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Shrinkage and cracking behavior of high performance concretes containing chemical admixtures*

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Abstract: Modern concretes often incorporate several chemical admixtures to alter the properties of fresh or hardened concrete. In this work, the influences of three types of chemical admixtures, calcium nitrite inhibitor (CNI), retarder (D – 17) and superplasticizer (W – 19) on free shrinkage and restrained shrinkage cracking of high performance concrete were experimentally investigated. The test results showed that, with the same water to binder ratio (0.4), mixtures containing D – 17 of 0.25 percent or higher ratio of W – 19 (2.76 percent) all exhibited a reduction in free shrinkage and shrinkage cracking width. However, the incorporations of various ratios of CNI into mixtures led to an increase in free shrinkage and shrinkage cracking width as compared to control mixture. In order to study the influence of CNI, the microstructure of concrete mixture containing CNI were investigated by Mercury Intrusion Porosimetry as well as Scanning Electronic Microscopy (SEM) technique.

Key words: Chemical admixtures, High-performance concrete, Free shrinkage, Restrained shrinkage cracking, Microstructure
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INTRODUCTION

Ask concrete contractors to name one of the most exasperating problems of building with concrete, and they are likely to say drying shrinkage cracking. By its nature, concrete tends to shrink and crack. Once the drying process begins, the concrete shrinks resulting in negative change of length. If concrete is restrained from shrinking freely by reinforcement, it leads to tensile stresses development. The combination of high tensile stresses and low fracture resistance of concrete leads to cracking. Once cracks occur, they provide easy access for oxygen, moisture, chlorides, and other aggressive chemicals into the matrix, and can therefore impact the long-term durability, resulting in increased maintenance expenses and reduced service life of concrete constructions.

A free shrinkage test alone may not offer sufficient information on the behavior of concrete structures because almost all concrete structures are under some kind of restrain. Thus, restrained shrinkage tests have been developed to measure the shrinkage cracking behavior of concrete. Several restrained shrinkage tests were proposed (Malhotra, 1970; Kraai, 1985). Among them, the ring test method has shown considerable advantages. Theoretical and modeling aspects of the ring-type specimen teat can be found in Grzybowski and Shah (1990) and Wiegrink et al. (1996).

In recent years, many different types of chemical admixtures are widely used in concrete to provide higher strength and superior properties, such as impermeability, freeze-thaw resistance and corrosion inhibition. However, the effect of some admixtures on durability of concrete reveals wide variations and apparent inconsistencies. In construction, shrinkage crackind of high-performance concrete is one of the main factors causing de-

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terioration of concrete durability. So, reduction of cracking is a key need. For this reason, it is necessary to investigate the relationship between chemical admixtures and the shrinkage cracking behavior of high performance concrete.

In this work, the influence of three kinds of chemical admixtures, calcium nitriteinhibitor (CNI), retarder (D – 17) and supersplasticizer (W – 19), on the free shrinkage and restrained shrinkage cracking of high performance concrete were investigated. As can be observed from contrastive samples, mixture containing retarder retarded free shrinkage and shrinkage cracking behavior. Mixture containing high content of superplasticizer had considerably larger reduction in restrained shrinkage cracking, but smaller decrease in free shrinkage. Moreover, the occurrence of first visible cracking was markedly delayed. However, mixtures incorporated with various ratios of CNI exhibited increase in free shrinkage and restrained shrinkage cracking width. The microstructure of concrete containing CNI was investigated by Mercury Intrusion Porosimetry and Scanning Electronic Microscopy, respectively.

EXPERIMENTAL PROCEDURE

1. Raw material and mix proportions

Seven sets of different component concrete mixtures were prepared. Each set included two specimens: one specimen was used to measure the free shrinkage, the other was used for restrained shrinkage test. Based on whether or not the concrete mixtures contained fly ash, they were also divided into two groups. The first group had three samples without fly ash, coded WD_1, WD_2 and W_3, respectively. The cement content of WD_1 and WD_2 containing two ratios of W – 19 was 1.38 percent and 2.76 percent respectively; that of WD_2 and W_3 containing two ratios of D – 17 was 0.25 percent and 0 percent respectively. All other ingredients were the same. The second group included four samples (F_4, $FCNI_5$, $FCNI_6$ and $FCNI_7$) with 25% fly ash. The cement content in these samples containing various proportions of CNI was 0, 5, 15, 20 L/m^3.

For all samples, the mixture proportion by weight for cement: sand: coarse aggregate was 1:1.84: 2.67. The water to binder ratio was kept at 0.4, and type I portland cement (OPC) was used. Coarse aggregate used was crushed limestone with maximum size of 10 mm. Fine aggregate used was natural river sand with fineness modulus of 2.3. In this work, fly ash was used to decrease bleeding and segregation; CNI was used to improve the anticorrosive ability of concrete; D – 17 was added to delay setting time and W – 19 was added to decrease the use of water when keeping the same workability of the fresh concrete. The details of the mix proportion are presented in Table 1.

Table 1 Mixture proportion of concrete (by weight)

Group	No.1			No.2			
Sample	WD_1	WD_2	W_3	F_4	$FCNI_5$	$FCNI_6$	$FCNI_7$
OPC	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Water	0.400	0.400	0.400	0.500	0.500	0.500	0.500
Fly ash	–	–	–	0.250	0.250	0.250	0.250
Fine-Agg.	1.84	1.84	1.84	1.84	1.84	1.84	1.84
Coarse-Agg.	2.67	2.67	2.67	2.67	2.67	2.67	2.67
Inhibitor (CNI)	–	–	–	–	5 L/m^3	15 L/m^3	20 L/m^3
Retarder (D – 17)	0.25%	0.25%	–	0.25%	0.25%	0.25%	0.25%
Superplasticizer (W – 19)	1.38%	2.76%	2.76%	2.00%	2.00%	2.00%	2.00%

2. Test specimen and curing

A ring - type specimen was used in this study. The mold dimensions are shown in Fig. 1. A concrete ring (35 mm in thickness, 140 mm in height) was cast around the outer perimeter of a steel ring (with 254 mm and 305 mm inner and outer diameters, respectively) cut from a steel tube. The outer mold was a thin-wall steel ring. Both these rings were fixed concentrically on a wooden base so that the free space between them could be filled with concrete mix. For restrained ring specimen, the outer mold of a specimen was demolded 24 hours after casting. Then the top surface of the concrete ring was sealed with epoxy resin to avoid moisture diffusion through it. For free shrinkage test, the steel ring was cut into four pieces and removed during demolding. The concrete ring for free shrinkage test was of the same size with the restrained ring. However, its inner surface was sealed with epoxy resin. In this way, drying would be allowed only from the outer circumferential surface. Uniform shrinkage along the width of the specimen can be assumed. After being moisture-cured for four days at 100% relative humidity (RH) and 20 ℃, the specimens were exposed to drying in a room (40% relative humidity, 20 ℃ temperature). At the same time the specimen was monitored for cracking development. The extent and severity of the shrinkage deformation and the crack width were recorded regularly.

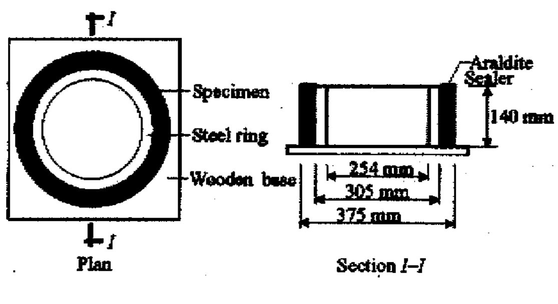

Fig. 1 Description of ring-type restrained specimen

3. Measurement

A dial-gauge extensometer with a 200 mm gauge length was used to measure the length change on demec studs fixed on the top surface of free shrinkage specimens along the circumferential direction. The average of five measurements was used as the free shrinkage strain of the specimen. Measurement was taken every 24 hours for 120 days. For restrained shrinkage specimens, the onset time of a new crack was recorded. The crack width was measured with a 30 magnification microscope. The crack width on the surface of a specimen was the average of three measurements: one at the center of the ring and the other two at the quarter positions of the ring. The crack width was measured every 24 hours for 120 days.

TEST RESULTS AND DISCUSSION

1. Influence of superplasticizer on shrinkage and cracking behavior

The development of free shrinkage and restrained shrinkage cracking of mixtures WD_1, WD_2 are presented in Fig.2 and Fig.3 respec-

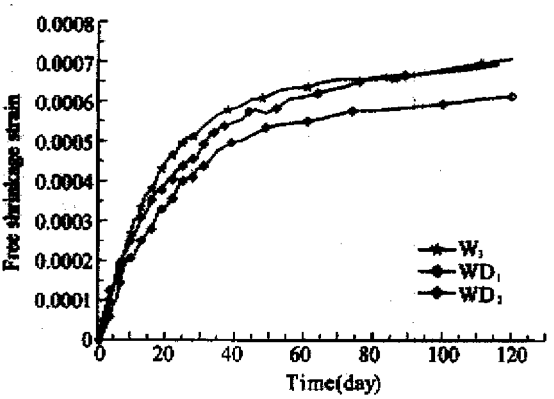

Fig. 2 The development of free shrinkage with time for concrete mixtures WD_1, WD_2, W_3

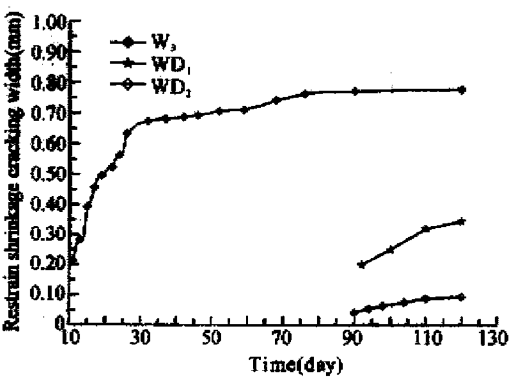

Fig. 3 The development of restrained shrinkage crack width with time for concrete mixtures WD_1, WD_2, W_3

tively. The result indicated that the free shrinkage of mixture WD_2 was slightly smaller than that of WD_1. However, the shrinkage cracking width of mixture WD_2 was much smaller than that of WD_1. Moreover, as found in measurement, the major advantage of incorporation of 2.76 percent superplasticizer into concrete mixture was the significant delay in occurrence of the first visible crack. Both samples with 2.76% superplasticizer cracked after 90 days. Meanwhile, the initial crack width of samples was also greatly decreased. The test results showed that higher superplasticizer content in concrete mixture was effective in inhibiting crack opening and propagation. The reason for this phenomenon may be explained as follows.

Shrinkage of concrete is a property of the microstructure of hydrated cement paste and is due to the strong interaction between the hydrophilic surface and water (Verbeck, 1978). It results from the combined action of capillary stress, disjoining pressure, and surface tension. As the water in the capillary pores dries, a meniscus is formed. Capillary tension effects are due to meniscus formation in the capillary pores. This process results in equal hydrostatic compression in the solid phase which push the voids in the CHS body closer (Parrott et al., Young 1982; Young et al., 1972). In addition, the removal of adsorbed water creates a disjoining pressure between the CSH surfaces and van der Wall forces draw the particles together (Wittman, 1976). For these reasons, it is conceivable that a higher water content would lead to an increase in drying shrinkage of concrete. To minimize the drying shrinkage, the total water content must be decreased, i.e., keeping the water content per unit volume of concrete as low as possible. Many investigations showed that the use of high-range water reducers can greatly decrease the amount of water required without loss of workability (Lane et al., 1979). The action of high-range water reducers mainly derives from a better particle dispersion as admixture is adsorbed on the cement particles and, as a result, reduction of the surface tension of water result in lower capillary pressure (Shah et al., 1992). Hence, the presence of water reducing admixture can decrease free shrinkage and shrinkage cracking width because of the reduction of such pressure.

2. Influence of retarder on shrinkage and cracking behavior

By comparing WD_2 and W_3 (also showed in Fig. 2 and Fig. 3), it can been seen that the addition of 0.25 percent retarder reduces the free shrinkage of concrete by 15%. The cracking width of concrete reduces by nearly 75%. The result showed that the incorporation of retarder into concrete protects it from shrinkage cracking.

The ingredients used as retarders are very much the same as the ingredients used for water reducers (Paillere, 1995). So, it can also reduce the mixing water requirement of the mixture. When retarder is added to the cement-water system, physical adsorption and chemical reactions occur generally with the cement components, and especially with the C_3A and the C_3S. On the one hand, the incorporation of retarder promotes the dissolution and hydration of C_3A, which helps the initial formation of hydration product (ettringite) in the C_3Acgypsum-H_2O. According to Wu and Wang (1998), the production of ettringite can consume a lot of mixing water used in concrete mixture. On the other hand, the incorporation of retarder reduces the concentration of Ca^{2+} ions in pores of the paste, which reduces the formation of CH and C-S-H gel. The action delays the strength development of the concrete. Some researches reported that as strength increases, the material becomes more brittle, consequently cracking occurred often and the crack width became larger (Weiss et al., 1997). Contrarily, the onset time of crack is delayed and the overall cracking width is reduced as a result of the slow development of strength and material stiffness, as well as lower degree of hydration.

3. Influence of CNI on shrinkage and cracking behavior

Previous studies showed that the incorporation of fly ash of 25 percent by weight could markedly improve the restrained shrinkage cracking behavior of high-performance concrete, even though it has similar free shrinkage behavior as that of control mixture. However, if CNI is added into concrete with fly ash of 25 percent by weight, the free shrinkage of the concrete mixture increases, and its shrinkage cracking becomes wider. In this study, the development of free shrinkage and shrinkage cracking of mixtures containing various ratios (0, 5, 15 and 20 L/m^3) of CNI are presented in Fig. 4 and Fig. 5, respectively. The results demonstrate that the shrinkage and shrinkage cracking behaviors of such mixtures are enlarged to different extent. Moreover, the initial cracking width of concrete is greatly widened, and the onset time of first crack is greatly preceded as advanced.

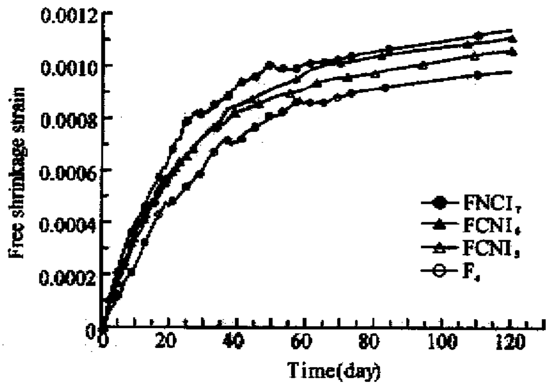

Fig.4 The development of free shrinkage with time for concrete mixtures F_4, $FCNI_5$, $FCNI_6$, $FCNI_7$

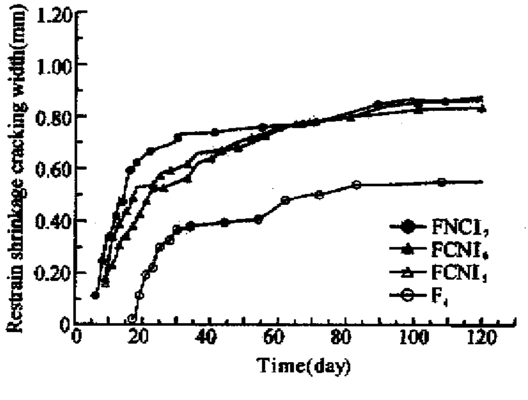

Fig.5 The development of restrained shrinkage crack width with time for concrete mixtures F_4, $FCNI_5$, $FCNI_6$, $FCNI_7$

(1) Micropore of hardened cement

Porosity is a major parameter affecting drying shrinkage. To see the effect of CNI on the pores size distribution of hardened paste, mercury intrusion porosimetry (MIP) test was conducted. The resulting curves of the micropore structure of mixtures F_4 and $FCNI_6$ are presented in Fig.6, showing that the cement paste containing CNI had the larger cumulative pore volume, the lower parts of the curves shows that big pores with diameter from 0.03μm to 0.1μm are more in $FCNI_6$ than in F_4 as the addition of CNI accelerates the formation of larger size calcium hydroxide crystal. According to Shoya et al., (1990), the pore radius can decrease in proportion to the lowering of the surface tension in the same humidity conditions; and according to Shah et al., (1992); the increase of volume of macropores can enlarge free shrinkage of concrete, the increase of both cumulative pore volume and portion of big pores increase free shrinkage of concrete and substantially increase the crack widths of concrete because of restrained shrinkage.

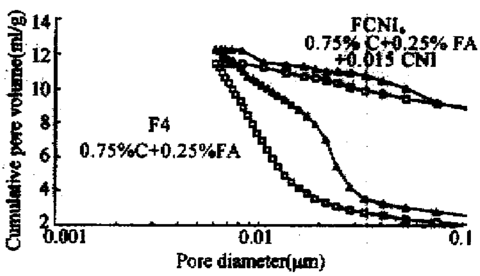

Fig.6 MIP results for concrete mixtures F_4 and $FCNI_6$ at 91days

(2) Microstructure of hardened cement

The image characteristics of mixtures F_4 and $FCNI_6$ are presented in Figs. 7 and 8. Obviously, the incorporation of CNI greatly changes the microstructure of paste. A large amount of plate-shaped and short column-shaped calcium hydroxide crystals was observed on the surface of the particles. This is in agreement with the testing results of MIP.

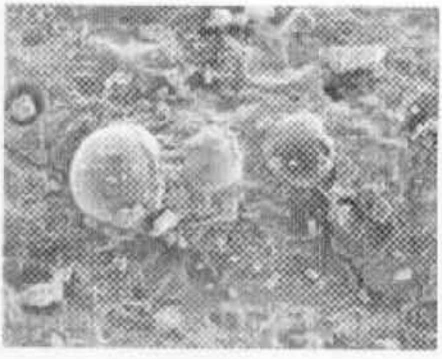

Fig.7 SEM images of concrete mixture with 25% fly ash (F_4)

Fig.8 SEM images of concrete mixture with both 25% fly ash and 15 L/m^3 CNI ($FCNI_6$)

CONCLUSIONS

The addition of higher content superplasticizer into high-performance concrete reduces the free shrinkage. The most obvious advantage is not only a considerable reduction in shrinkage cracking width by 90%, but also a significant delay in onset of first visible cracking.

The addition of 0.25% retarder into high-performance concrete decreases both the free shrinkage and restrained shrinkage cracking width by 15% and 75%, respectively.

The addition of calcium nitrite inhibitor into high-performance concrete, the free shrinkage and restrained shrinkage cracking of concrete are all increased. Hence CNI should be used cautiously in practical engineering.

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