimens.

By using a literature study, the one-day behavior of plate, beam, and column mechanism can be obtained.

3. Results and discussion

3.1. Result

Data of the three beams laboratory size specimens were analyzed using Dixon's criteria as the standard practice for dealing with outlying observation can be seen in Niken [3]. One day behaviour of plate, beam, and column can be seen in Figure 3a, the inner temperature of the three elements structure and surrounding temperature shown in Figure 3b.

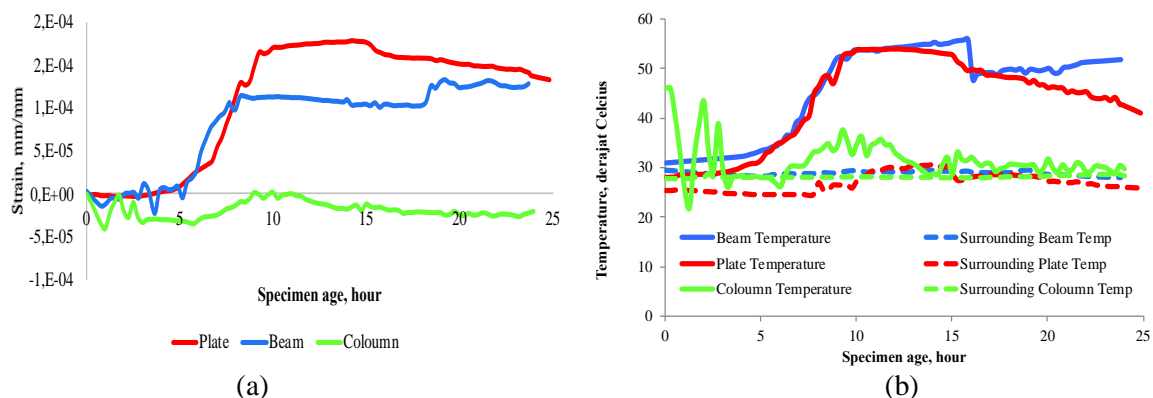


Figure 3. (a) One day of plate, beam and column, (b) Inner temperature in plate, beam and column and surrounding temperature

One day behavior of the plate, beam and column has similar type to its inner temperature. Inner temperature type of beam is identical to the plate, while internal column temperature shows fluctuation type (Figure 3a and 3b).

3.2. Discussion

Lura and Wyrzykowski [13] have studied the use of low water-to-cement ratio and silica fume in HPC. The both makes internal relative humidity decrease. If no extra water is available for cement hydration, all pore water is progressively consumed. This condition occurs in concrete element with is sealed. Decreasing internal relative humidity leads self-desiccation because the growth of CSH need high internal humidity. Emptying pores leads the increase of capillary pores tension and because of its, external volume contraction become increase. Autogenous deformation to be a major factor with w/c less than 0.40. The change of a part of the water to be a chemically bound in product hydration makes deformation in concrete. Inner temperature, energy, molecules velocity, density and momentum can't be separated from the chemical reaction. The chemical and physical are interrelated. The both bounds water has smaller specific volumes than free water. Contrary to drying shrinkage, autogenous shrinkage occurs without any loss of moisture from the concrete [13].

Internal temperature appears from the hydration process; all concrete behavior follows temperature pattern (Figure 3a, 3b). Inner temperature in plate, beam, and column are higher than its surrounding temperature, with the except at 15-24 hours, the inner temperature of column is equal to surrounding

temperature (Figure 3b). Klemczak and Wroble [19] were studied concrete deformation using macroscopic and microscopic phenomena. The macroscopic behavior such as temperature, volume, pressure and mass some time can't be explained deeply concrete deformation mechanism. The good explanation of the mechanism depends on well-known microscopic phenomena. Although the average interatomic spacing is constant, the atoms are in continual vibration; thus, a spring model is useful in some instances. Spring model does permit us to depict the effect of atomic vibration, thermal expansion, activation energies, and other properties. On the basic of the spring model of interatomic forces, it is easy to see how elastic waves travel through solids. By elastic waves, heat is conducted through opaque solids. It will be noted that the spring is non-linear because of the "spring constant" under compression increase rapidly [20]. Particles in the column were under pressure by its weight. The nonlinearity of spring in the column and hydration process caused high fluctuation of temperature and shrinkage (Figure 3a and 3b).

Figure 3a shown there are two types of behaviors: shrinkage (uphill curve) and expansion (decreases curve). Expansion in autogenous deformation is not due to retarder or the increase of bellite in cement, but it was led by re-absorption of water at the start of the cement setting process [21]. At the range time pf 0-5 hour, significant expansion occurs in the column (Figure 3a). At that time solution and dispersion, process occur [22], CH and ettringite formed [23], optimum Ca^{2+} from alite reaction occur [24] and the number of pores decreased slightly [23]. Solution and dispersion process, ettringite, and Ca^{2+} lead a volume expansion. The axial stress alters the interstitial sites. This movement permits additional strain because the lattice distortion is reduced. Axial stress occurs in the column by its weight. Consequently, additional strain occur and the expansion in the column is more significant than in the beam and plate. Inner temperature in column more fluctuating than in plate and beam (Figure 3b). C-S-H begins to form at the age of 3 hours with the rate increase until the period of 28 days. During 3 – 10 hour, the shrinkage rate is high and reaches the highest value for one day of observation. Shrinkage in the column shows the lowest value because of abnormally expansion phenomenon due to chemical reactions that occurs under pressure which inhibits shrinkage due to the formation of C-S-H. Inner temperature in column much lower and more fluctuating than in plate and beam, but with similar pattern. After 15 hours, inner temperature in column similar to surrounding temperature.

At the age of 10 hours, C-S-H begins to thicken [25]. When the layer of C-S-H becomes sufficiently thick, the diffusion process occurs, and the porous layer of hydrates covers the surface of the anhydrous cement. The volume of the formed C-S-H is larger than the initial volume of C3S. The fact that the topochemical reaction of the anhydrous product may lead to swelling. According to these data, the volume of C-S-H represents 155% of the volume of the cement anhydrous [26][27]. Capillary stress by emptying pores caused expansion. As a result of this mechanism, autogenous behavior in beams and plates shows a balance between shrinkage and expansion which is shown as a flat line, while in the expansion column it dominates (Figure 3a).

Marušić and Štirmer was mentioned that autogenous shrinkage is a function of compressive strength as follow

$$\varepsilon_{ska\ 1} = 0.0046 f_{cm} - 0.2821 \quad (3)$$

$\varepsilon_{ska\ 1}$ is autogenous shrinkage of concrete at one day of age (10^{-3} or mm/m), f_{cm} is mean compressive strength of concrete at 28 days tested on a 15 cm cube (MPa).

By using Equation 3, autogenous shrinkage is equal to 0.0002476. This value has not been reached by all three specimens. The maximum autogenous shrinkage in the plate, beam and column is 70%, 50% and 0,8% of Equation 3 respectively.

4. Conclusion

One day behavior of plate, beam, and column showed a similar type to its inner temperature. There are two types of the one-day behavior: shrinkage and expansion. Shrinkage caused by product hydration growth, and expansion caused by dissolution and dispersion, ettringite, Ca^{2+} , the topochemical reaction of un-hydrous product and special in column plus reducing lattice distortion. One-day deformation in

beam and plate almost has similar values, while in the column the autogenous is smaller and more fluctuating than in beam and plate. The minor deformation in the column due to shrinkage by-product hydration growth held by swelling abnormally because the chemical reaction occurs under pressure reducing lattice distortion. Column fluctuation caused by the change of interatomic spacing modeled by the change of “spring constant” due to domination of shrinkage and expansion take turns quickly by the own column weight and product hydration growth.

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