Drying Shrinkage of Heat-Cured Fly Ash-Based Geopolymer Concrete

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Abstract

Fly ash-based geopolymer concrete is manufactured without using portland cement at all. This type of concrete has environmental benefit as it has very low greenhouse gas emission compared to that resulted from the production of portland cement. In addition, it also utilizes waste or by-product material that makes it more environmentally friendly. This paper presents the study of drying shrinkage of heat-cured fly ash-based geopolymer concrete. Geopolymer concrete in this study used low-calcium fly ash as its source material, alkaline solution and aggregates normally used for ordinary portland cement concrete. Four series of test specimens with different compressive strength were prepared to study the drying shrinkage of this concrete. The test results were then compared with the calculated results of drying shrinkage as predicted by Gilbert Method which is normally used for ordinary portland cement concrete. Test results show that the heat-cured fly ash-based geopolymer concrete undergoes very low drying shrinkage. The drying shrinkage strain at one year as calculated using Gilbert Method is much higher, about five to seven times, compared to the measured drying shrinkage strain from the tests.

Keywords: Drying shrinkage, Fly ash, Geopolymer concrete, Heat-cured

1. Introduction

Environmental issue has become a crucial issue in concrete industry. This is mostly because of the emission of greenhouse gasses from the production of portland cement as the primary binder in making concrete in the meantime. Many efforts have been trying in order to reduce the use of portland cement in concrete that in turn will also reduce the greenhouse gas emission. Those efforts include the use of supplementary cementing materials and finding alternatives for portland cement. In this regard, fly ash-based geopolymer concrete is a good alternative since it does not use portland cement at all. This type of concrete becomes more environmentally friendly because it also uses waste or by-product material which is fly ash. As a relatively new material, extensive studies are still needed to explore this type of concrete as a construction material. One area that needs to be studied is its shrinkage behaviour, which is an important long-term property of concrete. This paper reports the study of drying shrinkage of fly ash-based geopolymer concrete by conducting relevant testing of drying shrinkage and comparing the test results with the developed formula or equation normally used for predicting drying shrinkage of ordinary portland cement (OPC) concrete.

2. Shrinkage of Concrete

Shrinkage is the decrease in volume of concrete with time. Unlike creep, another long-term property of concrete, shrinkage is independent of the external actions to the concrete. There are some types of shrinkage in the concrete which should be distinguished. Gilbert (2002) divided them into plastic shrinkage, chemical shrinkage, thermal shrinkage and drying shrinkage.

Plastic shrinkage occurs in wet concrete or when the concrete is still in plastic state due to loss of water by evaporation or suction by the underlying concrete or soil. This could lead to significant cracking during setting. The magnitude of plastic shrinkage is affected by temperature, ambient relative humidity and wind velocity (Neville, 2000). Plastic shrinkage also depends on the cement content of the mix and the water cement ratio, it is greater for greater cement content and low water cement ratio.

Chemical shrinkage is caused by various chemical reactions within the cement paste, including the hydration shrinkage. While thermal shrinkage is related to the liberation of the heat of hydration as Portland cement reacts with water.

Drying shrinkage is the reduction in volume which is primarily caused by the loss of water during the drying process. Drying shrinkage normally accounts for the biggest proportion of the total long-term shrinkage. Factors which affect the

drying of concrete also affect the magnitude and rate of development of drying shrinkage. Those factors include the type and content of cement or binder, water content and water to cement ratio, type of aggregate, maximum size and its proportion in the concrete, relative humidity and the size and shape of the member.

The aggregates plays a significant role in affecting the shrinkage of concrete (de Larrard et. al., 1994; Neville, 2000). This is related to the restraining effect of the aggregate on shrinkage. The higher aggregate content results in smaller shrinkage and also concrete with aggregates of higher modulus or rougher surfaces is more resistance to the shrinkage process.

The higher water to cement ratio normally results in higher shrinkage due to interrelated effects. As water to cement ratio increases, paste strength and stiffness decrease and as the water content increases, shrinkage potential increases because it also reduces the volume of restraining aggregates.

The relative humidity affects the magnitude of shrinkage as the rate of shrinkage is lower at higher values of relative humidity. The rate and magnitude of shrinkage decrease with an increase in the volume of concrete member, but the duration of shrinkage is longer for large members since more time is needed for shrinkage effects to reach the interior regions (de Larrard et. al., 1994).

The shrinkage strain of concrete which is usually considered to be the sum of drying, chemical and thermal shrinkage components, continues to increase with time at a decreasing rate (Gilbert, 2002). And as for creep, shrinkage is also assumed to approach a final value as time approaches infinity. Shrinkage is a concern in concrete structures since it is probably the most common cause of cracking. Shrinkage also causes axial deformation and warping which could lead to significant deflection and the shrinkage induces tension and resulting cracks, if not controlled, can lead to serviceability, durability and even shear strength failure (Gilbert, 1988; Rusch et. al., 1983).

There are some formulas or equations that have been developed to estimate the shrinkage of concrete. One of them is as proposed by Gilbert (2002) that will be used in this study as a comparison to the experimental results.

The method proposed by Gilbert divides the total shrinkage strain (ε_{cs}) into endogenous shrinkage (ε_{cse}) and drying shrinkage (ε_{csd}). Endogenous shrinkage is taken to be the sum of chemical and thermal shrinkage. The total shrinkage strain is given by Equation 1 and the endogenous shrinkage at any time t (in days) after concrete placement is given by Equation 2.

$$\varepsilon_{cs} = \varepsilon_{cse} + \varepsilon_{csd} \tag{1}$$

$$\varepsilon_{cse} = \varepsilon_{cse}{}^{*}(1.0 - e^{-0.1t}) \tag{2}$$

Where $\varepsilon_{cse}{}^{*}$ is the final endogenous shrinkage and may be taken as

$$\varepsilon_{cse}{}^{*} = (0.06 f'_c - 1.0) \times 50 \times 10^{-6} \tag{3}$$

in which f'$_c$ is in MPa.

The drying shrinkage at time t (in days) after the commencement of drying may be taken as

$$\varepsilon_{csd} = k_1 k_4 \varepsilon_{csd.b} \tag{4}$$

where $\varepsilon_{csd.b}$ is given by Equation 5. In Equation 5, $\varepsilon_{csd.b}{}^{*}$ depends on the quality of the local aggregates and may be taken as 800 x 10^{-6} for Sydney and Brisbane, 900 x 10^{-6} for Melbourne and 1000 x 10^{-6} elsewhere.

$$\varepsilon_{csd.b} = (1.0 - 0.008 f'_c) \times \varepsilon_{csd.b}{}^{*} \tag{5}$$

The factor k_1 in Equation 4 is given by Equation 6, and the factor k_4 is taken equal to 0.7 for an arid environment, 0.65 for an interior environment, 0.6 for a temperate inland environment and 0.5 for a tropical or near-coastal environment.

$$k_1 = \frac{\alpha_1 t^{0.8}}{t^{0.8} + 0.15 t_h} \tag{6}$$

where

$$\alpha_1 = 0.8 + 1.2 e^{-0.005 t_h} \tag{7}$$

and the hypothetical thickness, t_h is given by Equation 8, where A is the cross-sectional area of the member and u_e is that part of the perimeter of the member cross-section which is exposed to the atmosphere.

$$t_h = \frac{2A}{u_e} \tag{8}$$

3. Fly Ash-Based Geopolymer Concrete

Fly ash-based geopolymer concrete is geopolymer concrete utilizes fly ash as its source material. The source material for making geopolymer concrete should be rich in silica and alumina. Unlike the   cement-based concretes that utilise the formation of calcium-silica hydrates (CSHs) for matrix formation and strength, geopolymers involve the chemical reaction of alumino-silicate oxides with alkali polysilicates yielding polymeric $Si - O - Al$ bonds (Davidovits, 1991; van Jaarsveld, et. al., 2002).   In geopolymer concrete, the silica and the alumina present in the source materials are first induced by alkaline activators to form a gel. This geopolymer gel binds the loose aggregates and other unreacted materials in the mixture to form the geopolymer concrete. In this experimental work, fly ash is used as the source material to make geopolymer paste as the binder, instead of cement paste, to produce concrete. The geopolymer paste binds the loose coarse aggregates, fine aggregates and other un-reacted materials together to form the fly ash-based geopolymer concrete. The manufacture of geopolymer concrete is carried out using the usual concrete technology methods. As in the Portland cement concrete, the aggregates occupy the largest volume, i.e. about 75-80 % by mass, in fly ash-based geopolymer concrete. The silicon and the aluminium in the fly ash are activated by a combination of sodium hydroxide and sodium silicate solutions to form the geopolymer paste that binds the aggregates and other un-reacted materials.

Previous research has been reported on the studies of fly ash-based geopolymer concrete as in Hardjito et. al. (2004) who studied the development of this concrete including the effects of various parameters. Previous studies also indicates that fly ash-based geopolymer concrete possesses good long-term properties and durability (Wallah, et al., 2004; Wallah and Rangan, 2006). Moreover, fly ash-based geopolymer concrete is a potential material for structural application (Sumajouw and Rangan, 2006; Chang, et. al., 2007). The use of geopolymer technology in making concrete has environmental benefit as it could reduce the CO_2 emission to the atmosphere up to 80% compared to OPC concrete (Davidovits, 1994).

4. Experimental Work

Geopolymer concrete in this study utilized the low calcium (class F) fly ash from Collie Power Station, Western Australia as the source material. Aggregates, comprising 20 mm, 14 mm and 7 mm coarse aggregates and fine aggregate in saturated surface dry conditions, were used. The coarse aggregates were crushed granite-type aggregates and the fine aggregate was fine sand. The alkaline activator was a combination of analytical grade sodium hydroxide (NaOH) in flake form with 98% purity dissolved in water and sodium silicate (Na_2O= 14.7%, SiO_2=29.4%, and water=55.9% by mass solution). A high range water-reducing admixture with a dosage of 1.5% by mass of the fly ash was added to the mixture. The specimens were cured at 60^oC for 24 hours. Two types of curing were applied, dry curing or steam curing. For dry curing, the specimens were cured in an oven and for steam curing the specimens were cured in the steam curing chamber. After curing, the specimens were left to air-dry in the laboratory until testing.

This study focused on the drying shrinkage of fly ash-based geopolymer concrete, where the procedure as in Australian standard, AS 1012.13 (1992) was used as the basis to determine the drying shrinkage through an experimental or laboratory testing.

Test specimens for drying shrinkage test were 75x75x285 mm prisms with the gauge studs as shown in Figure 1. Three specimens were prepared for each type of test. In addition, for each type of test, four 100x200 mm cylindrical specimens were also prepared for compressive strength test.

Four series of concrete specimens (Table 1) were used for drying shrinkage test designated with 1DS, 2DS, 3DS and 4DS. The first two comes from one mixture proportion designed for higher strength while the other two comes from one mixture proportion with lower strength. Two types of heat curing which is dry curing and steam curing, were applied with one type for one test series in each mixture.

The shrinkage strain measurements started on the third day after casting the concrete. On the third day after casting, the specimens were demoulded and the first measurement was taken. Horizontal length comparator (Figure 2) was used for length measurements. The next measurement was on the fourth day of casting, considered as Day 1 for the drying shrinkage measurements. The measurements then continued every day in the first week, once a week until the fourth week, once in two weeks until the twelfth week, and then once in four weeks until one year.

During the drying shrinkage tests, the specimens were kept in a laboratory room where the temperature was maintained at approximately at 23^oC. The relative humidity of the room varied between 40% and 60%.

5. Results and Discussions

5.1 Shrinkage Test Results

Table 2 presents the resulted 7th day compressive strength of each test category. For concrete from mixture-1, the compressive strength is 65 MPa and 57 MPa for 1DS and 2DS respectively, while for mixture-2, those values are 50 MPa and 41 MPa for 3DS and 4DS respectively.

Figures 3 and Figure 4 show the plots of drying shrinkage strain versus age in days for the heat-cured test specimens. It can be seen from these Figures that heat-cured fly ash-based geopolymer concrete undergoes very low drying shrinkage. For all test specimens, from both mixtures and curing types and different compressive strength, the final value of drying shrinkage strain after a one-year period was only around 100 microstrain. Although each type of mixture and curing type results in different compressive strength, the drying shrinkage strain does not have significant difference among those four series of tests.

The test data plotted in Figures 3 and 4 show that the drying shrinkage strains fluctuated slightly over the period of measurement. This could be attributed to the moisture movement from the environment to the concrete or vice versa which causes reversible shrinkage or swelling of the concrete. Also, there were some minor differences in the measured values of drying shrinkage strains between dry and steam cured specimens. However, these variations are considered to be insignificant in the context of the very low drying shrinkage experienced by the heat-cured geopolymer concrete specimens.

5.2 Comparison of Test Results and Prediction

The drying shrinkage of heat-cured fly ash-based geopolymer concrete is generally very low compared to that of ordinary portland cement concrete. This can also be seen if the test results are compared with the values predicted by using one of the available prediction formula for OPC concrete.

In this study, the measured drying shrinkage strains are compared with the values predicted by a method proposed by Gilbert (2002). which is also included   in the Australian Standard for Concrete Structures AS3600 as described in Section 2.

The measured shrinkage strains are compared with the predictions by Gilbert method in Figure 5 to Figure 8.   In these calculations, the factor k_4 was taken as equal to 0.65 as the test specimens were exposed to an interior environment and the value of f'$_c$ was taken as the 7th day compressive strength of the test specimens as given in Table 2.

It can be seen from Figures 5 to Figure 8 that the measured drying shrinkage strains of heat-cured fly ash-based geopolymer concrete specimens are significantly smaller than the predicted values.

In heat-cured fly ash-based geopolymer concrete, most of the water released during the chemical reaction may evaporate during the curing process (Davidovits, 1999; Hardjito & Rangan, 2005).   Because the remaining water contained in the micro-pores of the hardened concrete is small, the induced drying shrinkage is also very low.

Davidovits (Personal communication) suggested that the smaller drying shrinkage strain of heat-cured fly ash-based geopolymer concrete may be explained by the 'block-polymerisation' concept.   According to this concept, the silicon and aluminium atoms in the fly ash are not entirely dissolved by the alkaline liquid. The 'polymerisation' that takes place only on the surface of the atoms is sufficient to form the 'blocks' necessary to produce the geopolymer binder. Therefore, the insides of the atoms are not destroyed and remain stable, so that they can act as 'micro-aggregates' in the system and this could 'increase' the aggregate content in concrete. As for OPC concrete, aggregate content will influence the magnitude of shrinkage as the shrinkage of concrete will decrease with the increase in the quantity of aggregates. The proportion of aggregates in the mixtures of fly ash-based geopolymer concrete used in this work is approximately similar to that used in OPC concrete. However, the presence of the 'micro-aggregates' due to the 'block-polymerisation' gives the effect of increasing the aggregate content in the concrete. In other words, the presence of the 'micro-aggregates' increases the restraining effect of the aggregates on drying shrinkage.

7. Conclusion

Heat-cured fly-ash based geopolymer concrete undergoes very low drying shrinkage. The drying shrinkage strains fluctuated slightly over the period of measurement and the value at one year measurement is only around 100 microstrain. The test measurement at one year for all test series of specimens with different compressive strength, which were produced from different mixtures and curing types, does not have significant difference. The values of drying shrinkage strain predicted using Gilbert Method is much higher, about five to seven times of the measured drying shrinkage strain..

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Table 1. Test Parameters for Drying Shrinkage Test

Test Designation	Mixture	Curing type
1DS	Mixture-1	Dry
2DS	Mixture-1	Steam
3DS	Mixture-2	Dry
4DS	Mixture-2	Steam

Table 2. Compressive Strength of Heat-Cured Fly Ash-based Geopolymer Concrete Shrinkage Specimens

Test Designation	Type of mixture	Curing type	7th Day compressive strength (MPa)
1DS	Mixture-1	dry	65
2DS	Mixture-1	steam	57
3DS	Mixture-2	dry	50
4DS	Mixture-2	steam	41

Figure 1. Specimens for Drying Shrinkage Test

Figure 2. Horizontal Length Comparator with a Drying Shrinkage Test Specimen

Figure 3. Drying Shrinkage of Heat-Cured Mixture-1 Specimens

Figure 4. Drying Shrinkage of Heat-Cured Mixture-2 Specimens

Figure 5. Comparison of Test and Predicted Shrinkage Strains for 1DS

Figure 6. Comparison of Test and Predicted Shrinkage Strains for 2DS

Figure 7. Comparison of Test and Predicted Shrinkage Strains for 3DS

Figure 8. Comparison of Test and Predicted Shrinkage Strains for 4DS