EARLY – AGE SHRINKAGE OF HIGH -PERFORMANCE CONCRETE BEAM
IN LABORATORY AND FULL-SCALE

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Early – Age Shrinkage of High-Performance Concrete Beam in Laboratory and Full Scale

Chatarina Niken (Corresponding author)
University of Lampung, Jl. Sumatri Brojonegoro No 1 Bandar Lampung, Indonesia
Tel: +6281329055304 E-mail: chatarinaniken@yahoo.com

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Abstract

The beam is a major element structure in bridge and high - rise building. The aim of this study is to obtain the difference of early age shrink age between beam with laboratory scale and full scale. High-performance concrete with compressive strength of 60 MPa were used. This research was done experimentally in Indonesia during 24 hours. Three pieces specimens measuring laboratory size of 150 mm × 150 mm × 600 mm, and one specimen measuring 200 mm ×600 mm ×3000 mm as full - scale specimen were used. All specimens were covered with styrofoam to eliminate transfer humidity. Early age shrinkage was obtained by using an embedded vibrating wire strain gauge for each laboratory size specimen and four embedded vibrating wire strain gauge for full scale specimen. As the result the shrinkage type of full- scale specimen is similar type to laboratory size. Shrinkage in laboratory size specimen is 31.5% larger than in full-scale specimen. Maximum shrinkage in full scale specimen is about 0.8E-04 occurs at the concrete age of 15.8 hour, while in laboratory size specimen is about 1.255E-04 occur at the age of 22.2 hour. Fluctuation expansion and shrinkage is smoother in full-scale than in laboratory size specimen. This is because in full scale ettringite can expand more optimally so that it can with stand shrinkage losses due to the growth of hydration products. High rate deformation of the both specimens scale is occur in the age range of 5-9 hours. Therefore, it is safe to assume the behaviour of real beam of high-performance concrete similar to laboratory size beam.

Keywords: Beam, Concrete, Early, Shrinkage, Size

1. Introduction

Understanding of early ages behaviour is very important and useful for the design of durable and sustainable structures (Klemczak and Wroble, 2011). Volume change of concrete resulting from structural and environmental factors are the acceptable phenomenon. In reality a volume changes commences immediately after the cement and water come in contact during concrete mixing. Shrinkage of concrete takes place in two distinct stages: early and later ages. The early stage is commonly defined as the first day, while the concrete is setting and starting to harden. Later ages, or long term, refers to the concrete at an age of 24 hours and beyond (Bažant, 2012).

These early age volume changes are typically ignored in design of concrete structures since their magnitude can be much less than shrinkage resulting from drying. But even when the concrete curing condition are ideal, the first day shrinkage can significantly contribute to the ultimate shrinkage and thus the cracking risk

(Bažant, 2012). The difference of long-term deformation in column sand beams is in their early-age deformation behavior (Niken et al, 2017). Cutting at rigid pavement should be done at the age of 5-8 hour to prevent early or micro cracking. Early cracking can growth to macro–crack. Nonuniform residual stresses relaxing due to creep and microcracking affects average shrinkage of cross-section of long members (Hubler et al, 2015).

The major insident at the early age is hydration. Hydration is a chemical process. Chemical process always correlated to volume change. It is merely a result of the internal chemical and structural reactions of the concrete components. Enough water for this process is really important; thus, no moisture transfer should be avoided. Autogenous shrinkage is a volume change resulting when there is no moisture transfer to the surrounding environment. Moisture movement caused by capillary condensation was thought to be the cause of flexural strength reduction for sealed specimens (Tazawa and Mujazawa, 1995). Effects of water-binder ratio on autogenous shrinkage was studied (Zhang et al, 2015). Autogenous shrinkage is usually a concern in high strength or high performance concrete (> 40 MPa or 6000 psi) where there is a low water-to-cement (w/c) ratio. The shrinkage was well correlated to the cements' chemistry and the development of internal capillary pressure within the cement paste (Holt, 2001).

Autogenous shrinkage has a different physical mechanism and is important for modern high-performance concrete (HPC), very and ultra-high-performance concrete with admixtures, additive and low water-cement ratio. Some admixtures which were able to reduce autogenous were found (Tazawa & Miyazawa 1, 1995). Paillere et al, 1989 was found that in very high-strength silica fume, concrete undergo early cracking when deformation is restrained. This phenomena attributed to an intense autogenous shrinkage of the concrete exceptionally low w/c (0.26).

Admixture and additive generally used in making self-consolidating concrete (SCC). Early autogenous shrinkage of self-consolidating concrete was also published (Li and Li, 2014). Long et al, 2011 was studied autogenous shrinkage of prestressed SCC. Soliman, 2011, have studied early-age shrinkage of ultra-high-performance concrete. Jun et al, 2011 was developed an autogenous shrinkage model base on chemical shrinkage and interior humidity reduction. The model agree well with experimental measurement of autogenous shrinkage in early age normal and high strength concrete.

Concrete as quasi-brittle structures, fail at the macro-crack initiation which can appear from the microcrack growth. The characteristic is a strong non-statistical size effect on both the structural strength and on the rate of creep and shrinkage (caused by size dependence of the drying rate). This kind of size effect is by now universally accepted by the IA-FRAMCOS and by the Engineering Mechanics Institute of ASCE, and also by the ACI Committees 446 (Fracture Mechanics) and 447 (Finite Element Analysis) which, unfortunately, have almost no say on the ACI design code formulation. The size effect is now widely acknowledged to be a serious issue even in the ACI code-making committees, ACI 318 and 445 (Hubler et al, 2015). The size dependency of the fracture energy and the effective length of fracture process zone of concrete determine as per the Bažant size effect method and RILEM work-of fracture methods (Rao, 2013). Safety factors for quasi-brittle structures should significantly increase with structure size (Bažant, 2012).

Beam is the major element structure in frames and bridges. Beam failure causes fail of bridges. Base on the mention above, the research of difference early age behaviour between laboratory size specimen and full scale is needed especially for high-performance concrete.

2. Experimental Programme

The research was conducted in Jakarta, Indonesia, with humid tropical weather. This research was performed experimentally using 3 specimens of 150 mm × 150 mm × 600 mm for flexural test according to ASTM C78-08, with one embedded vibrating wire strain gauge (EVWSG) per specimen and one full scale specimen of 200 mm × 600 mm × 3000 mm. The shrinkage in the beam centre 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 (Figure 1a) and 70 cm for full scale specimen (Figure 1b). HPC with a target compressive strength of 60 Mpa and slump flow diameter of 35 ± 2 cm were used.

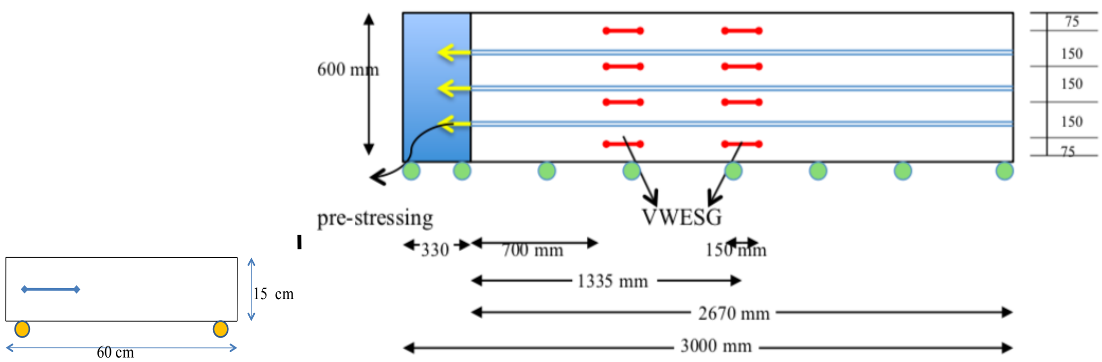


Figure 1: (a) Laboratory size specimen; (b) Full scale specimen

2.1 Materials

The mix design was conducted in compliance with ACI 211.4R (1993) with a limit of 500 kg/m^3 cement content to meet theshrinkage 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 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, specific gravity of 2.636, and absorption of2.26%. The added material used was silica fume of 8% cement weight, produced by Sika Indonesia Ltd. To achieve the desired high strength with low ratio of water to cementitious material and good work ability, poly carboxylic super plasticizer under the commercial name Visco Crete 10 from Sika Indonesia Ltd was added to the concrete mixas the high range water reducer (HRWR). A dose of HRWR of 1.4% cement weight was added according to that generally used in Indonesia. Local water was supplied by the Structureand Material Laboratory of Universitas Indonesia. An electrical scale was used for cementitious material sand water to obtain the accurate ratio of water to cementitious material.

The mix composition was 500 kg/m^3 of OPC, 40 kg/m^3 of silicafume, 142.6 kg/m^3 of water, 800 kg/m^3 of sand, 935 kg/m^3 of coarse aggregate, and 7.6 kg/m^3 of HRWR. During the concrete mix design stage, all of the aggregate was assumed to be under saturated surface-dry condition. A tilting drum mixture with a 0.3 m^3 capacity was used. The mixing started with all cementitious material in a dry condition, followed with 50% fine aggregate. Subsequently, 50% water was added to the revolving mixture. Then, these materials were mixed for approximately 1½ minutes. Next, 50% water was slowly poured in, which was homogenously mixed with HRWR. Thereafter, 100% coarseand 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 up side down.

2.2. Methods

In this research shrinkage was measured as strain change against time by installing one EVWSG in each specimen, and four EVWSGs in full scale specimen (Figures 1a and 1b). The EVWSG able to detect the strain up to 3000 με with an accuracy of about .025% and concrete temperature between -80^{o}C and 60^{o}C with about .5% accuracy. Right after casting, specimens were covered with styrofoam to eliminate water evaporation (Figure 2).

(a) (b)

Figure 2. Styrofoam were covered specimen: (a) Laboratory size specimen, (b) full scale specimen

Observation was performed right after pouring every 15 minutes until 24 hours using a read out. 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 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 $x_1 \leq x_2 \leq \ldots \leq x_n$ are as follows.

If smallest value is suspected: $r_{10} = (x_2-x_1)/(x_n-x_1)$ (1)

If largest value is suspected: $r_{10} = (x_n-x_{n-1})/(x_n-x_1)$ (2)

Using Equations 1 and 2 for data at ages with large difference of shrinkage from the 3 specimens were computed. Shrinkage of laboratory size specimens was found by using average of accepted data.

Shrinkage of full scale specimen was found by using the average value of all VWESG.

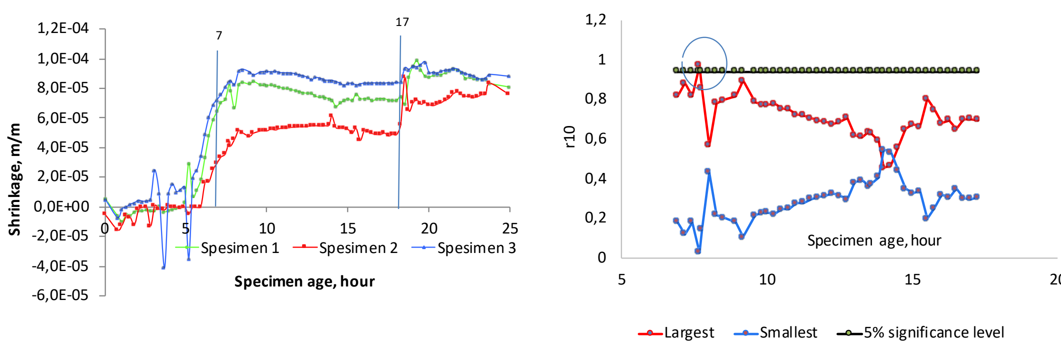
The both shrinkage were compared and by using literature study the conclusion can be obtained.

3. Result

The results of research from laboratory size specimens are presented separately and then the mean results are presented together with the results of full-scale processing.

3.1. Shrinkage of Laboratory Size Specimens

From the third specimen, large different shrinkage value occurs at the age of 7-17 hour (Figure 3a). By using a 5% significance level, we anticipated both suspects: largest and smallest. Age range of 7-17 hour was selected because at this age the shrinkage difference is large (Figure 3a). By anticipating both suspects, the r_{10} graph may appear fluctuating and oppositional (Figure 3b).



(a) (b)

Figure 3. (a) shrinkage of three laboratory specimens, (b) Outlying graph

There is one data from 94 data or one percent is over the 5% significance level (Figure 3b); therefore, all of the data were used to define the shrinkage of laboratory size specimen by using average value.

3.2. Shrinkage of Laboratory Size and Full - Scale Specimens

Comparison of early age behavior which are happen in laboratory size and full - scale specimen can be seen in Fig. 4.

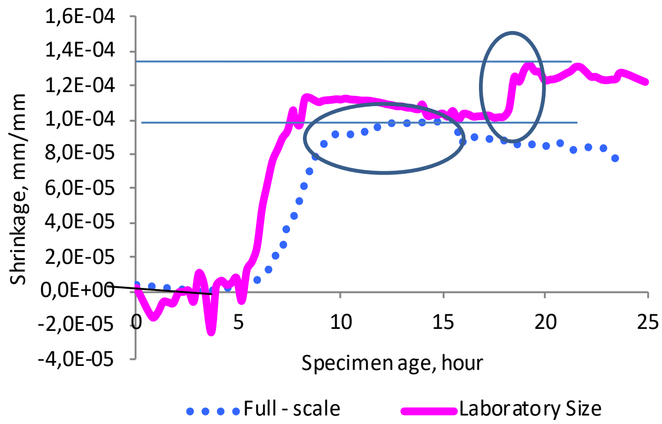


Figure 4. Early age behaviour in laboratory size and full - scale specimens

4. Discussion

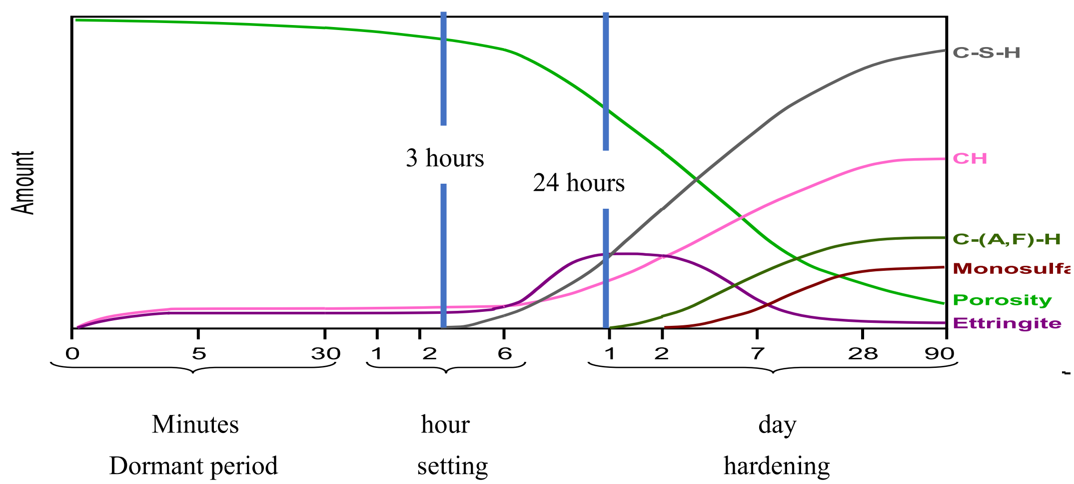
Early–age shrinkage in full - scale specimen is smaller than in laboratory size specimen, but with smooth curve. Fluctuation between expansion and shrinkage in laboratory specimens is more than in full scale specimen (Fig. 4). The phenomenon represents the change of the macroscopic behaviour of concrete directly related to the modification of the internal material structure, which, in turn, is due to the evolution of nano- and micro-scale physical mechanisms and chemical reactions.

Right after cement, silica fume meet with water, dissolution and diffusion occur. Particles scattered and expansion volume occur. It leads chemical reaction process. Chemical reaction rate depend on concrete age. Two main early- age reactions can be identified: cement hydration–the reaction of free-water with un-hydrated cement particles, and silica-fume reaction; the reaction of silica particles with portlandite or $CaOH_2$ (Di Luzio and Cusatis, 2009a). CH and ettringite were formed right after mixing (Fig. 5). The reaction makes concrete become porous media. Distribution of pores dimension including large range. Pores with minimum diameter of 0.5 nm, were formed between C-S-H gel. Morin et al, 2002 was mentioned there are two pores class. Pores with dimension of 10-20 nm start when concrete reach solid hyperstatic state and about 1-2 nm. The first was correlated to pores space of cluster hydrat C-S-H, and the second correlated to porosity of internal hydrat..

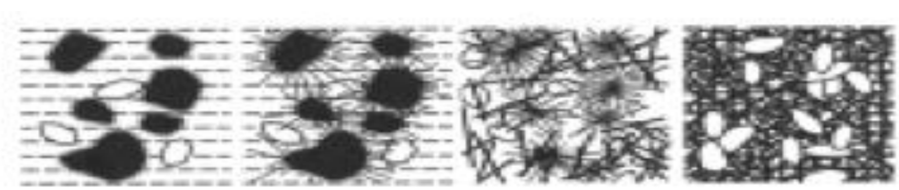
A porous media consist of a solid porous matrix saturated by one or more fluids phases. There are interactions and momentum exchanges between the fluid phases and between these and the solid skeleton (Klemczak and Wroble, 2011). Hence, part of strains is associated with the fluids-solid mechanical interactions (Klemczak and Wroble, 2011). Inter-connectivity of pores was affected by age, size and shape. Environment affects the interactions and momentum exchange.

All of specimens in this research are covered by styrofoam; therefore, porous medium is not in hygral equilibrium between internal and external environment, particles interaction and momentum exchanges occur without environmental influences. The consequence of it is mass transport of the different fluid phases and species occurs. Mass exchanges between the different phases of the system may arise (Klemczak and Wroble, 2011). Mass exchange and hydration caused micro-prestress and it lead strain in concrete. Concrete strain appear as shrinkage and expansions as a behaviour of concrete (Fig.4). The macroscopic behaviour of a porous medium is significantly connected with the microstructure of the solid matrix and with the micro-scale physics. Sometimes the macroscopic behaviour cannot be explained exhaustively at the macroscale but depends on well-known microscopic phenomena; in that case the introduction of closure relationships at the microscale can be helpful (Klemczak and Wroble, 2011).

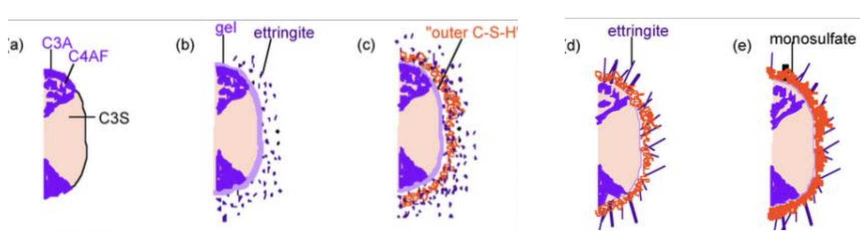
Hydration give a big contribution to concrete behaviour at early age. Hydration product growth can be shown in Fig. 5.



(a)



(b)



Un-hydrated cement 10 minute 10 hour 18 hour 1-3 days

(c)

Fig. 5. Product hydration growth and cement hydration scheme:
(a,b) Product hydration growth and concrete growth period (Kurtis, 2015),
(c) Cement hydration scheme (Taylor, 1997)

The reactions cause evolution shape and properties of material. Evolution of material properties depend on hydration degree. The early-age evolution of material properties require preliminary calculation of hydration degree, humidity and temperature (Di Luzio and Cusatis, 2009a,b). The change of temperature and inner humidity occur only by chemical reaction of cement hydration, silica fume pozzolanic reaction and silicate polymerization because the specimens are protected against external influences. The coupled effect of the chemical reaction influence moisture transport and heat transfer in the specimens. The reactions makes constituent to be solid and gradually becoming hardener according to hydration degree (Fig. 5b). The hydration degree affect volume growth of the solidifying constituent. The solidifying constituent is assumed to be age-independent and the chemical aging (Di Luzio and Cusatis, 2013).

Chemical reaction and behaviour of alite should be pay attention because approximately alite typically about 50-80% of the total cement (Kumar et al, 2012). Because of that, concrete behaviour was affected by alite hydration which was Ca^{2+} as shown in Fig. 6., and Ca^{2+} caused expansion occur in the concrete.

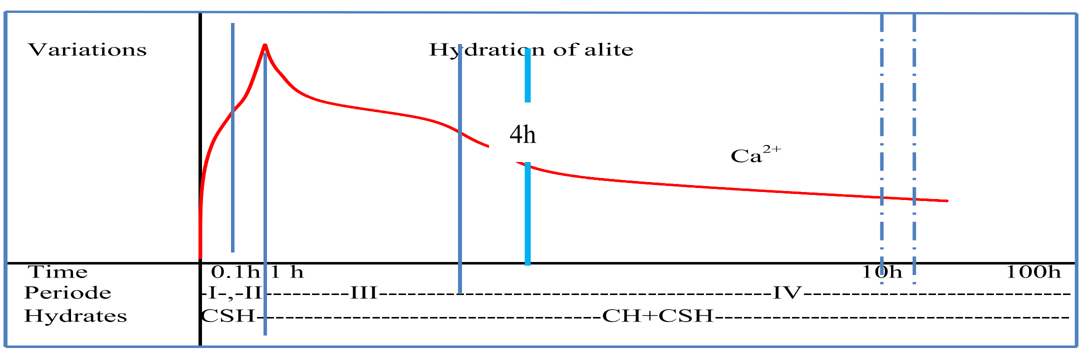


Fig. 6. Alite hydration (Paulini, 1990)

Ability of ettringite, Ca^{2+} and pressure leads concrete expansion, while product hydration growth makes shrinkage because product hydration volume is less than its ingredients (Fig. 6).

Duration of expansion and shrinkage for full scale and laboratory specimens as described in Fig. 4 can be seen in Table 1.

Table 1. Full scale and laboratory scale specimens behaviour

	Duration (hour)	Duration (hour)

Behaviour	Laboratory Scale	Full Scale	Behaviour	Laboratory Scale	Full Scale
Expansion	0.75	4.3	Expansion	9.1	
Slow rate shrinkage	4.65	2.3	Shrinkage	1.5	5.5
High rate shrinkage	3.5	3.2	Expansion	4.5	8.7

In the first hour, highest expansion can be occur because of highest Ca^{2+} (Fig. 6). This matter is fit with laboratory scale behaviour (Fig. 4). In full scale, expansion appear with low slope but with longer duration that is 4.3 hours or 5.7 than in laboratory specimens (Table 1, Fig.4). In full scale specimen, Ca^{2+} and ettringite can expand more freely than in laboratory specimen cause expand of volume to be larger than shrinkage caused by CH. The volume expansion occur until Ca^{2+} almost constant (Fig. 4). In laboratory specimens, the expansion occur only until the peak of Ca^{2+}, furthermore, shrinkage by CH dominate. At the range time of 4.75 – 6.5 hour, setting time also generally occur (Piyasena et al, 2013). At the age of 5 hour, the both type specimens has similar value (Fig.4).

In the age range of 5-9 hour, high rate shrinkage occur in the both specimens with similar duration (Fig.4 and Table 1). Ettringite reach maximum value, CSH and CH rate showing a slight increase (Fig. 5) and Ca^{2+} reach constant value (Fig. 6). Rate and magnitude of shrinkage in laboratory specimen is more than in full scale. It can be occur, because chemical reaction in full scale occur under pressure by specimen weight its self. This causes the volume develop abnormally (Van Vlack, 1973).

In the age range of 9-18 hour, full scale was shrink with low rate, and laboratory specimen was expand with low rate until reach same value at the age of 15 (Fig. 4). It can be mean, at the age of 9-15, the influence expansion by Ca^{2+} and increasing ettringite needles is smaller than shrinkage caused by the growth of outer CSH (Fig. 5b), by CH, and by decreasing pores (Fig. 5a and Fig. 6). Decreasing pores number in full scale is more than in laboratory specimen because of weight its self, makes deformation rate to be slow.

In the age of 15-20 hour, there is only one shrinkage mechanism in full scale; while in laboratory specimen there are two mechanism behaviour: shrinkage with high rate during 1.5 hours and followed by expansion. At the age of 15 hours, the rate growth of ettringite is highest, and rate growth of CSH start to increase. It makes laboratory specimen show high rate shrinkage. Expansion in the both specimen occur because chemical reaction happen under product hydration growth stress and mass transport due to decreasing pores number.

At the age of 20-24 hours, the both specimen has similar behaviour that is expansion (Fig. 4). At this time reaction of simple ions to form complex ions, or complex ions were absorbed in solid surface ettringite needles become longer and in maximum number condition. At the age, concrete start to have it strength (Fig. 5a, 5b). Reactions of generate calcium–silicate–hydrates (CSH) which is the main constituent providing stiffness and strength. Similarly, the silica-fume reaction can be described through the ratio between the amount of reacted silica-fume and the total amount of silica-fume (Di Luzio and Cusatis, 2009a). Inner CSH and silica bridges become more and stronger than before. All of the phenomenon, caused swelling more dominant than shrinkage.

5. Conclusion

Full-scale beam behaviour is similar to laboratory size specimen. Maximum shrinkage in full-scale specimen occurs at the age of 15.8 hour with shrinkage value of 0,86E-04, while in laboratory size specimen occurs at the age of 22.2 hour with shrinkage value of 1.255 E-04; therefore, shrinkage in laboratory specimens 31.5% more than full-scale. Fluctuation between expansion and shrinkage is smoother in full-scale than in laboratory size specimen. This is because expansion volume caused by Ca^{2+}, ettringite, and pressure by beam weight its self has more space so that can decrease shrinkage.

Expansion with long duration in full-scale specimens at the first hydration process occur (Table 1). Process hydration was started by dispersion and solution. The two mechanisms makes particles scatter and expand. The expansion and solution are more easy in full-scale specimen than in laboratory scale specimens. Expansion with long duration can be obtained at the end of the first day. This condition corelated with the available maximum ettringite in the end of the first day with long duration.

Shrinkage caused by CSH growth is similar for the both specimens, with larger rate and number in laboratory specimen than in full scale specimens. This condition caused by pressure from weight its self on particles which was in chemical reaction, makes expansion volume reduce shrinkage number.

It is safe to treatment real beam by assuming similar behaviour with laboratory scale specimen.

Aknowledment

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