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Combination Effects of Internal Curing and Permanent Formwork on Shrinkage of High Strength Concrete

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Received 14 June 2014, accepted 26 October 2014 doi:10.3151/jact.12.456

Abstract

In this paper, the influences of internal curing using pre-soaked lightweight aggregate (PSLWA) and pre-fabricated fiber reinforced engineered cementitious composite (ECC) board as permanent formwork on shrinkage and internal relative humidity of high strength concrete were investigated. Three mixture proportions with induced curing water-to-cement ratios (WIC/C) of 0, 0.08 and 0.12 were utilized in the experiments. The test results show that the progress of the internal relative humidity of high strength concrete since casting exhibits first a vapor saturated stage (RH=100%, stage I), followed by a gradually reducing stage (RH<100%, stage II). As PSLWA is added, the reduction rate of internal relative humidity in stage II is greatly decreased. As ECC cover is used, the reduction on internal humidity of high strength concrete is further reduced. Shrinkage of high strength concrete decreases with increase of induced internal curing water. However, internal curing cannot completely eliminate the shrinkage of high strength concrete developed in the stage I. The combined effects of internal curing and ECC cover can reduce the shrinkage not only developed in the stage II, but also the shrinkage developed in stage I.

1. Introduction

Concrete shrinks as moisture is lost to the environment or by self-desiccation. As concrete shrinks, a certain tensile stress will be developed in a structure due to restraints from adjunct materials or connected members. The stress may exceed the cracking strength and cause concrete to crack. Therefore, shrinkage of concrete may be one of the major sources of the formation of cracks in concrete structures. The magnitude of the shrinkage strain is normally proportional to the amount of moisture loss (Bissonnette, et al. 1999; Baroghel-Bouny et al. 1999; Ayano et al. 2002; Zhang et al. 2006). In general, environmental drying and cement hydration are the two main processes causing moisture loss of concrete. As environmental humidity is lower than the humidity inside of concrete, the water in concrete evaporates and shrinkage of the concrete arises. This kind of shrinkage is called drying shrinkage. Another process causing moisture loss is through cement hydration, which is known as self-desiccation and the corresponding shrinkage of concrete is called autogenous shrinkage.

Generally, the autogenous shrinkage of concrete is inversely proportional to water to cement ratio. The higher the water to cement ratio, the lower the autogenous shrinkage. High strength concrete generally has a low water to cement ratio, therefore marked autogenous shrinkage is more noticeable in high strength concrete structures. In addition, a similar problem may emerge likewise in high performance concrete due to its high content of cementitious materials normally. In order to avoid the shrinkage induced cracking in high strength or high performance concrete structures, it is necessary to compensate for the moisture loss from cement hydration. Use of pre-soaked lightweight aggregate (PSLWA) as an internal reservoir to provide water as the concrete dries is an effective method to reduce autogenous shrinkage of high strength concrete (Bentur et al. 2001; Henkensiefken et al. 2009). However, recent investigations show that the internal curing with PSLWA cannot completely eliminate the drying shrinkage because the capillary pores close to the drying surface cannot continuously be filled by the released water from PSLWA (Zhang et al. 2013; Han et al. 2013). Thus, internal curing with PSLWA cannot wholly eliminate the surface drying induced cracking, even it does effectively delay the cracking time (Henkensiefken et al. 2009). More effective techniques are definitely needed for preventing surface drying resulted cracking.

Shrinkage of concrete at a given place in a structure is the sum of drying and autogenous shrinkages. The shrinkage along the depth from drying surface to center of a concrete member is not uniformly distributed. At present, there are two different ways to measure the autogenous deformation of cement-based materials. One

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is volumetric deformation method and the other is one-dimensional deformation method (Paulini 1992; Tazawa et al. 1992; Sellevold et al. 1994; Jensen et al. 1995; Jutnes et al. 1996). These methods were specially developed for cement paste. Recently, Zhang et al. developed a testing method to measure both deformation and interior humidity inside concrete simultaneously starting from concrete setting, meanwhile a drying environment for surface drying of the tested specimen was created as well in the experiments (Zhang et al. 2010). Thus the total shrinkage resulted from both self-desiccation and environmental drying can be measured at the same time by the above testing method through using two parallel specimens.

The purpose of this paper is to investigate the integrated effects of the permanent formwork made by fiber reinforced cementitious composite (ECC) and internal curing using PSLWA on autogenous and drying shrinkage of high strength concrete and to contribute to the designing of concrete structures with the consideration of reducing the risk of both of autogenous and drying shrinkage induced cracking. Utilizing of ECC board as permanent formwork of concrete structure have been studied recently, that mainly focus on the crack width control in concrete structures (Leung et al. 2010). In this application, the ECC board was made in factory or laboratory before concrete casting. Therefore, most of shrinkage of ECC was already finished when it was used as formwork. In the study, shrinkage of internal cured high strength concrete with and without permanent formwork covering the specimen surfaces under environmental drying was experimentally investigated by measuring deformation, interior humidity and temperature simultaneously. PSLWA was used as the internal curing agent for the concrete. The global deformation, internal humidity and temperature were immediately measured after a few hours of the specimens casting to 35 days. During processing the shrinkage strain from global deformation, the temperature induced deformation is properly considered and the shrinkage strain produced only by cement hydration and environmental drying is obtained.

2. Experimental program

2.1 Details of materials and specimens
A kind of concrete with compressive strength about 90 MPa at 28 days was used in the tests. For internal cured concrete, the mixture was modified based on the basic proportions with a certain amount of normal aggregates replaced by PSLWA. Slightly changed water to cement ratio compared with the reference was used for the mixtures with PSLWA in order to maintain a similar compressive strength among all the mixtures. Fly ash based lightweight aggregate with particle size of 2 to 5 mm, porosity of 0.37, water absorption of 21% after 7 days of soaking, dry density of 1375 kg/m³ was used as the carrier of internal curing water. Figure 1 is the photograph of the lightweight aggregate used in experiments. All mixtures were made with the same Portland cement. Natural sand and crushed limestone with a maximum particle size of 5 mm and 15 mm, respectively, were used as customary fine and coarse aggregates. The concrete mixture proportions used in the present work are listed in Table 1. A polycarboxylate superplasticizer with 30% solid content was used in these mixtures to guarantee that the fresh concrete has a similar slump of 90-120 mm. The mold used to cast the specimens was made of plexiglass with inner dimensions of 100×100×400 mm. The four inner sides of the mold were covered with four pieces of removable plastic sheets with 20 mm thickness and the bottom of the mold was covered with a thin vinyl sheet with 1 mm thickness to decrease the frictional resistance between the mold and the concrete specimen. After the initial set of the concrete, the inner four removable plastic sheets were lifted to create a “restraint-free” condition for the shrinkage test.

2.2 Devices for measuring the relative humidity, temperature and deformation
In this study, the humidity and temperature at the center
of the tested specimen were measured. Electric resistance based digital sensor that can measure humidity and temperature at the same time was used. The measuring accuracies of relative humidity and temperature are 2% and 0.5 ºC, respectively. In order to maintain the sensor at the designated location in the concrete, a PVC tube with an inner diameter of 15 mm was used to hold the sensor. The bottom end of the PVC tube was glued with a plastic sheet. To maintain the moisture exchange with the surrounding concrete, two oblong holes were made at the surface of the PVC tube. In order to prevent fresh cement paste from flowing into the tube through these rectangular holes, a steel bar with a little smaller diameter than that of the PVC tube was placed into the tube in advance during concrete casting. About 2 hours after casting, the steel bar was removed from the tube and the sensor was inserted. To ensure the measured humidity and temperature reflect the actual values inside the concrete, two rubber O-shaped rings with a 2 mm thickness were used to isolate the free gap between the PVC tube and the sensor bar. The O-shaped ring was slightly above the sensory section of the sensor. In the meantime, at the top of the tube, the gap was sealed by an industry sealant to make sure that the moisture does not leak through the gap. Thus, the sensory section was only connected to the concrete just at the point where humidity and temperature were measured. The structural details of the PVC tube can be found in Fig. 2. The deformation was measured by two linear variable differential transducers (LVDTs) mounted on the two long ends of the specimen. The measuring range of the LVDT was 2 mm and the measuring accuracy was 1 μm. To assure the LVDTs were in good contact with the concrete, two small cylinder bars (see Fig. 2a) were pre-cast into the concrete at the centers of the two long ends of the specimen. The sensory bar of the LVDT was in contacted with the small bar during testing.

2.3 Concrete mixing, specimen casting and curing procedures

The lightweight aggregate was pre-soaked in water for 7 days. Before concrete mixing, the PSLWA was surface dried in the laboratory and kept in a sealed container. The concrete mixing procedure can be described as follows. First, the normal fine and coarse aggregates were mixed together. Next, the cement was added followed by the required water with the superplasticizer mixed in and the mixing continued for 2 minutes. Then the PSLWA was added and the mixing continued for another 2 minutes. Before the concrete casting, plastic sheets used to seal the specimen were put into the mold first. In the mean time, the two copper measuring probes were fixed at the designated locations (see Fig. 2a). Then, the fresh concrete was cast into the mold in two layers and was consolidated by a vibrating table. After compacting, the PVC tube with the steel bar inserted was put into the concrete at the appointed depth from the casting surface. While placing the tube, the vibration was started again to make sure the PVC tube was in effective contact with the surrounding concrete. After finishing the surfaces, the casting face was also covered with a plastic sheet to prevent moisture exchange with its surroundings. About

\[
\text{Humidity Sensor} \quad \text{PMMA Mould} \\
\text{Displacement Sensor} \quad \text{PVC Tube} \\
\text{Thin Plate to be Pulled Out} \quad \text{Pre-buried Copper Shrinkage-measuring Probe} \\
\text{Unit: mm} \\
\]

\[
\text{Humidity Sensor} \quad \text{O-Shaped Ring} \\
\text{PMMA Mould} \quad \text{ECC Cover} \\
\text{Concrete Sample} \quad \text{PTFE Plate} \\
\text{Unit: mm} \\
\]

Fig. 2 Schematic diagrams of concrete humidity and deformation measurement, (a) test set-up, (b) specimens under drying without permanent formwork and (c) with permanent formwork.
2 hours after casting, the steel bar was removed from the tube and it was verified that there was no liquid water left inside the tube before the humidity sensor was inserted. Meanwhile, after the initial set of the concrete (about 2 hours from casting), the four removable thin sheets were slowly lifted and a 20 mm gap between the specimen and the mold was made.

For specimens with fiber reinforced boards used as permanent formwork on the two long faces, the above 20 mm gap pre-filled was replaced with 10 mm thick one and the remaining 10 mm space was filled with fiber reinforced cementitious boards pre-fabricated in the laboratory. A Polyvinyl Alcohol fiber (PVA) reinforced cementitious composite called engineered cementitious composite (ECC) originally developed by Li was used to make the board (Li 2002; Zhang et al. 2009). The ECC board was pre-fabricated with extruding technique, which ensures the density of the board meets the requirements of surface decoration for concrete members (Zhang et al. 2011). There were small special scraggly layers on one side of the board to enhance the bond between concrete and the board, as showed in Fig. 2c. The mix proportion of the ECC board used is listed in Table 2.

The physical properties of raw materials of the ECC board as well as the tensile behaviors and shrinkage properties of the low shrinkage ECC material used in this study can be found in the author’s previous publications (Zhang et al. 2009). The ECC boards were cured in room for 28 days and soaked in water for 24 hours before used as the formwork. By casting fresh concrete between the two ECC boards, the specimen with permanent formwork on both two long sides was made, see Fig. 2c.

Afterward, two LVDTs were installed at the two long ends of the specimen. In order to investigate the shrinkage behavior of high strength concrete with and without ECC cover under drying conditions, two specimens with the same mixture proportion were cast for each concrete, one with ECC cover and another without. After 3 days of concrete casting, the plastic sealing film covering the five surfaces of the two specimens was removed. Figure 3 is a photo showing the two parallel specimens under testing. The tests were continued until 35 days since concrete casting. All tests were carried out in a laboratory with a temperature of 23±2°C controlled by air-condition.

After the tests, the humidity sensors were calibrated using a saturated salt solution under a constant temperature of 22°C. The saturated salt solution was prepared with distilled water and salts. The sensory section of the sensor and saturated salt solution were placed in a sealed container made of the corrosion resistant and non-hydrophilic material. For each calibration process, the final displayed relative humidity that does not change with time was used as the measured value of the sensor under the specific moisture environment. Each sensor was calibrated at five different humidity levels (Zhang et al. 2013). Based on the calibrating results, the measured humidity data was revised.

3. Experimental results and discussion

3.1 Development of deformation, internal humidity and temperature with age

The compressive strength measured by cubic specimens with the dimension of 100mm×100mm×100mm of the three mixtures of concrete at 28 days are listed in Table 3. Clearly, the differences in compressive strength between normal concrete and concretes with PSLWA are small, means the reduction on compressive strength due to the addition of PSLWA was compensated by adjusting the water to cement ratio in each internal cured mixture as listed in Table 1. From the compressive strength test results, we can see that a similar compressive strength for all mixtures was achieved in the experimental program. This should guarantee the comparison of drying and autogenous shrinkage between different mixes is based on the condition that all of the concretes have a similar mechanical performance.

Figures 4 to 9 present the test results of the development of internal humidity, global deformation and inside temperature with age since concrete casting of the three high strength concretes, C80-0, C80-1 and C80-2 respectively, under with and without ECC cover conditions. Each pair of figures displays (a) the maximum time scale results and (b) the beginning portion of the results in order to present the details in the beginning few days.
since mixing with water. From the results shown in the figures, first we can observe that the internal relative humidity of concrete since cast can be described as a water-vapor saturated stage with 100% relative humidity (stage I) followed by a stage that the relative humidity gradually decreases (stage II). The reduction on internal relative humidity in early-age concrete is significantly influenced by the three actions, surface drying, addition of PSLWA and use of ECC cover. As long as surface drying starts, the internal humidity immediately decreases at a faster rate. Surface drying speeds up the loss of moisture inside of concrete. Accordingly, the deformation grows with a faster speed also as drying starts. As PSLWA is added, the reduction rate of interior humidity is obviously decreased, and accordingly the growing rate of deformation is decreased. More interesting observation is found that as the ECC board was used as permanent formwork of the specimens, both of

Fig. 4 The development of internal humidity and global deformation with age of C80-0 concrete, (a) full range of test, (b) initial period of test.

Fig. 5 The development of inside temperature and global deformation with age of C80-0 concrete, (a) full range of test, (b) initial period of test.

Fig. 6 The development of internal humidity and global deformation with age of C80-1 concrete, (a) full range of test, (b) initial period of test.
the reduction on internal humidity and the deformation growing rate were decreased notably even in the case with PSLWA addition. This indicates that both autogenous and drying shrinkage may be reduced by applying internal curing and permanent formwork covering respectively. More detailed analysis of the effect of permanent formwork and internal curing on shrinkage of high strength concrete will be given in the later section together with the analysis of developing characteristics of shrinkage.

Second, looking at the details of global deformation-time curves shown in the figures, the free deformation of concrete without ECC cover at a very early age is characterized by double expanding behavior, see Figs. 4b-9b. The specimen first swelling, which was likewise found by Kamen et al. on ultra-high performance fiber reinforced concrete and by Sule et al. and Bentur et al., Zhang et al. respectively on conventional concrete.
(Kamen et al. 2008; Sule et al. 2000; Bentur 2001; Zhang et al. 2010). After achieving the first peak of swelling (P1 in Figs. 5b, 7b, 9b), the specimen starts to shrink at a gradually decreasing rate. After achieving a first shrinkage peak P2, at around 0.2 to 0.4 days since concrete cast, the specimens start to expand again and achieving a peak, P3, which corresponds well to the temperature peak of the specimen. After that the specimen begins to shrink monotonously. The first swelling peak should be attributed to the volume changes produced by cement hydration, moisture diffusion and by temperature variation result in plastic settlement, which, in turn, produces lateral swelling and top shrinking in general, because at this moment the concrete behaves as a plastic material. In addition, uptake of bleed water may contribute to the initial swelling as well.

After a period of time, a combination of particle interference and hydration products gives stiffness which is sufficient to permit the concrete to support its own weight. In general, we call this point as the setting time of the concrete that may be determined more precisely by a lateral pressure test, in which the setting time is defined as the time when the lateral pressure becomes zero (Amziane 2006). After passing the setting point, lateral deformation exhibits shrinking instead of swelling. The end of the first swelling should correspond to the point of the transformation of concrete from a plastic state to a solid state (Zhang et al. 2010). Thus, the setting time of fresh concrete can be determined by measuring a complete deformation-time diagram under free boundary conditions. After setting of concrete, the deformation of the specimen behaves shrinking. At a certain age after setting, such as about 0.4, 0.2 and 0.4 days for concrete C80-0, C80-1 and C80-2 respectively, the specimen deformation behaves expansion again and stops at 0.55, 0.58 and 0.60 days respectively for the concretes. It is interesting to note the second expansion peak accords with the temperature peak measured at the center of specimen well, see Fig. 5b, Fig. 7b and Fig. 9b. The second expansion peak is notably enhanced by addition of PSLWA. After that, specimens continue to shrink with age monotonously. As ECC cover was used in the specimens, this complicate deformation pattern in early age is simplified through reduction on both swelling and shrinkage due to the restraining action of the ECC board. Certainly, the first and the second expansion peaks can still be observed. As one of the both parallel specimens undergoes surface drying, the shrinkage deformation accordingly develops at a fast rate. Apparently, deformation behavior of concrete at early-age is a complex process and generally shrinkage and thermal deformation are the two primary sources of the deformation after setting of concrete.

3.2 Autogenous and drying shrinkage of concrete with addition of PSLWA

To obtain the shrinkage deformation from the total global deformation, the temperature-induced displacement must be subtracted first. The typical results showed in Figs. 5, 7 and 9 display the temperature inside the concrete specimen, which first rises then decreases after achieving a peak and finally follows with the variation of environmental temperature. Assuming the moisture-induced deformation is \( \varepsilon_{\text{m}} \) and temperature variation produced deformation is \( \varepsilon_t \), the experimentally measured total deformation \( \varepsilon \) after setting of concrete is assumed mainly composed of the above two parts, i.e.:

\[
\varepsilon = \varepsilon_{\text{m}} + \varepsilon_t
\]  

The temperature-induced deformation can be calculated if the temperature and thermal expansion coefficient of concrete are known. Test results on thermal expansion coefficient of concrete at early-ages measured by using a temperature stress testing machine shows the thermal expansion coefficient of concrete at very early-age decreases with age and finally goes into a plateau stage after the initial descending stage (Zhang 2005). Results obtained by Yang and Sato (2001) shows the thermal expansion coefficient of high strength concrete at early-age first decreases with age and then slightly increases a bit with age. Apparently, it is still a difficult work at present to extreme accurately measure the thermal expansion coefficient of concrete at very early age due to the high variation of material content in this stage (Turcley et al. 2002). In the present work, the thermal expansion deformation is calculated with an estimated thermal expansion coefficient obtained by Zhang (Zhang 2005). According to that study, the thermal expansion coefficient of concrete used in the present work at early-age is estimated as:

\[
\beta_t = C \cdot \exp(-\gamma \cdot t_{eq}) + \beta_0
\]  

where \( \beta_t \) is the thermal expansion coefficient at a given time \( t_{eq} \) (in hours) after casting. \( t_{eq} \) is called equivalent age that taking the influence of temperature on cement hydration into account. \( C, \gamma, \beta_0 \) are constants, which are listed in Table 3 for the three concretes. The equivalent age \( t_{eq} \) can be calculated by the following procedures. The equivalent age concept assumes that samples of a concrete mixture of the same equivalent age will have the same mechanical properties or cement hydration degree, regardless of the combination of time and temperature yielding the equivalent age (Kjellsen et al. 1993). Based on above definition, the equivalent age \( t_{eq} \) can be expressed as

\[
t_{eq} = \int_{0}^{t} e^{\frac{1}{\beta_0}} \cdot \frac{U_{ar}}{298} \cdot \frac{U_{ar}'}{298} \cdot dt
\]  

where \( t_{eq} \) is the equivalent age at the reference temperature (here the reference temperature equal to 20°C is assumed in the present paper). \( U_{ar} \) and \( U_{ar}' \) are the apparent activation energy (J/mol) at the reference and actual temperature respectively. \( R \) is the universal gas constant, 8.314J/molk. \( T \) is temperature in Celsius (°C).
In regard to the apparent activation energy, a number of researchers have concluded that it could not be considered as a constant independent of time except during the beginning of cement hydration (Chanvillard et al. 1997; Kim 2001). Based on these findings, the apparent activation energy of concrete is expressed as a function of temperature and curing time as (Pane et al. 2002):

\[ U_a = (42830 - 43T) e^{40000/T} \]  

(4)

where \( T \) is curing temperature (°C) and \( t \) is curing time in days. Because the actual curing temperature \( T \) inside of concrete varies with time, it is convenient to solve \( t_{eq} \) in matrix form instead of integrating. If the curing time is divided into \( n \) sections and the temperature in each time interval is assumed to be a constant, then we have

\[ t_{eq} = \sum_{i=1}^{n} \frac{1}{293} \left( \frac{U_a}{373} \right) (t_i - t_{i-1}) \]  

(5)

The section number \( n \) may depend on the required accuracy and normally can be equal to the time intervals for temperature measurement.

**Figure 10** presents the thermal deformation coefficient as a function of equivalent age of the three concretes used in present experiments. Typical result of deformation-time diagrams before and after subtracting the thermal dilation is displayed in **Fig. 11**, in which (a) presents the results of 35 days and (b) presents the results of the initial 3 days to view the deformation characteristics just before and after setting clearly. The development of temperature inside of concrete is also displayed in the figures. From the figures, we can observe that the shrinkage value for a given age is increased as the thermal deformation is subtracted. It should be noted that the second expansion peak is not compensated completely after subtracting the thermal deformation. This phenomenon was also observed by Turcry et al. in studying autogeneous shrinkage and thermal deformation of cement paste at an early age (Turcry et al. 2002). But the dilation peak is decreased indeed after considering the thermal deformation and we may conclude that the thermal deformation should be one of the main sources of the succeeding expansion occurred in experiments. The accuracy of the thermal deformation coefficient may also be the cause of leaving a slight dilation peak on shrinkage-age diagram. Certainly, the other mechanisms, such as the formation of expansive products of cement hydration may also be the possible reasons for the formation of the second expansion. To clearly understand the above phenomena, more detailed studies will be needed in the future.

After subtracting the thermal dilation and moving the beginning point of deformation to the end of the swelling, we can obtain the effective free shrinkage strain vs. time diagrams under with and without ECC cover. These results are shown in **Figs. 12 to 14** for induced curing water to cement ratio (W/C) of 0, 0.08 and 0.12 respectively, labeled as C80-0, C80-1 and C80-2 concrete,
in which figure (a) presents the results of 35 days and figure (b) presents the results of initial 2 days to view the deformation characteristics just before and after setting clearly after subtracting the thermal dilation. To analyze the correlation between shrinkage and interior humidity, the progress of interior humidity with age of each concrete is also presented in the figures. From the results shown in the figures, first we can observe that as PSLWA is added, the reduction rate of internal humidity is obviously decreased and the reduction trend with age changes from no-linear pattern to an almost linear pattern. For a given age, the greater the PSLWA addition, the lower the reduction of interior humidity. As the ECC cover is used as permanent formwork of the specimen, the reduction rate of internal humidity decreases also like the way of PSLWA does. In present experiments, the relative humidity at 28 days after cast is 83.8%, 95.2% and 98.8% respectively for C80-0, C80-1 and C80-2 concrete, in the case of ECC cover applied. For the case without ECC cover, corresponding humidity values are 73.7%, 94.0% and 98.8% respectively for C80-0, C80-1 and C80-2 concrete. Clearly, the self-desiccation resulting from cement hydration in high strength concrete is significant and surface drying will also increase the moisture loss from concrete. The introduction of internal curing water by adding PSLWA into high strength con-
concrete can greatly improve the moisture status inside of concrete under both ECC cover and drying conditions. Application of pre-fabricated ECC board as permanent formwork of the specimen can also delay the moisture loss of concrete. In the case without PSLWA addition, the internal humidity at 28 days increased from 73.7% to 83.8%. As W/C IC/C=0.12, almost the identical internal humidity at 28 days increased from 73.7% to 94.0% respectively for C80-0, C80-1 and C80-2 concretes. As the ECC board is used as permanent formwork, the shrinkage strain of high strength concrete completely, especially the reducing efficiency on the shrinkage developed in the initial few hours since concrete set, such as ε1, defined in the present paper, is relatively low. This is understandable because internal curing can principally reduce the capillary stress in the stage of interior humidity decreasing (RH stage II) from initial saturated stage, which in turn reduces the shrinkage strain developed in this stage. In the case of ECC cover used, the shrinkage strain, including ε1, is decreased notably. This means that the impact of ECC cover on ε1 is more significant than that internal curing does. Therefore, the overall shrinkage strain after ECC cover used is reduced notably as well comparing to the internal cured concrete without ECC cover. After applying the combination of internal curing and permanent formwork, the shrinkage strain of high strength concrete at 28 days under drying condition can be reduced from 582 μm/m to 70.6 μm/m, which means such concrete should be able to prevent not only autogenous shrinkage induced cracking, but also drying shrinkage induced cracking. This interesting finding may help to improve the design of high strength concrete structures focusing on prolonging its service life.

Second, from the shrinkage-age diagrams, an obvious two-stage pattern of the development of shrinkage strain versus age starting from concrete setting can be observed and displaying as a fast developing stage within a few hours followed by an increasing stage at a gradually reduced rate (Zhang et al. 2013). The first stage shrinkage strain, ε1, is ordinarily developed within the humidity saturated stage (RH stage I). In the present work, the value of ε1 is 278, 222 and 184 μm/m respectively for C80-0, C80-1 and C80-2 concrete in the case of without ECC cover. Apparently, the value of ε1 decreases with the increase of PSLWA, but the minimum value of ε1 is still as much as 184 μm/m even with the highest amount of internal curing water was used in the present experimental program. The narrow effect of the addition of PSLWA on ε1 may be due to its impact on water to cement ratio of concrete as additional water is released from LWA to cement paste during hardening. The more PSLWA is added, the more curing water should be released. Existing results show that the lower the water to cement ratio, the higher the ε1 (Zhang et al. 2012). Therefore, addition of PSLWA in concrete will lead to reduction of ε1. In the case of ECC cover used, the shrinkage strain of ε1 was continually reduced compared with the case without ECC cover. The value of ε1 becomes 110, 145 and 50 μm/m respectively for C80-0, C80-1 and C80-2 concrete in the case of with ECC cover. The efficiency is significant regarding the impact of the ECC board on first stage shrinkage strain of high strength concrete even with PSLWA addition. This may principally owe to the restraint between ECC board and fresh concrete. Prevention of moisture loss of the ECC cover resulting shrinkage reduction should be pronounced in the second stage of shrinkage progress.

In the second stage of shrinkage development, the magnitude of shrinkage strain for a given age depends on both surface status of specimen, with and without ECC cover, and addition of PSLWA. Once surface drying starts, the shrinkage is also developed with a fast speed in the case of without ECC cover. Meanwhile, drying shrinkage is reduced with the increase of internal curing water. In present experiments, shrinkage at 28 days after casting under drying conditions in the case without ECC cover is 582, 381 and 305 μm/m respectively for the induced curing water to cement ratio (W/C IC/C) of 0, 0.08 and 0.12, corresponding to C80-0, C80-1 and C80-2 concrete. The corresponding humidity values measured at the center of specimen at 28 days are 73.7%, 94.0% and 98.8% respectively for C80-0, C80-1 and C80-2 concretes. As the ECC board is used as permanent formwork of the specimen, the drying shrinkage is continually reduced comparing to the case without ECC cover, likewise the reduction on ε1. Shrinkage strain at 28 days after casting under drying conditions in the case of with ECC cover is 340.3, 199.4 and 70.6 μm/m respectively for C80-0, C80-1 and C80-2 concrete. And the corresponding humidity values measured at the center of specimen at 28 days are 83.8%, 95.2% and 98.8% respectively. The experimental measured interior humidity value, shrinkage strain under with and without ECC cover at 28 days, as well as the ε1 of all mixtures in terms of induced curing water to cement ratio is plotted in Fig. 15. From above results, we may conclude first that the internal curing cannot compensate the shrinkage of high strength concrete completely, especially the reducing efficiency on the shrinkage developed in the initial few hours since concrete set, such as ε1, defined in the present paper, is relatively low. This is understandable because internal curing can principally reduce the capillary stress in the stage of interior humidity decreasing (RH stage II) from initial saturated stage, which in turn reduces the shrinkage strain developed in this stage. In the case of ECC cover is used, the shrinkage strain, including ε1, is decreased notably. This means that the impact of ECC cover on ε1 is more significant than that internal curing does. Therefore, the overall shrinkage strain after ECC cover used is reduced notably as well comparing to the internal cured concrete without ECC cover. After applying the combination of internal curing and permanent formwork, the shrinkage strain of high strength concrete at 28 days under drying condition can be reduced from 582 μm/m to 70.6 μm/m, which means such concrete should be able to prevent not only autogenous shrinkage induced cracking, but also drying shrinkage induced cracking. This interesting finding may help to improve the design of high strength concrete structures focusing on prolonging its service life.

Fig. 15 Interior humidity, shrinkage strain ε1, drying shrinkage of high strength concretes versus induced curing water-to-cement ratio, under with and without ECC cover.
4. Summary and conclusions

In this paper, the influence of internal curing using pre-soaked lightweight aggregate (PSLWA) and pre-fabricated fiber reinforced engineered cementitious composite board (ECC) as permanent formwork on shrinkage and internal humidity of high strength concrete are investigated by continuously measuring the deformation and interior humidity of test specimen since specimen casting under drying condition. Three mixture proportions with induced curing water to cement ratio (W/C) of 0, 0.08 and 0.12, called C80-0, C80-1 and C80-2, were utilized in the experiments. The following conclusions can be drawn from the present study:

1. The development of the internal relative humidity of concrete since casting exhibits first a vapor saturated stage (RH=100%, stage I), followed by gradually reducing stage (RH<100%, stage II). As PSLWA was added, the reduction rate of interior humidity in stage II is noticeably decreased. Surface drying can still lead to reduction of internal humidity of concrete even internal curing is used. As the ECC cover is used, the reduction of internal humidity of high strength concrete can effectively be delayed.

2. A two-stage pattern of development of shrinkage strain with age starting from concrete setting can be observed, displaying a fast developing stage within a few hours (stage I) followed by an increasing stage at a gradually reduced rate (stage II). Shrinkage of high strength concrete decreases with the increase of induced internal curing water. However, the effect on shrinkage developed in the initial fast growing stage (stage I) is not obvious.

3. As the pre-fabricated ECC board is used as permanent formwork, the combined effects of internal curing and ECC cover can greatly reduce the shrinkage not only developed in the stage I, but also the shrinkage developed in stage II.

Acknowledgements

This work has been supported by a grant from the National Science Foundation of China (51178248) and a grant from a Specialized Research Fund for the Doctoral Program of Higher Education (20130002110034) to Tsinghua University.

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