WATER WITHIN LIGHTWEIGHT AGGREGATE CONCRETE AND ITS RELATION TO AUTOGENOUS SHRINKAGE

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Abstract
Autogenous shrinkage of lightweight aggregate concrete (LAC) has been investigated with the aims of studying if water within LAC is effective in preventing autogenous shrinkage as suggested by Bentz's model. By calculating ratios of water supplied by lightweight aggregate (LA) at various degrees of saturation to water required for maximum hydration and plotting these against ultimate values of autogenous shrinkage, it seems that only when the ratio is high (above 3.5) then the water within LAC supplied from LA is immediately ready to fill the empty pores and in turn, reducing autogenous shrinkage. The case is also confirmed when ratios of total void (porosity) of concrete to total volume of water within concrete are plotted against autogenous shrinkage.

Keywords:
autogenous shrinkage, Bentz's model, lightweight aggregate, porosity.

INTRODUCTION

In the progress of hydration concrete consumes moisture in the capillary pores when external curing is absent. This phenomenon, referred to self desiccation, bring about internal relative humidity to drop and in turn gives rise to formation of water-air menisci. The presence of menisci causes tensile stresses and as a result concrete shrinks. The shrinking of concrete instigated by self desiccation is termed as autogenous shrinkage.

Autogenous shrinkage observed in high-strength concrete could be in the magnitude of 700 microstrain (Tazawa and Miyazawa, 1994). The high magnitude of this type of shrinkage will be a source of problem in the utilisation of high-strength concrete in the structure. As the movement of structural concrete by autogenous shrinkage is restrained, it will induce tensile stress leading to cracking of concrete.

A suggestion was proposed by previous investigators for examples Kohno et al (1999) and recently Jensen et al (2001) and Bentur et al (2001) to use lightweight aggregate with the intention of reducing autogenous shrinkage. Kohno showed that the reduction depends on type, moisture content and quantity of lightweight aggregate. The explanation is that the space originally occupied by cement particles and water is gradually replaced by the space filled by hydration products. The space not taken up by solid components such as the unhydrated cement particles or hydration products consists of capillary pores. At the early stage of hardening, most of the capillary pores and most of lightweight aggregate are fully saturated with water. As the hydration reaction progresses, the capillary water are consumed to form new and fine capillary pores. However, the internal relative humidity in the capillary pores is not lowered due to continuous supply of moisture from lightweight aggregate. As a result, the cement paste does not shrink.

The relationship of moisture provided by lightweight aggregate and the amount of autogenous shrinkage reduction is of interest. Bentz et al (1999) derived an equation for determining the replacement level of normal-weight aggregate by lightweight aggregate to ensure adequate water for "complete" curing of the concrete. In this case, complete curing means that the cement reaches the maximum degree of hydration that is possible, given the space limitations for forming hydration products in low w/c ratio systems. The volume of water per cubic meter of concrete needed to be supplied by the lightweight fine aggregate (LWFA) depends on the mixture proportions of the concrete in the following manner. Let CS denote the chemical shrinkage occurring during the hydration of the cement; typically, this value is on the order of 0.06 kg H_2O per kg cement hydrated. The amount of water necessary will depend on this quantity, as well as the cement content, C_f in kg cement/m^3 concrete, and the w/c ratio for the mixture proportions. For w/c ratios below 0.40 (typical of an HPC), complete hydration cannot be achieved and the maximum degree of hydration,

α_{max}, can be estimated as (w/c)/0.40. Then, the volume of water, V_{wat} that is "consumed" during hydration due to chemical shrinkage is given by Eq. [1]:

$$V_{wat}\,(m^3 water\,/\,m^3 concrete) = \frac{C_f CS \alpha_{max}}{\rho} \quad \text{.......[1]}$$

Where ρ is the density of water (1000 kg/m^3). Denoting the porosity of the LWFA by Φ_{LWFA} and its saturation (0–1) by *S*, the total volume fraction of LWFA necessary, V_{LWFA}, is given by Eq. [2]:

$$V_{LWFA} = \frac{V_{wat}}{S.\Phi_{LWFA}} \quad \text{..........................[2]}$$

The ratio of this quantity to the volume fraction of aggregate in the original mixture proportions is the required fractional replacement by LWFA. This equation assumes that all of the water in the LWFA will be readily accessible to the surrounding cement paste. Furthermore, this equation implies that as long as internal moisture/water within concrete is higher than that consumed during hydration autogenous shrinkage will be prevented.

This research observed autogenous shrinkage of lightweight aggregate concrete (LAC) at various lightweight ggregate (LA) degree of saturation. The results are then used to clarify Bentz's model by assessing the amount of water available within LAC and that consumed during hydration in relation to the magnitude of autogenous shrinkage. The results indicate that the higher available water within LAC compared to that needed for hydration will not guarantee in preventing autogenous shrinkage. This is in contrast to that assumed by Bentz's model.

METHODS

Concrete Ingredients and their proportion

LAC investigated in this research was made from mixing of Ordinary Portland Cement, sand, LA, gravel and water at proportion listed in Table 1. Absorption characteristic of LA used thorough the research is about 13.73%.

Casting and Preparation of Specimen

Cylinder moulds made from PVC were prepared to cast concrete specimens. They were 75 mm in diameter and 275 mm in height. Inside the cylinder, a plastic sheet was attached on the cylinder wall. At least, two specimens were cast for each mix proportion. The specimens which have been taken out from the cylinder moulds were then marked at the points where the Demec points would be placed. For a single specimen eight Demec points were needed; four Demec points at equidistance of 90^o were located on the upper part of cylinder (at a distance of 37.5 mm from the top) and another four were located parallel to those of the upper at a gauge length of 200 mm. A reference bar was used to accurately set the Demec points at 200 mm gauge length. The Demec points were pasted on specimens using plastic steel paste.

Measurement of Autogenous Shrinkage

Autogenous shrinkage was measured using a Demec Gauge with resolution of 1 micron. Fig.1 shows the Demec Gauge used to test specimen. The procedure is as follows: Demec Gauge was positioned on a pair of Demec points at a gauge length of 200 mm. The reading of Demec Gauge was noted down. Five readings were taken and their average reading for that particular pair of Demec points was calculated. This average reading was considered as the representation of the true reading for that pair of Demec points. The procedure was repeated on another three pairs of Demec points on the same specimen. The average reading from four pairs of Demec points on each specimen was then calculated. The reading was taken at the age of 1, 3, 5, 7, 10, 14, 17, 21, 24 and 28 days.

Table 1. Mix proportion for producing 1 m^3 LAC used in this research

Sample Identification	Cement (kg)	Sand (kg)	LA (kg)	Gravel (kg)	water/cement ratio	LA degree of saturation %
LAC 0.6 - 100 %-0%	380.7	417.4	783	0	0.6	0%
LAC 0.6 - 100 %-25%	380.7	417.4	783	0	0.6	25%
LAC 0.6 - 100 %-50%	380.7	417.4	783	0	0.6	50%
LAC 0.6 - 100 %-75%	380.7	417.4	783	0	0.6	75%
LAC 0.6 - 100 %-100%	380.7	417.4	783	0	0.6	100%

Fig.1. Measurement of autogenous shrinkage using Demec Gauge

The change in length of the specimen was computed from the difference between the first and subsequent readings. Autogenous shrinkage was then calculated from the change in length divided by the original length (200 mm).

RESULTS AND DISCUSSION

Autogenous Shrinkage

The observed autogenous shrinkage up to 28 days is plotted against time and presented in Fig.2. The autogenous shrinkage patterns observed on all mixes suggest that autogenous shrinkage increases at decreasing rate and will finally reach ultimate value. And it is this ultimate value, which is the interest of designer. The ultimate value might be obtained after continues measurement of autogenous shrinkage which may take up to 1 year.

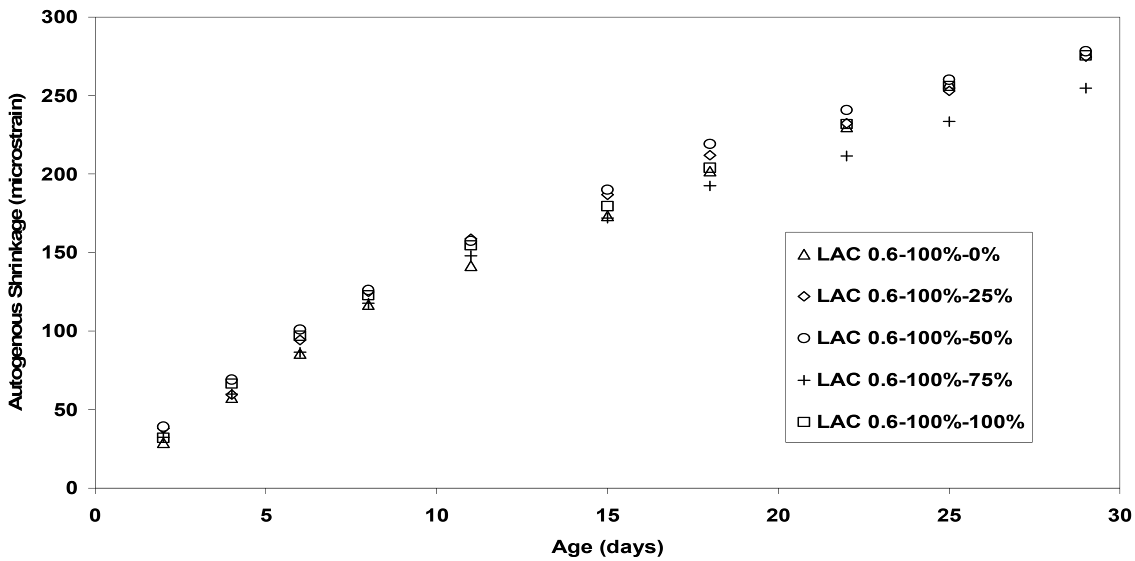

Fig. 2. Autogenous shrinkage of LAC up to 28 days measurement.

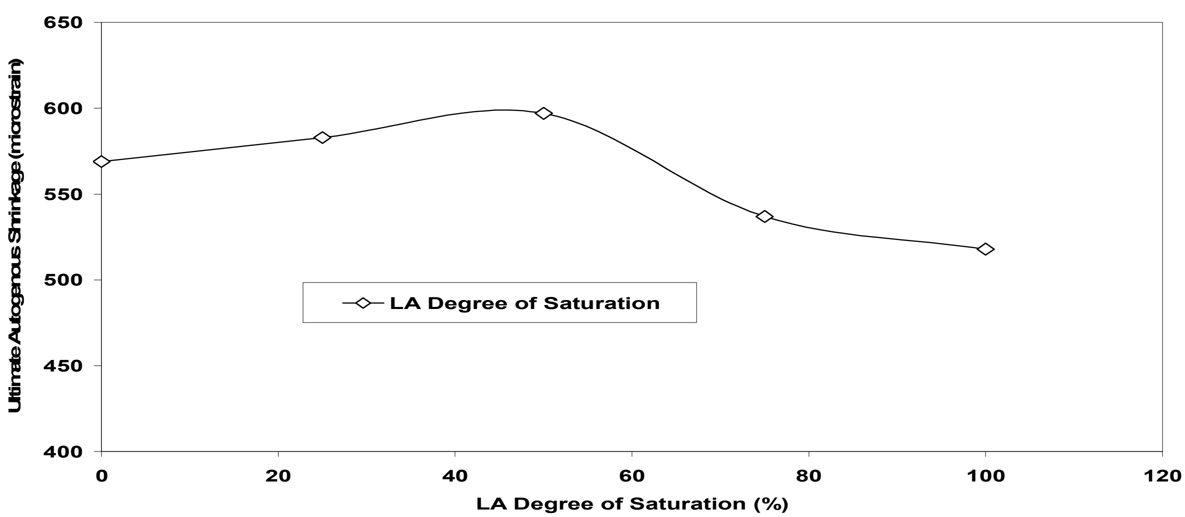

Fig.3. Ultimate autogenous shrinkage predicted by adopting ACI.209. R-92 method

To reduce the time for determining ultimate autogenous shrinkage by direct measurement, it is desirable to have shrinkage-time expression, which can be used to predict the ultimate value from short-term measurement. By adopting ACI 209.R-92 method as described in Kristiawan et al (2006) the ultimate values of autogenous shrinkage for all mixes are estimated and the results are given in Fig.3.

Ratio of Water Available from Saturated LA to Water Required for Maximum Hydration and Its Relation to Autogenous Shrinkage

Using Bentz model as described earlier, it is possible to calculate the amount of water required (V_{wat}) for maximum hydration of each mix. The water required will be assumed enough for internal curing during self-desiccation. The results of calculation are tabulated, in Table 2. The table also shows the available water from saturated water in LA (V_{WLA}). V_{WLA} is calculated by considering the LA degree of saturation. Theoretically, maximum hydration can be achieved as long as the available water is higher than that required for hydration. Giving this into consideration, most of the available water from the LA is higher than that required for hydration. capillaries tension are generated and autogenous shrinkage is expected to be low. However, this is In turn, it is expected that when hydration proceeds water pores consumed for this reaction is immediately replaced by that in the LA; there is no drop of relative humidity in the pores and as a result no not always the case as seen Fig. 4. When the ratio of V_{WLA} to V_{wat} is higher than 1, it means that the water available from LA is greater than that needed for hydration. However, the graphs suggest that from 25% to 50% degree of saturation, even though the ratio increases but the ultimate autogenous shrinkage is also increased. Only after the ratio is very high (above 3.5) the reduction of ultimate autogenous shrinkage is observed. It seems that water in LA will readily available to fill the empty pores due to self-desiccation when the ratio of V_{WLA} to V_{wat} is high.

Table. 2. Calculated water for hydration (V_{wat}) and available water from LA (V_{WLA})

Sample Identification	V_{wat}	V_{WLA}	V_{WLA}/V_{wat}
LAC 0.6 - 100 %-0%	0.022842	0	0
LAC 0.6 - 100 %-25%	0.022842	0.026876	1.176625
LAC 0.6 - 100 %-50%	0.022842	0.053753	2.353251
LAC 0.6 - 100 %-75%	0.022842	0.080629	3.529876
LAC 0.6 - 100 %-100%	0.022842	0.107506	4.706501

Ratio of Total Volume of Water to Total Volume of Porosity and Its relation to Autogenous Shrinkage

In this section, the water available for hydration is calculated not only due to that in the LA but also due to that from the original water for mixing. This water mixing is obviously dependent on the w/c ratio. The autogenous shrinkage could be prevented if the emptying pores as a result of continues hydration is refilled with water. The refilling of pores with water is possible only if the amount of water available in the mix both from mixing water and that in the LA is greater than the total porosity of concrete.

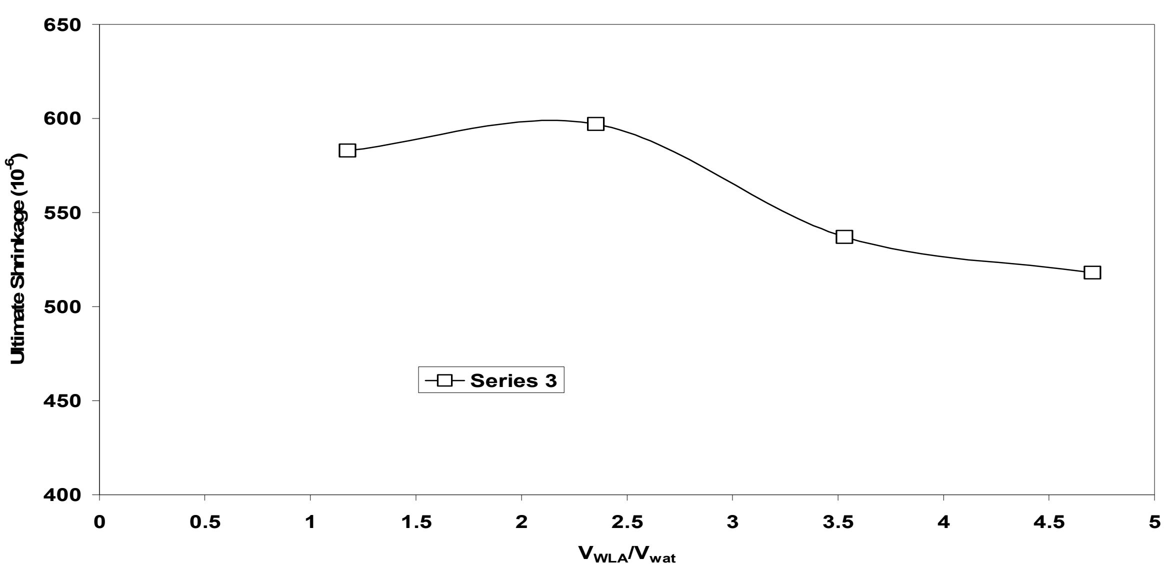

Fig.4. Relationship between ultimate autogenous shrinkage and V_{WLA}/V_{wat}

Table 3 shows total volume of water (TVW) and total volume of porosity of concrete (TVP). TVW is calculated from the amount of mixing water per m^3 concrete ($V_{w\text{-}c}$) and V_{WLA}. For example, for mix LAC 0.6-100%-100%; the cement content is 380.7 kg/m^3 concrete and w/c = 0.6. The mixing water per m^3 concrete is 0.6 x 380.7 = 228.42 kg. This equals to a volume of 0.22842 m^3. Meanwhile, the TVP consists of porosity of LA (P_{LA}) and porosity of concrete (P_c). P_{LA} is obtained from absorption characteristic of LA and P_c can be calculated using Expression 3 as follows (Neville and Brooks, 1987):

$$P_c = \frac{\frac{w}{c} - 0.17h + \frac{a}{c}}{0.317 + \frac{1}{\rho_f}\frac{A_f}{c} + \frac{1}{\rho_c}\frac{A_c}{c} + \frac{w}{c} + \frac{a}{c}} \quad \ldots\ldots\ldots.[3]$$

where w,c,a, A_f and A_c represent the amount of water, cement, entrapped air, fine aggregate and coarse aggregate, respectively, in concrete. Meanwhile, ρ_f and ρ_c are the specific gravity of fine and coarse aggregate, respectively, and h represents degree of hydration.

Most of TVW is greater than TVP. This fact ensures that there is water available for refilling of the pores when it is drying due to hydration consumption. Consequently, autogenous shrinkage is expected lower with higher ratio of TVW to TVP. However, Fig. 5 does not confirm this. The explanation seems to be similar to that suggested in previous section. Other fact that may affect this phenomenon is that some of the water is lost during mixing because of evaporation and bleeding.

Table 3. Calculated available water (TVW) and total porosity of concrete (TVP) for mixes series 3

Sample Identification	TVW	TVP	TVW/TVP
LAC 0.6 - 100 %-0%	0.22842	0.261072	0.874931
LAC 0.6 - 100 %-25%	0.255296	0.261072	0.977877
LAC 0.6 - 100 %-50%	0.282173	0.261072	1.080824
LAC 0.6 - 100 %-75%	0.309049	0.261072	1.183771
LAC 0.6 - 100 %-100%	0.335926	0.261072	1.286717

CONCLUSION

Water supplied by lightweight aggregate has been assumed to be immediately available for refilling the empty pores due to self-desiccation. Based on this assumption, Bentz's developed model for quantifying the amount of lightweight aggregate for the purpose of preventing autogenous shrinkage of concrete. However, this research suggests that only when the ratio of water supplied from lightweight aggregate to water required for hydration is high (above 3.5) then this assumption is valid as seen from the reduction of autogenous shrinkage. The case is also true for the relation between the ratio of total porosity to total volume of water against autogenous shrinkage.

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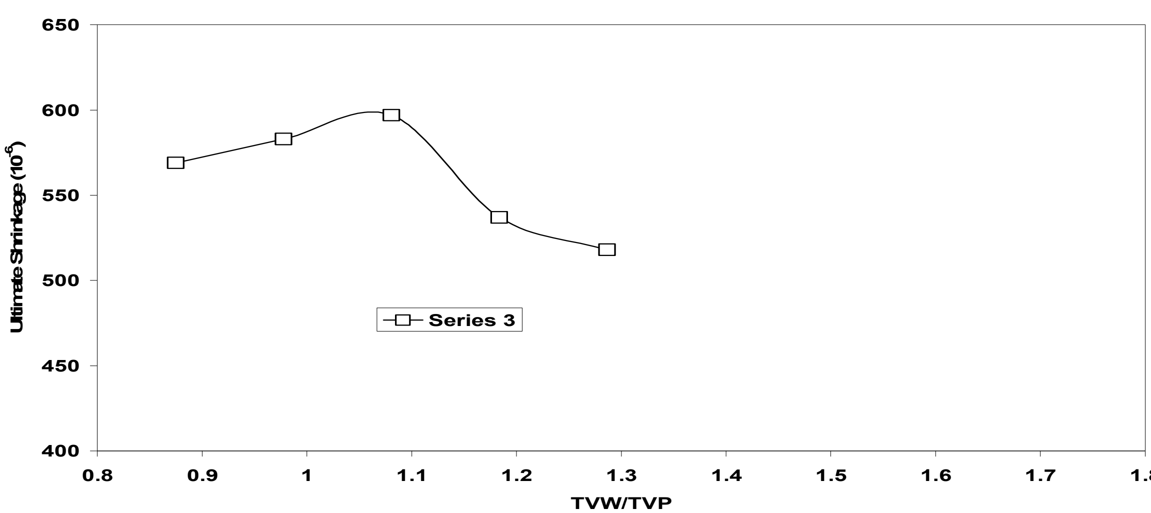

Fig.5. Relationship between ultimate autogenous shrinkage and ratio of TVW/TVP

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