A Study of the Coefficient of Thermal Expansion of Paste, Mortar and Concrete

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Abstract

This paper presents an experimental approach to determine the coefficient of thermal expansion (CTE) of paste, mortar and concrete at early age. The deformation of specimens was measured by using high-precision linear variable displacement transducers (LVDT) and the temperature was measured by thermocouples embedded in the specimens. It was found that the CTE decreased after setting and reached minimum values at a few hours after setting, then increased with time until becoming nearly constant. At the age before the mixtures gain enough stiffness, the use of fly ash increases CTE of the pastes and concretes. However, at later age, the CTE of pastes and concretes with fly ash is smaller than that of the mixtures without fly ash. Aggregate seems to be the main factor that affects the CTE of concrete because it occupies most of the concrete volume.

Keywords: Coefficient of thermal expansion, Mass concrete, Fly ash, Paste, Mortar

1. Introduction

Temperature variation in the concrete mass is the cause of thermal stress and thermal cracking. During construction of massive concrete structures such as dams and mat foundations, temperature gradients occur inside the structures due to heat of hydration causing thermal stress. This thermal stress may reach its critical value. Since concrete possesses a low thermal conductivity, cumulative hydration heat with temperature gradient can induce cracks, especially at early age. To predict thermal cracking of concrete, quantitative evaluation of heat evolution during hardening as well as thermal properties and related mechanical properties, especially at early age are necessary. All of these properties must be time-dependently predictable.

One of the significant properties is the coefficient of thermal expansion (CTE) which is used to compute strain due to temperature variation in mass concrete [1]. CTE can be defined as the change per unit length of linear dimension per a unit temperature change expressed in micro strain per degree Celsius ($10^{-6}.^{o}C^{-1}$). The CTE is calculated from Eq. (1).

$$CTE = \frac{\varepsilon}{\Delta T} = \frac{\Delta L}{L \cdot \Delta T} \qquad (1)$$

where CTE is the thermal expansion coefficient ($10^{-6}.^{o}C^{-1}$), ε is the strain due to temperature change, ΔL is the length

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change due to temperature change (mm.), L is the initial length (mm.) and ΔT is the temperature change (^oC).

Arshad et al. [2] found that the CTE of concrete was approximately equal to the volumetrically weighted average of the coefficients of its ingredients which are cementitious materials, water, hydration products and aggregates. The CTE of ingredients in concrete which are cement, fly ash, quartz sand, limestone, hydrated product and water are 14.4 [3], 6.45 [4], 10.4 [5], 4.5 [5], 20 [6] and 69 x $10^{-6}.^oC^{-1}$ [6], respectively. Many researchers [4, 6] found that CTE of concrete reached a minimum value about one day after setting and increased with time after that. The use of a constant CTE of about 10 x $10^{-6}.^oC^{-1}$ from the setting time to a later age (as often done in practice for stress analysis) would result in an inaccurate estimation of the true thermal expansion and restrained thermal strain of concrete [5].

The use of fly ash is effective for controlling temperature and thus reducing the risk of thermal cracking in mass concrete However, most of the experiments in the literatures [4-8] were conducted on high performance concrete or low w/b concrete while no fly ash was used in those experiments. Eventhough, Wesche [9] found that the use of fly ash reduced the CTE of concrete at a high replacement percentage, however, there were not much details on the magnitude of CTE of fly ash concrete. Choktaweekarn and Tangtermsirikul [10] conducted the CTE test on pastes but the test was done at the age after 1 day. As a result, the data on the effect of fly ash on CTE of concrete are extremely limited especially at early age. For mass concrete, it is important to evaluate its CTE at early age because thermal cracking occurs at early age. The modulus of elasticity of concrete at the age before setting is small then the stress induced by the rise in temperature is insignificant even in zones of full restraint [11]. The deformations occurring before the setting time can be ignored for stress calculation since they do not result in stress. As a result, the CTE of concrete before the setting is not important in this case [5] and is not included in this study. From the reasons above, it is important to investigate the CTE of concrete especially at very early ages. In this study, CTE's from the age just after final setting of paste, mortar and concrete were studied.

2. Experiment program

2.1 Mix proportions and materials

Cement-fly ash pastes, mortars with two different types of fine aggregate (natural river sand and crushed limestone sand) and fly ash concrete were produced and tested since the ages just after final setting until 28 days. Cement-fly ash pastes were tested to observe the effect of fly ash. Mortars were tested to observe the effect of type and content of aggregate. Four mixtures of concrete were produced and tested. For concrete, limestone was used as coarse aggregate whereas natural river sand was used as fine aggregate. The mix proportions of the tested pastes and mortars are shown in Table 1 while the mix proportions of the tested concretes are shown in Table 2.

2.2 Specimen preparation and test procedure

In each test, two sealed prisms were tested in the temperature control room from the age just after final setting until the age of 28 days. Figure 1 presents a diagram of the apparatus used for the test. Prism specimens with dimensions of 25x25x300 mm were used for cement-fly ash pastes and those with dimensions of 75x75x300 mm were used for mortars and concretes.

All instruments were setup on a steel base plate. The specimens were cast in steel molds that were laid on the steel plates. The end plates of the mold were removed before test.

Friction between the specimen and the mold was minimized by using thin plastic films This application of plastic film to reduce friction was widely used in the previous studies and it has been proved to perform well [12]. The specimens were firmly wrapped by using aluminum foils immediately after casting in order to prevent the evaporation of water from the specimens and to simulate the physical condition inside the mass concrete (no moisture loss or gain). The specimens were tested without removing the wrapped aluminum foil.

The uniformity of temperature inside specimen was measured by a set of thermocouples embedded in the specimen. In case of mortar and concrete, four thermocouples were installed in each specimen. Three thermocouples were installed in the specimen, one at the section center and mid-length (see A in Figure 1), one at 1 cm. each from bottom and side surfaces (see B in Figure 1) and the last one was installed at 5 cm from the end of specimen at mid section (see C in Figure 1). In case of paste, two thermocouples were installed, one at the mid-length and the other at 5 cm. from the end of specimen (all at the section center). The temperature range used in the experiment was adopted from the study of Cusson and Hoogeveen [4].

Table 1 Mix proportions of the tested pastes and mortars

Mix No.	Mixture Code	w/b	f/b	s/b	g/b
1	w25r0	0.25	0	0	0
2	w25r5	0.25	0.50	0	0
3	w40s1	0.40	0	1	0
4	w40s3	0.40	0	3	0
5	w40g1	0.40	0	0	1
6	w40g3	0.40	0	0	3

Remarks: w: water, f: fly ash, b: binder (cement + fly ash), s: natural river sand and g: crushed limestone sand

Table 2 Mix proportions of the tested concretes

Mix No.	Mixture Code	γ	w/b	f/b
1	g12w5	1.2	0.50	0
2	g14w4	1.4	0.40	0
3	g14w5	1.4	0.50	0
4	g14w4r5	1.4	0.40	0.50

Remarks: γ: the ratio of the volume of paste to volume of void in aggregate phase

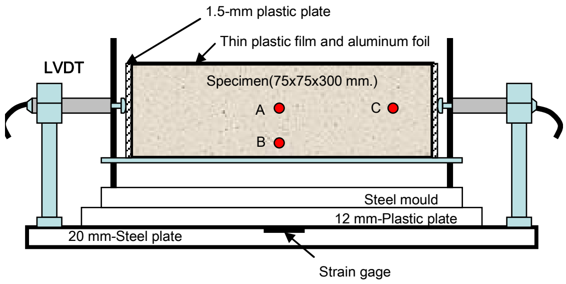

Figure 1 Schematic Diagram showing the test set up for the CTE measurement (for mortars and concretes)

The specimens were tested by heating them up, with a thermal pad, from room temperature (about 25 ± 1 ºC) to 40 ºC. The heating period is about 1.5 hours (30 minutes for every 5 °C). It has been reported that for a given concrete mixture, the magnitude of thermal expansion or contraction of concrete in normal range of temperature, including the range occurred in mass concrete, is the same for each unit temperature change. In other words, the CTE is constant in that range [5].

For every 5 ºC change of temperature, the longitudinal displacement of specimen was measured by the linear variable displacement transducers (LVDT). The CTE is calculated from Eq. (2).

$$\mathrm{CTE} = \frac{\varepsilon + \varepsilon_{AS}}{\Delta T} \quad (2)$$

where CTE is the tested thermal expansion coefficient (10^{-6}.$^{o}C^{-1}$) , ε is the strain due to temperature change, ε_{AS} is the strain due to autogenous shrinkage during the period of ΔT change and ΔT is the temperature change (ºC).

From some previous studies, the effect of autogenous strain during the measurement of the CTE was considered and some measuring methods were developed to separate the effect of autogenous shrinkage strain from the thermal strain, especially for low w/b concrete at early age [4, 8, 9, 13]. The measuring methods of Kada et al. [8] and Cusson and Hoogeveen [4] were adopted and modified to be used in this study due to simplicity. The CTE test method was designed to minimize the effect of autogenous shrinkage deformation by controlling the measuring duration to be as short as possible. The temperature range must be controlled to prevent the moisture transfer during testing.

Even though the test duration was short and autogenous shrinkage strain can be minimized, autogenous shrinkage strain was calculated and deducted from the measured strain by applying the two-phase model shown in Eq (3) for computing concrete autogenous shrinkage strain in each step of temperature change (5 °C for each step) Details of the model can be found in the published papers by Tangtermsirikul et al. [13, 15-16] and Tongaroonsri [14].

$$\varepsilon_{conc} = \frac{\varepsilon_{AS,\,p} \cdot E_p \cdot (1-n_a)}{E_p + E_a} \qquad (3)$$

where ε_{conc} is the autogenous shrinkage strain of concrete (10^{-6}), $\varepsilon_{AS,\ p}$ is the unrestrained autogenous shrinkage of paste phase in concrete (10^{-6}), n_a is the volume concentration of aggregate, E_p is the modulus of elasticity of paste (MPa), E_a is the modulus of elasticity of aggregate phase (MPa).

By using the proposed model together with the unrestrained autogenous shrinkage of the sample estimated from the test results published in the previous studies [13-14], the autogenous shrinkage strain in each step of temperature change was considered in the calculation of the CTE. It was found that the amount of autogenous shrinkage in each step of temperature change was very small especially for mortar and concrete because the test period in each step was short. This is in consistent with the study conducted by a group of researchers [8] which concluded that the effect of autogenous shrinkage strain could be neglected because the duration for measuring CTE was short.

3. Experimental results and discussions

3.1 Effect of age on CTE of paste, mortar and concrete

From Figures 2 to 5, it is obvious that CTE of pastes, mortars and concretes are time-dependent especially during a few hours after setting. CTE of pastes, mortars and concretes decreased sharply after setting and reached minimum values at a few hours after setting, then increased with time. Many studies also indicated the similar results [5, 6-8]. The rapid reduction of CTE at early age is caused by the decrease of liquid phase, which have much higher CTE than solid phase, together with the progress of hydration and increase of the paste stiffness. The effect of liquid phase decreases as the stiffness of paste increases.

At later age, when the stiffness of paste is strong enough, the solid phase becomes the main parameter that affects the CTE. Another reason is that at later age, the continuity of paste structure is higher when compared to its structure at early age as a result of increasing hydrated products and the change of humidity due to the development of self-desiccation.

3.2 Effect of fly ash on CTE of paste and concrete

The effect of fly ash content on CTE of paste is shown in Figure 2. In case of paste, the results showed that at few hours after setting or at very early age before paste gained enough stiffness, CTE of cement-fly ash paste was higher than CTE of cement-only paste. This can be explained by using the same concept as that mentioned in section 3.1 that the CTE at this stage is mainly depend on the stiffness of paste and CTE of liquid phase. At very early age, the stiffness of cement-fly ash paste is less than that of cement paste then the liquid phase gave more impact to CTE of fly ash paste than cement paste. As a result, the CTE at early age of cement-fly ash paste is higher than CTE of cement paste.

At later age when paste gained enough stiffness, the test results showed that the CTE of cement-fly ash paste increased from the first day and continued to increase in long term. However, the CTE of cement-fly ash paste was lower than that of the cement paste. This is because fly ash has a lower CTE than cement and so using fly ash to replace cement reduces the CTE. The use of fly ash also delays the reaction of concrete at an early age but continues in long term. Consequently, the CTE at a later age of the mix with fly ash is lower.

The effect of fly ash on CTE of concrete is shown in Figure 5. It was found that the time dependent behavior and the effect of fly ash on CTE of concrete are the same as those in case of paste. At very early age, the CTE of fly ash concrete is higher than that of cement-only concrete. The reason is the same as that explained in the case of paste.

3.3 Effect of aggregate type and content on CTE of mortars

Figure 3 shows the effect of type and content of aggregate on the CTE of mortars. CTE of concrete depends on CTE's of its ingredients [2]. Since the CTEs of aggregates are lower than those of the pastes, the mixtures with higher sand content have lower CTEs than those with lower sand content.

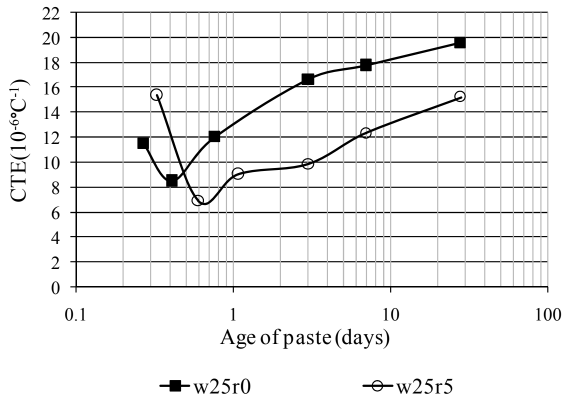

Figure 2 Test results of CTE of cement-fly ash pastes with replacement ratios of 0 and 0.50, w/b = 0.25

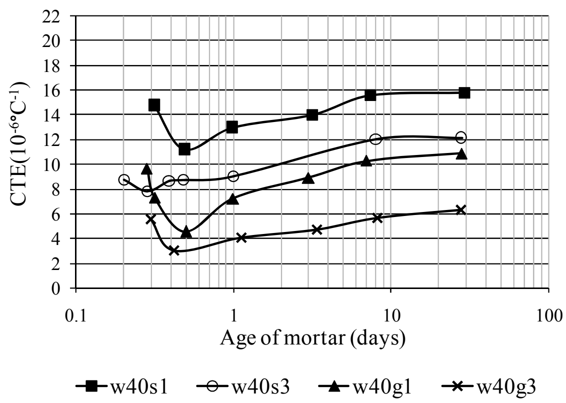

Figure 3 Test results of CTE of river sand and crushed limestone mortar with sand to binder ratio of 1 and 3, w/b = 0.40

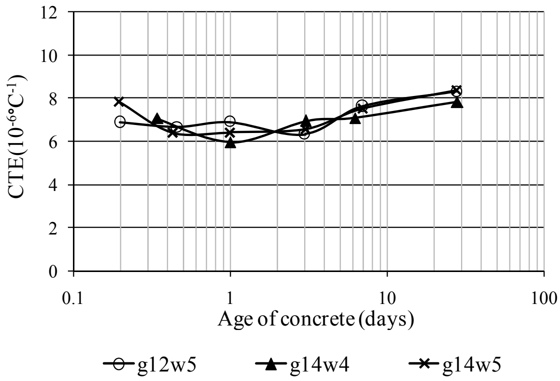

Figure 4 Test results of CTE of concrete with γ of 1.2 and 1.4, w/b = 0.40 and 0.50

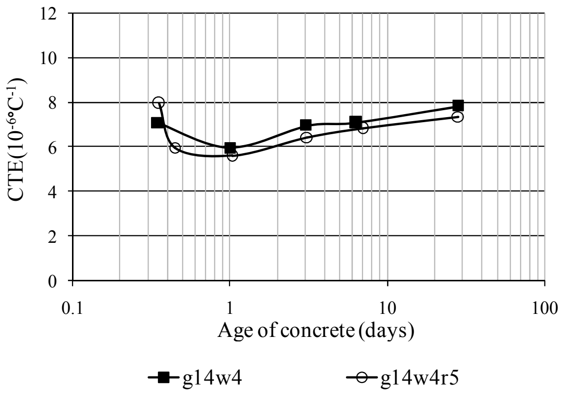

Figure 5 Test results of CTE of concrete with γ of 1.4, w/b = 0.40 and fly ash to binder ratios of 0 and 0.50

However, the time-dependent behavior is similar to that shown by paste specimens. Mortars with natural river sand show higher CTEs than the crushed limestone sand mortars because the CTE of natural river sand is higher than that of the crushed limestone sand.

3.4 Effect of w/b on CTE of concrete

The effect of w/b on the CTE of concrete is not significant (see Figure 4). This is because after the formation of a strong paste structure, water behaves differently from the solid structure. When temperature increases, the volume of water in the capillary pores of paste can also increase. However, unlike the solid structure, water can move from high pressure capillary pores to other lower pressure pores, causing an insignificant effect on the thermal expansion of paste.

3.5 Effect of paste content on CTE of concrete

The effect of paste content on the CTE of concrete is shown in Figure 4. It was found that the effect of paste content is not significant. This is because aggregate occupies most of concrete volume so a small change in volume of paste does not significantly affect the CTE of concrete

4. Conclusions

From the test results, it was found that CTE of paste, mortar and concrete was a time-dependent property which decreased considerably after setting and reached minimum values at a few hours after setting, then increased with time until becoming nearly constant. At the age before paste gains enough stiffness, the use of fly ash increases CTE of paste and concrete. However, at later age, the CTE's of paste and concrete with fly ash are smaller than those of the mixes without fly ash. Aggregate is the main factor that affects the CTE of concrete.

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