Study on the stress relaxation properties of self-compacting concrete under restrained autogenous shrinkage

Wang Guojie¹, Liu Jiding², Zheng Jianlan¹,² and Fan Wei¹,²

1. School of Engineering, Fujian Jiangxia University, Fuzhou 350108, China
2. Fujian Province Collaborative Innovation Center for Environment-Friendly and Energy-Saving High Performance Concrete, Fuzhou 350108, China
3. State Grid Fujian Ningde Electric Power Supply Company, Ningde 352100, China

Abstract. The development of internal stress and stress relaxation induced by restrained autogenous shrinkage of self-compacting concrete (SCC) with different water to binder ratios and different amount of cementitious materials was investigated. Test results at more than 100 days showed that the free autogenous deformation expands within 1 day and then shrinks rapidly from 3 days to 7 days, after that, the autogenous shrinkage grows slowly and steadily. The induced stress in the restrained autogenous shrinkage also had the similar law; the stress relaxation of restrained autogenous shrinkage mainly developed in the early ages within 7 days, and then growth of the stress relaxation was almost stagnant. Stress relaxation rate of self-compacting concrete increased with the increase of cementitious content, and it increased significantly with the increase of water to binder ratio.

1. introduction

Autogenous shrinkage and dry shrinkage are the main factors that cause cracking of concrete. Self-compacting concrete (SCC) has the characteristics of low water to binder ratio and high cementitious material dosage and its shrinkage is often dominated by autogenous shrinkage. Restraint shrinkage stress generates in the concrete and the higher stress causes greater risk of cracking when the shrinkage is restrained. The stress relaxation caused by creep will make the value of restraint shrinkage stress lower than theoretical elastic stress, which will help to reduce the risk of concrete cracking. Therefore, it is necessary to study the stress relaxation property of SCC under restraint autogenous shrinkage.

However, for a long time, the research on autogenous shrinkage of concrete still stays in the cognition stage of free autogenous shrinkage. The research on the laws of autogenous shrinkage stress growth under the constraint is very limited, and the study of stress relaxation under restraint autogenous shrinkage is still lacking. Conclusions of different researchers are not the same in the only study [1-3]. The reason, on the one hand, many researchers, who were influenced by the conception that concrete autogenous shrinkage mainly occurs in the early ages, mainly focus on short age concrete autogenous shrinkage instead of long-term shrinkage property; on the other hand, external testing as the main test method of autogenous shrinkage, is not only vulnerable to environmental influences such as external temperature, but also difficult to obtain complete and stable data measured once concrete is moulded, resulting in the lack of foundation for further research on stress relaxation property.

Based on the previous research [3], this paper further optimizes the method of autogenous shrinkage test. By comparing the method of external eddy-current testing, common buried vibrating wire strain...
gauge and high precision vibrating wire strain gauge, high-quality and automatically collected data of the free autogenous shrinkage was acquired once concrete is moulded, and through the restraint shrinkage ring test, steel ring stress of restrained shrinkage was collected automatically. On the basis of theoretical analysis, stress relaxation property of SCC under autogenous constrained shrinkage is obtained, the foundation of autogenous shrinkage and restrained shrinkage stress development of SCC in long-term age and the stress relaxation property are provided for further study.

2. The stress relaxation property of the concrete under restrained ring shrinkage

In the restraint shrinkage ring test, concrete shrinkage compresses the steel rings. The autogenous shrinkage of each point in the concrete is uniform, unlike the dry shrinkage which is affected by the humidity gradient. Therefore, the actual residual stress at each point of the concrete ring can be calculated by measuring the strain of the steel ring inner wall. In addition, the theoretical elastic stress at different ages of concrete ring can be calculated by the free autogenous shrinkage value combined with the elastic modulus of the concrete. The theoretical elastic stress and the actual residual stress are calculated to obtain the stress relaxation of SCC under restrained ring shrinkage.

2.1 Theory of elastic stress

The theoretical elastic stress $\sigma_{\text{max}}$ of the inner wall of concrete ring caused by concrete shrinkage is deduced by Hossain and Weiss [4], as shown in Equation (1).

$$\sigma_{\text{max}} = \frac{\varepsilon_{\text{SH}} \cdot E_C \cdot C_3}{E_s C_1 + C_2}$$

$\varepsilon_{\text{SH}}$: the autogenous shrinkage value of concrete measured by free autogenous shrinkage test

$E_C$, $E_s$: the concrete elastic modulus, elastic modulus of the steel ring (take 206 GPa)

$C_1$, $C_2$, $C_3$: the ring size effect coefficient in different wall thickness,

$$C_1 = \left[ \frac{(1+\nu_s)R_{IS}^2 + (1-\nu_s)R_{IC}^2}{R_{OS}^2 - R_{IS}^2} \right], \quad C_2 = \left[ \frac{(1-\nu_s)R_{OS}^2 + (1+\nu_s)R_{OC}^2}{R_{OC}^2 - R_{OS}^2} \right], \quad C_3 = \left( \frac{R_{OC}^2}{R_{OS}^2} + 1 \right) / \left( \frac{R_{OC}^2}{R_{OC}^2} - 1 \right) ;$$

$R_{IS}$: inner radius of steel ring, $R_{OC}$: outer radius of concrete ring, $\nu_s$: Poisson's ratio of steel, take 0.28, $\nu_C$: Poisson's ratio of concrete, regardless of its change with age, take 0.18.

Since the elastic modulus of SCC takes the measured value of every age, it is assumed that the elastic modulus of SCC does not change much after 60 days(d). In this latter age, the theoretical elastic stress is calculated by the elastic modulus of 60 d instead of the elastic modulus of each age (90 d).

2.2 Residual stress

In order to analyze the residual stress of concrete in steel ring, the following reasonable assumption is made for the mechanical equilibrium system of steel ring and concrete [5]:

1. the steel ring is in close contact with the concrete and the contact surface is completely bonded, the relative slip deformation does not occur during the development progress of the autogenous shrinkage stress.
2. steel ring deformation and concrete deformation is synchronous, and the deformation between the two are equal.
3. elastic deformation and creep occurs in concrete, and the steel ring only elastic deformation occurs.
4. no matter the steel ring or the concrete, the deformation in the circumferential direction or the radial direction is uniform.
Dally and Riley [6] made a theoretical analysis of the mechanical equilibrium system of steel ring and concrete. The residual stress of concrete can be deduced from the strain of steel ring inner wall, as shown in Equation (2).

\[
\sigma_{\theta - \text{max}} = -C_3 \cdot C_4 \cdot \varepsilon_{\text{steel}} \cdot E_S
\]

\(\varepsilon_{\text{steel}}\): Strain value of steel ring under restrainted autogenous shrinkage.
\(C_4\): the ring size effect coefficient in different wall thickness,
\[2\left(\frac{R_{\text{OS}}}{R}\right)^2 - \left(\frac{R_{\text{IS}}}{R}\right)^2\],

2.3 Stress relaxation
In the ring test, the stress relaxation \((\sigma_{cr})\) is generally expressed as the difference between the theoretical stress \((\sigma_{\theta - \text{max}})\) and the residual stress \((\sigma_{\text{max}})\) of the concrete, as shown in Equation (3).

\[
\sigma_{cr} = \sigma_{\theta - \text{max}} - \sigma_{\text{max}}
\]

3. Test program
3.1. Raw materials and mix proportions of the concrete
The cement used was ordinary Portland cement (P.O) 42.5(C) in SCC, the specific surface area of 372 m\(^2\)/kg; the fly ash used was If grade fly ash (FA) with the specific surface area of 442 m\(^2\)/kg; the sand used was river sand (S) with fineness modulus of section (2.1) and an apparent density of 2719 kg/m\(^3\); the aggregate used was natural coarse aggregate (NCA) with a particle size of 5-20 mm, a compact packing density of 1593 kg/m\(^3\), a bulk packing density of 1491 kg/m\(^3\) and an apparent density of 2652 kg/m\(^3\); polycarboxylic superplasticizer (SP) used was with the water reduction rate of 15% to 20%.

Concrete mix proportion, workability and compressive strength of 28 d cubes are shown in Table 1. The replacement ratio of fly ash in mixture ratio is 36% and the sand ratio is 0.48. Table 2 shows the elastic modulus of each mix proportion of key age. SCC-A, SCC-B1, SCC-C and SCC-D represent the SCC with the water to binder ratio of 0.28, 0.32, 0.36 and 0.42 respectively in the first batch of experiments; SCC-1, SCC-2, SCC-B2 and SCC-3 represent the second batch of SCC with the binder amount of 450kg/m\(^3\), 500kg/m\(^3\), 550kg/m\(^3\) and 600kg/m\(^3\), respectively.

### Table 1. Mix proportions and mechanical properties of concrete

| Group   | Mix proportion(kg·m\(^{-3}\)) | Slump (mm) | Slump flow(mm) | 28d cube compressive strength (MPa) |
|---------|---------------------------------|------------|----------------|-----------------------------------|
| SCC-A   | C 350, FA 200, S 780, NCA 850, W 154, SP 9.10 | 255        | 570            | 59                                |
| SCC-B1  | C 350, FA 200, S 780, NCA 850, W 178, SP 6.75 | 260        | 580            | 50                                |
| SCC-C   | C 350, FA 200, S 780, NCA 850, W 198, SP 4.40 | 260        | 600            | 41                                |
| SCC-D   | C 350, FA 200, S 780, NCA 850, W 231, SP 2.45 | 265        | 650            | 36                                |
| SCC-1   | C 286, FA 164, S 840, NCA 924, W 144, SP 7.00 | 260        | 600            | 50                                |
| SCC-2   | C 318, FA 182, S 812, NCA 884, W 162, SP 7.25 | 260        | 580            | 50                                |
| SCC-B2  | C 350, FA 200, S 780, NCA 850, W 178, SP 6.75 | 260        | 590            | 51                                |
| SCC-3   | C 382, FA 218, S 748, NCA 816, W 194, SP 5.40 | 265        | 620            | 52                                |

### Table 2. Elastic modulus of SCC at different ages(Unit:GPa)

| age (d) | SCC-A | SCC-B1 | SCC-C | SCC-D | SCC-1 | SCC-2 | SCC-B2 | SCC-3 |
|---------|-------|--------|-------|-------|-------|-------|--------|-------|
| 3       | 27.5  | 24.5   | 21.3  | 19.2  | 24.5  | 25.8  | 23.5   | 25.7  |
| 7       | 31.8  | 27.9   | 26.3  | 23.4  | 27.9  | 29.0  | 29.1   | 28.1  |
| 14      | 34.0  | 30.0   | 27.9  | 25.8  | 30.0  | 30.3  | 30.8   | 30.7  |
| 28      | 36    | 32.1   | 29.1  | 27.2  | 32.1  | 33.8  | 32.9   | 33.7  |
| 60      | 36.7  | 33.0   | 30.0  | 28.5  | 33.0  | 34.2  | 33.6   | 34.4  |
3.2 Free autogenous shrinkage test program
According to GB/T 50082-2009 Standard Test Method for Long-Term Performance and Durability of Ordinary Concrete [7], the test was carried out with 100 mm×100 mm×515 mm prismatic test pieces and each mix proportion took three test pieces. In order to obtain the reliable autogenous shrinkage results, the test results of different test methods and different instruments were compared. Every mix proportion took a specimen buried in a common vibrating wire strain gauge and a specimen buried in a high-precision vibrating wire strain gauge, and three samples were tested by eddy current sensor simultaneously. The autogenous shrinkage test device, test mold preparation and testing process are shown in Figure 1-3.

The concrete autogenous shrinkage value can be obtained through the autogenous shrinkage test of SCC, which provides the basis for the calculation of elastic stress theoretical value of restraint autogenous shrinkage of SCC.

3.3. Restrained autogenous shrinkage ring test program
Reference to the American Society for Testing and Materials ASTM C 1581-04 standard [8], the ring specimens were used for the mold test. Each mix proportion contains three ring specimens. Figure 3 shows the restrained autogenous shrinkage ring test device, Figure 4 shows the test step.

Through the restrained autogenous shrinkage ring test of SCC, the strain value of the steel ring inner wall can be obtained, which provides the data foundation for the analysis of the residual stress when the autogenous shrinkage stress of SCC is restrained.
4. The test results and analysis

4.1. Free autogenous shrinkage test results

4.1.1. The effect of different test methods: Figure 5 shows the autogenous shrinkage results of external eddy current method, results collected by buried ordinary vibrating wire strain gauge (ZS2120) are shown in Figure 6 and Figure 7. Figure 8 shows results collected by the embedded high-precision vibrating wire strain gauge (BGK4200). It can be seen that the data obtained by the method of external eddy-current method fluctuates greatly, and the data obtained by the ordinary vibrating wire strain gauge test is generally less affected by the external environment but has larger data noises. The data obtained by the high-precision vibrating wire strain gauge has a very good effect in long-term or short-term. Comparing the results obtained by different test methods with the same mix proportion (Figure 9), it can be seen that the results obtained by different methods are consistent on the long-term trend and the order of the overall data, but in the short run, there is obvious difference in the same age. The eddy current test data shows obvious fluctuation with the external environment. The test result of the high-precision vibrating wire strain gauge in the early age is greater than other methods, which is supposed to be caused by its higher sensitivity.

4.1.2. Laws of the autogenous deformation with the development of age: The development laws of the concrete autogenous shrinkage with age can be found through the high-precision vibrating wire strain gauge BGK4200 test results. The specimens were poured into the mold at 30°C, and the ambient temperature reduced to 20°C within 2 d, especially the temperature drop within 1 d is very significant, and even concrete hydration temperature is submerged in the overall cooling, but between 0~0.8 d, the specimen did not shrink because of cooling, but showed significant expansion, indicating that expansion is not caused by the temperature rise of hydration, but the tendency of autogenous deformation. After about 0.8 d, autogenous deformation turns into the shrinkage stage, in the early age, especially within 3 d the shrinkage rapidly increases to -30 ~ -50 με, then it turns into the long-term, slow and sustained growth stage, the autogenous shrinkage strain of 14 d is -10 ~ -80 με, 28 d autogenous shrinkage strain is -70 ~ -130 με, 90 d autogenous shrinkage strain is -130 ~ -230 με.

![Figure 5. Effect of water-binder ratio on autogenous shrinkage](image1)

![Figure 6. Effect of water-binder ratio on autogenous shrinkage (ZS2120)](image2)
4.1.3. Laws of autogenous deformation with water-binder ratio and binder amount: The water to cement ratio had a significant effect on autogenous shrinkage. With the decrease of water-binder ratio, the autogenous shrinkage of each stage of SCC increased significantly, and the water to binder ratio was 0.28, 0.32, 0.36, 0.42 (the 28 d compressive strength was 59 MPa, 50 MPa, 41 MPa, 36 MPa), the autogenous shrinkage strain at 14 d is about -46 με, -34 με, -18 με, -14με, respectively, and 28 d: -111 με, -82 με, -51 με, -40 με, respectively, 90 d: -195 με, -161 με, -120 με, -83 με, respectively. The value of concrete autogenous shrinkage with different amount of cementitious material is quite different. With the increase of the amount of cementitious material, the value of concrete autogenous shrinkage increases. For the SCC specimens with the amount of cementitious material of 450 kg/m³, 500 kg/m³, 550 kg/m³ and 600 kg/m³ respectively (compressive strength is about 50 MPa), the autogenous shrinkage strain at 14 d is about -54 με, -64 με, -53 με, -82 με, respectively; 28 d: -78 με, -99 με, -99 με, -133 με, respectively; 90 d: -131 με, -154 με, -170 με, -215 με, respectively.

4.1.4. Determine a "time zero" of autogenous deformation: Since concrete is plastic when pouring into mold, autogenous deformation of concrete does not result in internal stress in concrete, so a "time zero" needs to be determined when calculating the theoretical elastic stress with free autogenous shrinkage. Based on the existing research [9], this paper determines the "time zero" through the hydration test of concrete slurry. When the SCC mixing is completed, the proper amount of fresh concrete was obtained from the concrete mixer, and the concrete slurry was sieved with a sieve size of 2.36 mm to conduct hydration heat release test of SCC, finally, the hydration heat release curves of the SCC in different water to binder ratio and different amount of cementitious materials were obtained. The second hydrated exothermic peak of concrete slurry appears within 13~20 h [10]. The micro expansion point of concrete in different mix proportions are close to the second exothermic peak.
Taking the second exothermic peak of hydration of SCC slurry as the "time zero" of autogenous shrinkage, it is roughly equivalent to take the expansion peak time of autogenous deformation as the time zero, and the free autogenous shrinkage test data was processed according to the "time zero".

4.2. Constrained autogenous shrinkage ring test results
The steel ring strain under restrained shrinkage of SCC rings in different water-binder ratio and the amount of cementitious materials was obtained by restrained shrinkage ring test and as shown in Figure 11 and Figure 12. The data acquisition began after 18 h from pouring into mold due to the acquisition system failure. It can be seen that the development trend of steel ring strain is similar to that of autogenous shrinkage. The strain values of steel rings with various mix proportion increase with age. The strain of steel ring at the same age decreased significantly with the increase of water to binder ratio; with the increase of the amount of cementitious material, the strain of steel ring at all ages increased.

![Figure 11. Steel ring strain curve in different water to binder ratio](image1)

![Figure 12. Steel ring strain in different amount of cementitious material](image2)

4.3. Stress relaxation property analysis
According to the second part of this paper, the theoretical elastic stress of concrete in ring-restrained shrinkage specimens at each critical age is calculated with the free autogenous shrinkage and elastic modulus. The actual residual stress in concrete is calculated with the steel ring strain measured in the ring test, and the stress relaxation value was obtained by the difference between the two in corresponding ages. The stress relaxation of each mix proportion is shown in Figure 13 to 20.

![Figure 13. Theory of elastic stress, actual residual stress and stress relaxation curve of SCC-A](image3)

![Figure 14. Theory of elastic stress, actual residual stress and stress relaxation curve of SCC-B1](image4)
It can be seen from the development of the stress relaxation curve with age that the stress relaxation of each mix proportion mainly occurs within 7 d, and then the residual stress curve develops almost in parallel with the theoretical stress curve. There is almost no growth of stress relaxation after 7 d. Although the autogenous shrinkage stress of SCC in long ages increases slowly and slowly over time, it can hardly be alleviated by stress relaxation, so autogenous shrinkage may lead to greater cracking risk in long age, it is worth to study further and pay more attention to structural design and cracking control.

Reference [2] calculates the stress relaxation coefficient (ratio of residual stress to theoretical elastic stress), as shown in Equation (4), and the stress relaxation rates of SCC with different water to binder ratio and different amount of cementitious material were obtained, as shown in Figure 21 and 22.

\[
\phi = \frac{\sigma_{cr}}{\sigma_{\theta_{max}}} \times 100\% \quad (4)
\]
It can be seen that with the increase of water to binder ratio, the stress relaxation rate of concrete increases significantly. At 7 d, the stress relaxation rates of SCC with water to binder ratio of 0.28, 0.32, 0.36 and 0.42 is 62%, 76%, 83%, 93%, respectively. With the increase of the binder amount, the stress relaxation rate tends to increase. At 7 d, the concrete stress relaxation rate of the binder amount of 450 kg/m$^3$, 500 kg/m$^3$ and 550 kg/m$^3$, 600 kg/m$^3$ is 53%, 52%, 51%, 64%, respectively.

5. Conclusion
1. The choice of autogenous shrinkage test method is crucial. The high precision vibrating wire strain gage can test and collect the autogenous deformation of the concrete automatically when pouring into mold, which is helpful to solve the problem of the data noise of the external test and the problem that the test results can easily be affected by the environment, the complete and stable test results can be obtained.
2. The effect of autogenous shrinkage on the structure of concrete in long age cannot be neglected. The test results of autogenous shrinkage up to 100 d show that autogenous deformation of SCC begins to shrink after a small expansion of 1 d and shrinks rapidly within 3 d~7 d, and then with the slow growth and continued growth; the strain of restrained shrinkage ring with age has a similar law, autogenous shrinkage stress has a tendency to increase with age;
3. The stress relaxation of restraint autogenous shrinkage mainly occurs in the early age before 7 d. After 7 d, the growth of stress relaxation is almost stagnant. Therefore, the long-term autogenous shrinkage stress is hardly relieved due to stress relaxation, resulting in the risk of cracking under restrained autogenous shrinkage increases.
4. The stress relaxation rate of SCC significantly increases with the increase of water to binder ratio, and increases with the amount of cementitious material.

6. Reference:
[1] Wei Dong, Xiang ming Zhou, Zhimin Wu. A fracture mechanics-based method for prediction of cracking of circular and elliptical concrete rings under restrained shrinkage[J]. Engineering Fracture Mechanics 2014 131: 687-701.
[2] Li F. Research on the development of restraint stress and Relaxation of concrete at early age[D]. Beijing: Tsinghua University, 2009.
[3] Wang H M. Experimental study on restrained shrinkage of self-compacting concrete by ring test[D]. Fuzhou: Fuzhou University, 2010.
[4] Hossain, A.B., Weiss, W.J. Assessing residual stress development and stress relaxation in restrained concrete ring specimens[J]. Journal of Cement & Concrete Composites, 2004 26 531-540.
[5] Ma X W. Study on Early Restraint Shrinkage and Tensile Creep of High Performance Concrete[D]. Harbin: Harbin Institute of Technology, 2006.

[6] Dally, James W, Riley, W.F., Experimental Stress Analysis, Third Edition. McGrawHill, Inc[J]. 1991, PP. 429-440.

[7] GB/T 50082-2009, Standard for test methods of long-term performance and durability of ordinary concrete[S].

[8] ASTM C 1581—04, Standard test method for determining age at cracking and induced tensile stress characteristic of mortar and concrete under restrained shrinkage[S]. ASTM International, 2004.

[9] Wang G J. Shrinkage and cracking performance of self-compacting-concrete at early age[D]. Fuzhou: Fuzhou University, 2011. 06.

[10] Liu J D. Study on the Stress Relaxation Properties of Self-Compacting Concrete Under Autogenous Shrinkage being Restrained[D]. Fuzhou: Fuzhou University, 2017.