Evaluation of Shrinkage Induced Cracking in Concrete with Impact of Internal Curing and Water to Cement Ratio
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Evaluation of Shrinkage Induced Cracking in Concrete with Impact of Internal Curing and Water to Cement Ratio

Zhang Jun¹*, Han Yudong² and Zhang Jiajia³

Abstract

In this paper, the effect of internal curing with pre-soaked lightweight aggregate (PSLWA) on shrinkage and interior relative humidity of four series concretes with compressive strength at 28 days around 30MPa, 60MP, 90MPa and 100MPa is investigated. The shrinkage induced cracking performance of concretes is evaluated with concrete-steel composite ring tests. The results show that 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). Under sealing, internal relative humidity at the center of the specimen for a given age is obviously decreased with increase of concrete strength. Under drying, similar internal relative humidity value is observed at 28 days for all concretes without internal curing. As PSLWA was added, the reduction rate on interior humidity in stage II is significantly decreased. But the efficiency on internal humidity rising is greatly influenced by concrete strength. The autogenous shrinkage is increased with increase of concrete strength. The drying shrinkage is decreased with increase of concrete strength. The total shrinkage of concrete is increased with increase of concrete strength. As PSLWA was added, the shrinkage reduction in both autogenous and drying shrinkages is obviously in high strength concretes, such as 90MPa and 100MPa concretes. The shrinkage reduction of internal curing on relatively low strength concrete, such 30MPa and 60MPa concretes is not obvious. Internal curing with PSLWA can greatly improve the shrinkage induced cracking performance. All concrete rings without internal curing are cracked under drying. The compressive strain in the steel ring at the concrete ring cracking is about 75 to 101μm/m. By contrast, the stable compressive strain at the inner steel ring for the concretes with internal curing becomes 10 to 40μm/m and no visible cracks were found on the specimens.

1. Introduction

Shrinkage of concrete is one of the major sources of the formation of cracks in concrete structures. Cracks allow water and chemical agents, such as deicing salt, to go through the cover layer to make contact with the reinforcement, leading to reinforcement corrosion and rupture in steel reinforced concrete. 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 and Wittmann 2002; Zhang et al. 2010). In general, environmental drying and cement hydration are the two major processes causing moisture loss inside the 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 called self-desiccation and the corresponding shrinkage of concrete is called autogenous shrinkage.

Generally, the autogenous shrinkage of concrete is dependent upon water to cement ratio of concrete. The higher the water to cement ratio, the lower the autogenous shrinkage. And strength of concrete is inversely proportional to water to cement ratio. Therefore, high strength concrete generally has higher autogenous shrinkage comparing with that of normal strength concrete. A similar problem arise in high performance concrete due to its high content of cementitious materials. On the other hand, high strength concrete generally has lower drying shrinkage comparing with that of normal strength concrete due to the difference in moisture diffusivity (Zhang et al. 2014; Zhang et al. 2016). To avoid the shrinkage induced cracking in concrete structures, including normal and high strength concrete structures, it is necessary to compensate or slow down the moisture loss from concrete. 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 and Bentz 2009; Zhang et al. 2013). However, many studies have focused merely on the effectiveness of internal curing using saturated lightweight aggregate on autogenous shrinkage. In actual concrete structures, cement hydration and...
surface drying generally take place simultaneously. Concrete shrinkage at a certain place is the sum of drying and autogenous shrinkages and the shrinkage along the depth from the drying surface to inside of concrete is not uniformly distributed. Therefore, integrative studies on autogenous and drying shrinkages of high strength concrete with internal curing are needed in order to know the effectiveness of such technique in the case of concrete suffering from environmental drying. In addition, the studies on the impact of internal curing on shrinkage of normal strength concrete are also required in order to know the applicable of the technique on it. Meanwhile, evaluations on the sensitivity of shrinkage induced cracking of concrete with impacts of internal curing and concrete strength or water to cement ratio are critically needed as well to learn how the reduced shrinkage strain may increase the load carrying capacity of structures before cracking.

The purpose of this article is to investigate the cracking sensitivity of internal cured concrete with PSLWA under shrinkage load. Four kinds of concretes with compressive strength at 28 days of about 30MPa, 60MPa, 90MPa and 100MPa were used in the experiments, which may represent low, middle, high and ultra high strength of concrete in practice. The progress of shrinkage and interior humidity with age of different concretes were quantified from this experimentally measured in order to assess the anti-cracking performance of the materials. Cracking sensitivity of concrete under shrinkage load is evaluated with steel-concrete composite ring tests by measuring the compressive strain along the circle direction in the steel ring and by observation of cracking status on the ring specimen. The shrinkage induced cracking performance of concrete with impact of internal curing and water to cement ratio is analyzed and conclusions are provided at end of the paper.

2. Experimental program

Two parts of tests are involved in the experimental program. First, development of shrinkage and interior humidity of concrete with and without internal curing under plastic film sealed and drying conditions were experimentally measured. The impacts of internal curing and water to cement ratio on the progress of shrinkage and interior humidity of concrete were quantified from this test. Second, cracking sensitivity of concrete under shrinkage load was assessed by ring tests through recording the compressive strain along the steel ring that resulted from shrinkage of composite and through observation on the cracking status of the ring specimen.

2.1 Materials

Four basic concrete mixtures with water to binder ratio (W/B) of 0.62, 0.43, 0.30 and 0.20 to form four kinds of concretes with compressive strength at 28 days around 30MPa, 60MPa, 90MPa and 100MPa, which are labeled as C30, C60, C90 and C100 respectively, representing low, middle, high and extra high strength concretes in practice, were used in the experiments. Based on the above four basic mixtures, four mixtures were designed with a certain amount of normal aggregates replaced by PSLWA to form additional four corresponding concretes with internal curing. The mixture of concrete containing lightweight aggregate is designed according to the amount of internal curing water required based on the above basic mixture proportion (Zhang et al. 2013). Slightly different water to cement ratios compared to the reference was used for the mixtures with PSLWA in order to maintain a similar compressive strength of all mixtures. It should be noted that the decrease of water to cement ratio may lead to increase of autogenous shrinkage of concrete a little. But on other hand, such increase of autogenous shrinkage will lead more challenges on shrinkage reduction with PSLWA. Fly ash based lightweight aggregate with particle size of 2 to 5 mm, porosity of 0.27, water absorption of 21% after 7 days of soaking, dry density of 1375 kg/m^3 was used as 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 20 mm, respectively, were used as normal fine and coarse aggregates. The concrete mixture proportions used in the present work are listed in Table 1. A superplasticizing admixture was used in these mixtures to guarantee that the fresh concretes have a similar slump of 90-120 mm.

2.2 Specimens, Curing and Testing Procedures

2.2.1 Shrinkage tests

In shrinkage tests, the mold used to cast the specimens was made of plexiglass with inner dimensions of 100×100×400 mm. Each of the two long inner sides of the mold was covered with two removable plexiglass sheets with 10×100×400 mm to create 20 mm wide spaces in each long side for specimen drying. Meanwhile,
the two short inner sides of the model were covered with two pieces of removable plastic sheets with 2 mm thickness as well and the bottom of the mold was covered with a thin vinyl sheet with 1 mm thickness to reduce the frictional resistance between the mold and the concrete. After initial set of the concrete, the removable inner sheets were lifted to create the drying space of the shrinkage test. The specimen size of concrete in shrinkage test is 60\times100\times400 mm. In the test, the humidity at the center of the specimen was measured. Resistance based digital humidity sensor with measuring accuracies of 2\% was used for interior humidity measurement. 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. One end of the PVC tube was covered with a plastic sheet glued to the end. To maintain the moisture exchange with the surrounding concrete, three rectangular holes were made at the surface of the PVC tube. In order to prevent fresh cement paste from flowing into the tube through the rectangular holes, a steel bar with a little smaller diameter than that of the PVC tube was placed into the tube first during concrete casting. A few minutes after casting, the steel bar was removed from the tube and the sensor was inserted. To ensure the measured humidity and temperature reflect the real values inside the concrete, two rubber O-rings with a 2 mm thicknesses were used to isolate the free gap between the PVC tube and the sensor bar. The O-ring was just 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 ensure that moisture did not transmit through the gap. Thus, the sensory section is only connected with the concrete where we wish to measure its humidity and temperature values. 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 is 2 mm and the measuring accuracy is 1 \mu m. To let the LVDTs were in good contact with the composite, two small cylinder bars were pre-cast into the specimen at the centers of the two long ends of the specimen. The sensory bar of the LVDT was direct contact with the small bar during testing. The overall schematic diagram of the humidity and deformation measurement set-up is illustrated in Fig. 2.

The lightweight aggregate was 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 with and without internal curing 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 supperplasticizer mixed in and the mixing was continued for 2 minutes. For internal cured concrete, the PSLWA was added then and continued for another 2 minutes of mixing. Before the material casting, plastic sheets used to seal the specimen were put into the mold. Meanwhile, two copper measuring probes were fixed at the designated locations. 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 fresh material at the designated depth from the casting surface. While placing the tube, the vibration was started again to sure the PVC tube was in contact with the surrounding material well. After finishing the surfaces, the casting face was covered with soft plastic sheet to prevent moisture exchange with its surroundings. About 1 to 2 hours after casting, the

<table>
<thead>
<tr>
<th>No.</th>
<th>Cement</th>
<th>Silica Fume</th>
<th>Fly Ash</th>
<th>Water</th>
<th>Sand</th>
<th>Stone</th>
<th>Dry LWA</th>
<th>Water provided by LWA</th>
<th>W/B</th>
<th>W_{IC}/C</th>
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<tr>
<td>C30-OC</td>
<td>240</td>
<td>-</td>
<td>60</td>
<td>186</td>
<td>750</td>
<td>1150</td>
<td>0</td>
<td>0.620</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>C30-IC</td>
<td>252</td>
<td>-</td>
<td>63</td>
<td>181</td>
<td>473</td>
<td>867</td>
<td>288</td>
<td>0.572</td>
<td>0.240</td>
<td></td>
</tr>
<tr>
<td>C60-OC</td>
<td>345</td>
<td>-</td>
<td>85</td>
<td>185</td>
<td>685</td>
<td>1090</td>
<td>0</td>
<td>0.430</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>C60-IC</td>
<td>367</td>
<td>-</td>
<td>92</td>
<td>175</td>
<td>409</td>
<td>808</td>
<td>287</td>
<td>0.381</td>
<td>0.165</td>
<td></td>
</tr>
<tr>
<td>C90-OC</td>
<td>450</td>
<td>50</td>
<td>-</td>
<td>150</td>
<td>580</td>
<td>1140</td>
<td>0</td>
<td>0.300</td>
<td>0.00</td>
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</tr>
<tr>
<td>C90-IC</td>
<td>494</td>
<td>55</td>
<td>-</td>
<td>134</td>
<td>309</td>
<td>864</td>
<td>281.3</td>
<td>0.250</td>
<td>0.120</td>
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<tr>
<td>C100-OC</td>
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<td>60</td>
<td>-</td>
<td>119</td>
<td>590</td>
<td>1156</td>
<td>0</td>
<td>0.200</td>
<td>0</td>
<td>0</td>
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<tr>
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<td>64</td>
<td>-</td>
<td>94</td>
<td>310</td>
<td>900</td>
<td>310</td>
<td>0.153</td>
<td>0.120</td>
<td></td>
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</tbody>
</table>

Fig. 2 Schematic diagram of concrete humidity and deformation measurement.
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, the removable sheets were slowly lifted and gap between specimen and mold was created after initial set of the concrete. Afterward, two LVDTs were installed at the two long ends of the specimen. The deformation was measured as the horizontal movement of the two bars placed centrally in both ends of the specimen. During the test, humidity and deformation were automatically recorded every 10 min by a personal computer. In order to investigate the shrinkage behavior under both sealing and drying conditions, two identical specimens were cast for each mixture. After 3 days of specimen cast, the plastic film covering the two long side surfaces of the one specimen was removed to simulate the drying condition. While the other specimen keeps the sealing state to compare with the drying specimen. A photo showing two parallel specimens under testing is presented in Fig. 3. The tests were continued until 28 days since concrete casting. All tests were carried out in a laboratory with a temperature of 20±2°C. Meanwhile, compressive specimens with dimension of 100mm×100mm×100mm of the four groups of concrete were prepared as well and cured under the same conditions as used in shrinkage tests.

After the tests, the humidity sensors were calibrated using saturated salt solution under constant temperature of 20°C. The saturated salt solution was prepared with distilled water and analytically pure 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 sensor’s measured value under the specific moisture environment. Each sensor was calibrated at five different humidity levels, and then it’s calibrating curve is obtained. Based on the calibrating results, the measured humidity data was revised. The calibration curves of the humidity sensors used in experiments are displayed in Fig. 4.

### 2.2.2 Ring tests

In order to investigate cracking sensitivity of concrete under shrinkage load, steel-concrete composite ring tests were carried out. A steel ring with the outer diameter of 320 mm and the inner diameters of 290 mm was used in the tests. The outer and inner diameters of the composite ring were 390 mm and 320 mm, i.e. the thickness of concrete was 35 mm. The height of the ring was 150 mm. The geometry of the ring specimen used in the present study is shown in Fig. 5. Each ring specimen was equipped with four strain gauges that were placed at mid-height on the inner circumference of the steel ring. The strain gauges were zeroed before composite ring cast and the strains were automatically recorded every 1 minute after finishing the specimen surface. Concrete mixing procedures with and without internal curing is the same as described previously. The fresh concrete was

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Fig. 3 Experimental set-up for humidity and deformation measurement of concrete at early age under plastic sealing and drying conditions.

![Fig. 3 Experimental set-up for humidity and deformation measurement of concrete at early age under plastic sealing and drying conditions.](image)

Fig. 4 Calibrating curves of RH sensors.

![Fig. 4 Calibrating curves of RH sensors.](image)

Fig. 5 Geometry of the ring specimen.

![Fig. 5 Geometry of the ring specimen.](image)
Table 2 Compressive strength of normal and internal cured concretes at 28 days.

<table>
<thead>
<tr>
<th>No.</th>
<th>Compressive Strength (MPa)</th>
<th>Sealing</th>
<th>Drying</th>
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<tr>
<td>C30-OC</td>
<td>38.0</td>
<td>33.4</td>
<td></td>
</tr>
<tr>
<td>C30-IC</td>
<td>40.6</td>
<td>34.3</td>
<td></td>
</tr>
<tr>
<td>C60-OC</td>
<td>69.0</td>
<td>56.9</td>
<td></td>
</tr>
<tr>
<td>C60-IC</td>
<td>69.6</td>
<td>63.9</td>
<td></td>
</tr>
<tr>
<td>C90-OC</td>
<td>93.1</td>
<td>89.7</td>
<td></td>
</tr>
<tr>
<td>C90-IC</td>
<td>93.5</td>
<td>93.5</td>
<td></td>
</tr>
<tr>
<td>C100-OC</td>
<td>104.1</td>
<td>102.6</td>
<td></td>
</tr>
<tr>
<td>C100-IC</td>
<td>106.2</td>
<td>105.8</td>
<td></td>
</tr>
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</table>

cast into the ring mold in two layers and was consolidated by a vibrating table. After finishing the surfaces, the casting face was sealed with soft plastic sheet to prevent moisture exchange with its surroundings. After 3 days of specimen cast, the outer circular form was removed and the outer circumference of composite ring was exposed to dry. While the top and bottom of the ring keeps sealing. All tests were performed in the same laboratory where the shrinkage tests were carried out. The tests were continued until 28 days since concrete casting.

3. Experimental results and discussion

3.1 Effect of internal curing on compressive strength of concrete

The compressive strength measured by cube specimens with dimension of 100mm × 100mm × 100mm of the four groups of concrete that cured under sealing and drying conditions as used in shrinkage tests at 28 days are listed in Table 2. From the compressive test results, first we can clearly see that differences on compressive strength between different groups are obvious and the concretes used in present work may represent the concrete types used in practice from low strength (30MPa) to high strength (100MPa). Second, the difference on compressive strength between normal concrete and concretes under sealing condition is small in each concrete type, we can first observe that the compressive strength of concrete decreases with increase of compressive strength. For example, the compressive strength reduction due to dry at 28 days after casting is 12.1%, 17.5%, 3.6% and 1.4% respectively for C30-OC, C60-OC, C90-OC and C100-OC respectively. This means the moisture loss due to drying is decreased with increase of concrete strength, which can also be found by comparing the moisture diffusivity of low and high strength concretes (Zhang et al. 2015). Meanwhile, above reduction on compressive strength further decreases as internal curing is used. For example, the compressive strength reduction due to dry at 28 days after casting becomes 15.5%, 8.2%, 0% and 0.4% respectively for C30-IC, C60-IC, C90-IC and C100-IC respectively. Obviously, above positive effect of internal curing on development of compressive strength indicates external moisture curing may not be needed for internal cured high strength concrete. The specific strength value or water to cement ratio of the above boundary may be determined through more detailed experiments. In addition, it should be noted that the addition of PSLWA may reduce the tensile and bending strength of concrete, early age compressive strength as well. Even that a similar compressive strength at 28 days is obtained between the mixtures with and without LWA. It is worthwhile to investigate the effect of internal curing with PSLWA on mechanical properties of concrete, apart from shrinkage behavior.

3.2 Development of shrinkage and internal relative humidity

The test results of the development of shrinkage and internal relative humidity with ages since concrete casting for the four groups of concretes without and with PSLWA under both plastic film sealing and drying conditions are displayed in Fig. 6 to Fig. 9. First, let we look at the progress of internal humidity of all kinds of concrete. From the results shown in the figures, we can observe that the general developing manner of the internal relative humidity of concrete since casting can be described by a water-vapor saturated stage with 100% relative humidity (stage I) followed by a stage in which the relative humidity is gradually decreasing (stage II) (Zhang et al. 2010; Zhang et al. 2012). The reduction of internal relative humidity in early-age concrete is significantly influenced by surface drying, water to cement ratio and addition of PSLWA. As long as surface drying starts, the interior humidity immediately decreases at a faster rate. The surface drying speeds up the loss of moisture inside of concrete. Accordantly, shrinkage grows at a faster speed also as drying starts. In addition, under sealing, the reduction of internal relative humidity in the case of without internal curing is obviously influenced by concrete strength or water to binder ratio. The higher the concrete strength or less the water to binder ratio, the more humidity drop due to self-desiccation. Under environmental drying, a similar level of internal relative humidity may achieve for all concretes without internal curing. This indicates that...
even higher humidity gradient may exist in low strength concrete members than that in high strength concrete elements.

As PSLWA was added, the reduction of internal relative humidity with age is decreased. But the efficiency of the humidity rising is obvious impact by concrete strength or water-binder ratio. Under sealing, internal relative humidity of all concretes of C30, C60, C90 and C100 is raised up close to 100% after PSLWA addition. Under two-faces drying, the amount of internal humidity rising declines with decrease of concrete strength. For C90 and C100 concretes, the internal relative humidity at 28 days is still close to 100%, but for C30 and C60 concrete, the value becomes 74% and 86% respectively. This phenomenon may be attributed to the factor that low strength concrete normally has higher moisture diffusiv-

Fig. 6 Shrinkage and interior humidity versus time diagrams of C30-OC (a) and C30-IC (b).

Fig. 7 Shrinkage and interior humidity versus time diagrams of C60-OC (a) and C60-IC (b).

Fig. 8 Shrinkage and interior humidity versus time diagrams of C90-OC (a) and C90-IC (b).
ity than that of high strength concrete (Zhang et al. 2015; Zhang et al. 2016). The superior moisture diffusivity of low strength concrete will speed up the moisture loss and lower the efficiency of internal curing. For example, the difference on humidity in the center of specimen at 28 days between sealing and drying specimens is 21.1%, 19.4%, 8.0% and 5.9% respectively for C30, C60, C90 and C100 concrete in the case of without internal curing. For internal cured concrete, the difference on humidity at 28 days between sealing and drying specimens becomes 25.8%, 12%, 1.3% and 1.9%. Clearly, moisture keeping ability of concrete is obviously impacted by concrete strength. The higher the strength of concrete, the higher the moisture keeping ability.

Second, from the shrinkage-age diagrams, obvious two stage pattern of the development of shrinkage strain versus age starting from concrete setting can be observed, behaving as a fast developing stage within several hours followed by an increasing stage with a gradually reducing rate (Zhang et al. 2013). This developing manner is displayed in Fig. 10 for the general demonstration, where the two stage mode of interior humidity development described in the previous section is presented accordingly also in the figure. The shrinkage strain developed in the first stage, named $\varepsilon_1$, is normally developed within the humidity saturated stage (RH stage I). In the present work, the value of $\varepsilon_1$ is 44.5, 147.7, 260, 340$\mu$m/m and 164.9, 160.5, 180, 240$\mu$m/m respectively for C30, C60, C90 and C100 without and with internal curing respectively. Apparently, $\varepsilon_1$ increases with increase of concrete strength or water to binder ratio in the case of without internal curing. With internal curing, even the value of $\varepsilon_1$ of concretes still increases with increase of concrete strength, but the rate of increasing is reduced. Meanwhile, $\varepsilon_1$ increases a little for C30 concrete with internal curing compared to that without internal curing, which may result from the change on the stiffness of concrete at very early-age due to the replacement of normal coarse aggregate with the lightweight aggregate. Principally, shrinkage occurred within moisture saturated stage is coming from chemical shrinkage of cement hydration. Certainly, only a part of chemical shrinkage is transformed into macro shrinkage of concrete due to the self-restraint of hardened concrete. A continuous liquid network existed in the moisture saturated stage may be the reason why relative humidity inside of concrete after concrete setting is equal or close to 100% (Zhang et al. 2016). In the second stage of shrinkage development, the magnitude of shrinkage strain for a given age depends on both surface status of specimen and addition of PSLWA. As surface drying starts, the shrinkage is developed at a faster speed accordingly like the internal relative humidity does. The shrinkage strain increases with increase of concrete strength or water to cement ratio under both sealing and drying condition in the case of without PSLWA addition. As PSLWA is added, the autogenous shrinkage is greatly decreased for C90 and C100 concretes. The improvement of internal curing on autogenous shrinkage of C30 and C60 concrete is not obvious as that observed in C90 and C100 concretes, but the improvement on the developing rate of autogenous shrinkage of C30 and C60 concretes is apparent, i.e. the slope of autogenous shrinkage versus age curve is close to zero.

As expected, shrinkage under drying, which is the sum of autogenous and drying shrinkages, increases with increase of concrete strength or water to binder ratio of
concrete. In the present study, shrinkage at 28 days after casting under drying is 336.8, 491.5, 575.8 and 706.4μm/m for C30, C60, C90 and C100 concretes respectively in the case of without internal curing. The corresponding shrinkage under sealing is 106.8, 248.9, 466.1 and 603.9μm/m for C30, C60, C80 and C100 concretes respectively. After subtracting the autogenous shrinkage, the contribution of environmental drying to the total shrinkage strain at 28 days is 230.0, 242.6, 109.7 and 102.5μm/m respectively for C30, C60, C90 and C100 concretes. Clearly, the contribution of environmental drying to the shrinkage of concrete decreases with increase of concrete strength, which is understandable that the moisture diffusivity of concrete decreases with increase of concrete strength or water to binder ratio in general. As PSLWA is added, the shrinkage under drying is obviously decreased for C90 and C100 concretes also as presented on autogenous shrinkage. However, the improvement of internal curing on shrinkage of C30 and C60 concretes under drying condition is almost negligible, especially for C30 concrete. For example, the shrinkage at 28 days under drying conditions is 461.4, 514.8, 349.4 and 382.3μm/m for C30, C60, C90 and C100 concretes respectively in the case of with internal curing. The corresponding shrinkage under sealing is 180.8, 197.8, 208.0 and 306.8μm/m for C30, C60, C90 and C100 concretes respectively with internal curing. The contribution of environmental drying to the total shrinkage strain at 28 days under sealing and drying conditions is 461.4, 514.8, 349.4 and 382.3μm/m for C30, C60, C90 and C100 concretes respectively. After subtracting the autogenous shrinkage and environmental drying to the shrinkage of concrete completely. Even it can obviously reduce the magnitude of both autogenous and drying shrinkage of high strength concrete, such as C90 and C100 concretes in the present work. For C30 and C60 concretes, which have relative low strength or relative high water to binder ratio, the effect of internal curing on shrinkage is not pronounced. However, the improvement on moisture status of these concrete may help to enhance their anti-cracking performance even the function on shrinkage reduction is not significant, which can be found in the following ring tests.

3.3 Development of strain in the steel ring and cracking status of ring specimen

The development of compressive strain along circle direction at middle location of the inner surface of the steel ring with age since concrete casting for concrete without and with internal curing are presented in Fig. 13 to Fig. 16 for C30, C60, C90 and C100 concretes respectively. From the results, first we can observe the compressive strain increases with age after concrete setting. Before setting, some disturbances on the circle strain are presented. After setting, due to shrinkage of concrete ring, a compressive strain along the circular direction of the steel ring is gradually developed. For concrete without internal curing, the circular strain increases with age until certain values, about 80 to 100μm/m, after that the strain value suddenly goes up at
a certain age. This sudden releasing on the compressive strain in the steel ring indicates the outer concrete ring is cracked. By observation on the ring specimen, some visible cracks were found on the outer circumference of concrete. Typical photographers of ring specimen with and without cracks are shown in Fig. 17. The compressive strain in the steel ring at the concrete ring cracking is 81μm/m, 101μm/m, 75μm/m and 98μm/m respectively for C30, C60, C90 and C100 concretes without internal curing. For concrete rings with internal curing, as displayed in the figures, the circular strain increases as well with age, but the increasing speed is obviously lower than that of concretes without internal curing. Meanwhile, such increasing is gradually stopped and a constant strain approached. The final steady strain of concrete with internal curing is much smaller than the corresponding value of concrete at cracking. From present tests, the steady value of compressive strain in the steel ring is
12μm/m, 43μm/m, 21μm/m and 38μm/m respectively for C30, C60, C90 and C100 concretes. No any visible cracks were observed in all internal cured concrete rings, including C40 and C60 concretes, in which the shrinkage reduction is not significant with internal curing. Apparently, internal curing can significantly improve the shrinkage induced cracking. The function of internal curing may present in two aspects. One is the action on shrinkage reduction. The second function may display on the enhancement on creep relaxation due to the improvement on moisture content, which may be used to explain why internal curing can improve the shrinkage induced cracking as well in C30 and C60 concretes. It is well known that increase of moisture content in concrete will increase creep strain of concrete. This increment on creep strain will lead to relaxation of shrinkage stress. Certainly, the issue regarding the impact of internal curing on stress relaxation behavior of concrete is interesting to be investigated in a more detailed manner in the future.

To summarize the experimental findings in ring tests, the measured compressive strain along circular direction at middle location of the inner surface of the steel ring at concrete cracking for the concretes without internal curing and the final stable value of the compressive strain of the corresponding concrete with internal curing is plotted in Fig. 18. The strain gap between each concrete group, such as C30-OC and C30-IC may provide the estimation how much additional shrinkage load should be allowed to be developed in the concrete ring before cracking. Certainly, in real concrete structures, cracking of concrete is also influenced by creep and cracking strength of concrete. High cracking strength and large creep relaxation will enhance the cracking resistance of the structures besides shrinkage of the concrete.

4. Summary and conclusions

Shrinkage of concrete is one of the major sources of the formation of cracks in concrete structures. A number of techniques either to reduce autogenous shrinkage or
drying shrinkage have been developed in the past a few years, such as internal curing with pre-soaked lightweight aggregate (PSLWA) or super absorbent polymer. In this paper, the effect of internal curing with PSLWA on shrinkage and interior relative humidity of four series concretes with compressive strength at 28 days around 30MPa, 60MP, 90MPa and 100MPa is investigated by continuously measuring the deformation and interior humidity of test specimen under plastic film sealing and surface drying conditions since specimen cast. The shrinkage induced cracking performance of all kinds of concrete is evaluated with concrete-steel composite ring tests. The following conclusions can be drawn from the present study:

- 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). Under sealing, internal relative humidity at center of specimen is obviously decreased with increase of concrete strength at given age. Under drying, similar internal relative humidity value is observed at 28 days for all concretes without internal curing. As PSLWA was added, the reduction rate on interior humidity in stage II is significantly decreased. But efficiency on internal humidity rising is greatly influenced by concrete strength. Under environmental drying, the higher the concrete strength, the higher the internal relative humidity.

- Two-stage pattern of development of shrinkage strain with age starting from concrete setting can be observed, behaving as a fast developing stage within a few hours followed by an increasing stage with a gradually reduced rate. The shrinkage strain developed in the first stage is normally developed within the humidity saturated stage (RH stage I). The autogenous shrinkage is increased with increase of concrete strength. The drying shrinkage is decreased with increase of concrete strength. The total shrinkage of concrete is increased with increase of concrete strength. As PSLWA was added, the shrinkage reduction in both autogenous and drying shrinkages is obviously in high strength concretes, such as C90 and C100 concretes in the present work. The shrinkage reduction of internal curing on relatively low strength concrete, such C30 and C60 concrete is not obvious.

- The cracking status of concretes with and without internal curing under shrinkage load was examined with ring tests. The test results shown that the internal curing with PSLWA can greatly improve the shrinkage induced cracking performance. All concrete rings with compressive strength from 30 to 100MPa at 28 days are cracked under drying in the case of without internal curing. The compressive strain in the steel ring at the concrete ring cracking is about 75 to 101μm/m. By contrast, the stable compressive strain at the inner steel ring for the concretes with internal curing becomes 10 to 40μm/m and no visible cracks were found on the specimens.

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