DISTRIBUȚIA TENSIUNILOR DETERMINATE DE FENOMENUL DE CONTRACȚIE ÎN BETOANE DE MARE REZISTENȚĂ CU O SUPRAFAȚĂ EXPUSĂ LA UMIDITATE

SHRINKAGE STRAIN DISTRIBUTION IN HIGH STRENGTH CONCRETE WITH ONE SURFACE EXPOSED TO DIFFERENT RELATIVE HUMIDITY

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Shrinkage strains of high strength concretes with and without silica fume were measured at various depths from the drying surface by using linear variable differential transformer (LVDT) displacement sensors, and only one surface of the prism specimen was exposed to drying conditions (RH=75%, 54% and 33%) during the experiment. The results show that the internal shrinkage strain becomes lower with the increasing depth from drying surface. Such shrinkage difference gets severer with the longer drying time and the lower relative humidity of drying condition. There is a linear relationship between the reduction of internal relative humidity and shrinkage strain at every depth of specimen. However, the increased shrinkage at inner position is higher than that at outer position of each specimen when the same reduction of relative humidity happens.

Tesiunile determinate de fenomenul de contracție a unor betoane de mare rezistență cu/fără silice ultrafină s-au măsurat la diferite adâncimi față de suprafața de uscare folosind un dispozitiv de tip LVDT (linear variable differential transformer) plasat pe probe prismatice care au expusă doar una dintre fețe unor medii cu umidități diferite (RH=75%, 54% și 33%). Rezultatele arată că tensiunea internă scade cu creșterea distanței de la suprafața expusă. Acesta diferență este cu atât mai mare cu cât timpul de expunere a probei la mediul de uscare crește și respectiv cu cât umiditatea mediului este mai redusă. Se poate stabili o relație liniară între diminuarea umidității interne relative și tensiunea determinată de fenomenul de contracție. Totuși, contracția în inetriorul probei este mai mare comparativ cu cea înregistrată în pozițiile exterioare pentru aceleași condiții de uscare.

Keywords: *concrete, drying shrinkage, relative humidity, differential strain distribution*

1.Introdction

Drying shrinkage induced cracking is a common source of distress in concrete structures. In addition to being unsightly, these cracks serve to accelerate other forms of damage in concrete (e.g., corrosion and freezing and thawing), thereby shortening the service life of structures [1-3]. This is particularly true in the case of concrete pavements and slabs on grade where drying occurs from one face only and shrinkage is hindered by external and internal restraints [4-5]. In the literatures, most researchers paid much attention to the external restrained shrinkage cracking [6-8], and the shrinkage of concrete was measured as an average deformation along the central axis of prism or cylinder concrete specimens [9-10]. However, the moisture distribution of a cross section of concrete is non-uniform when concrete structures are exposed to dry condition [11], which induces the differential drying shrinkage distribution according to depths from the exposed drying surface [12]. Therefore, the internal restraint exists among the different depth layer of concrete and tensile stresses is thus induced in the concrete. Such internal restrained stress may cause cracking or accelerate cracking on actual concrete structures. Unfortunately, there are few published studies on such differential shrinkage distribution in concrete exposed to dry condition [13], which make it difficult to understand the shrinkage cracking tendency of concrete structures exposed both external and internal restraints. On the other hand, the air relative humidity is varying with the seasonal transformation and it has very important influence on the moisture transportation and the shrinkage distribution in the concrete structure. Therefore the drying shrinkage and internal humidity distributions of two high strength concretes with and without silica fume were studied by using displacement sensors and humidity sensors when only one surface of the concrete specimens were exposed to three different relative humidity.

2. Experimental work

2.1 Raw materials and concrete mixtures

The cement used is ordinary Portland cement with strength grade of 42.5 (according to Chinese standard) from Harbin Cement Company of Yatai Group. It has a density of 3.1g/cm^3 and specific surface area of 347m^2/kg (Blaine). Silica fume (SF) was used as a mineral admixture with specific surface area of 1.5×10^5 cm^2/g. Chemical compositions of cement and silica fume are shown in Table 1. Crushed limestone gravel was used as coarse aggregate with a maximum nominal size of 25mm and crushing index of 4.8%. A quartz sand

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was used as fine aggregate with a fineness modulus of 2.85 and density of 2.65g/cm^3. To obtain a good workability, a commercially available, naphthalene-based, high-range water-reducing agent Mighty 100 produced by Kao Chemical Corporation Shanghai, was also used. Its recommended dosage is 0.7-1.2% weight percent of the total binder in concrete. Two concretes (*w/b*=0.32) with and without silica fume were prepared in this study. Table 2 shows the concrete mixing proportion, along with the test results of slump and 28-day compressive strength.

2.2 Test method

The concrete was mixed in a laboratory mixer. After all the dry materials were uniformly dispersed, water and the superplasticizer were added and mixed together until a consistent mixture was obtained. For each concrete mixture, the slump was tested immediately after the mixing and three 100×100×100-mm cubes were cast for determining the compressive strength. Prism specimens of 100×200×400-mm were cast with three 10mm diameter copper studs embedded on every end surface at depths of 10mm, 55mm and shown in Fig. 1 (a). A specifically designed mold was used and much attention was paid to ensure every pair of studs locating on one axial line at the same depth. After 3 days of storage in a moist-curing room, five surfaces of prism specimen, except for the bottom surface, were sealed with aluminum waterproofing tape to ensure the uniaxial moisture diffusion. Then the specimen was laid on a steel frame over a container filled up with saturated salt solution to control the drying condition. LVDT displacement sensors were used to measure shrinkage of concrete at different depths and the whole device system was located in a sealed container with constant temperature of (20±2) ^{0}C as shown in Fig. 2.

According to the laws of chemical equilibrium, a saturated salt solution at a fixed temperature gives a constant humidity level in a closed space [14]. In this study, three saturated salt solutions (NaCl, $Mg(NO_3)_2$, and $MgCl_2$) were used to provide three different humidity levels

Table 1

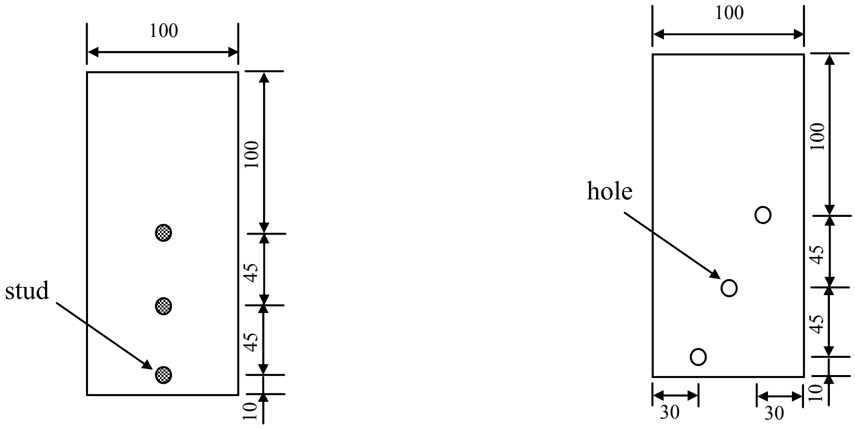
Chemical composition of cement and silica fume (%) / *Compoziția chimică a cimentului şi a silicei ultrafine* (%)

Sample /*Proba*	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	R_2O
Cement / *Ciment*	27.5	6.15	3.7	57.09	1.73	2.25	0.82
Silica fume / *Silice ultrafină*	95.4	0□3	0.8	0.2	0.2	—	0.5

Table 2

Mixing proportion of concrete / *Dozajul constituenților în beton*

Sample *Proba*	Mass of every gradient / *Dozajul gravimetric* (kg/m^3)						Slump *Tasare* (mm)	28-day compressive strength *Rezistența la compresiune la 28 de zile* (□Pa)
	Cement *Ciment*	Silica fume *Silice ultrafină*	Water *Apă*	Gravel *Pietriş*	Sand *Nisip*	Super plasticizer *Superplastifiant*		
A	460	0	147	1106	737	4.6	200	66.2
B	437	23	147	1106	737	5.06	185	72.5



(a) Position of copper studs on every end surface for shrinkage test / *Poziția ştifturilor de cupru pe suprafața supusă testului de contracție*

(b) Position of precast holes on one end surface for humidity test *Pozitia găurilor pe suprafața supusă testului de umiditate.*

Fig.1 - Specimens for shrinkage and internal humidity measurement. *Probele folosite pentru măsurarea contracției şi a umidității interne.*

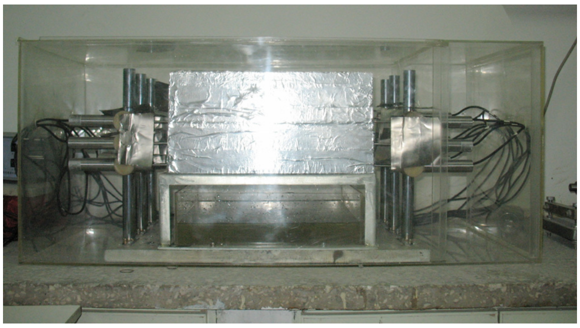


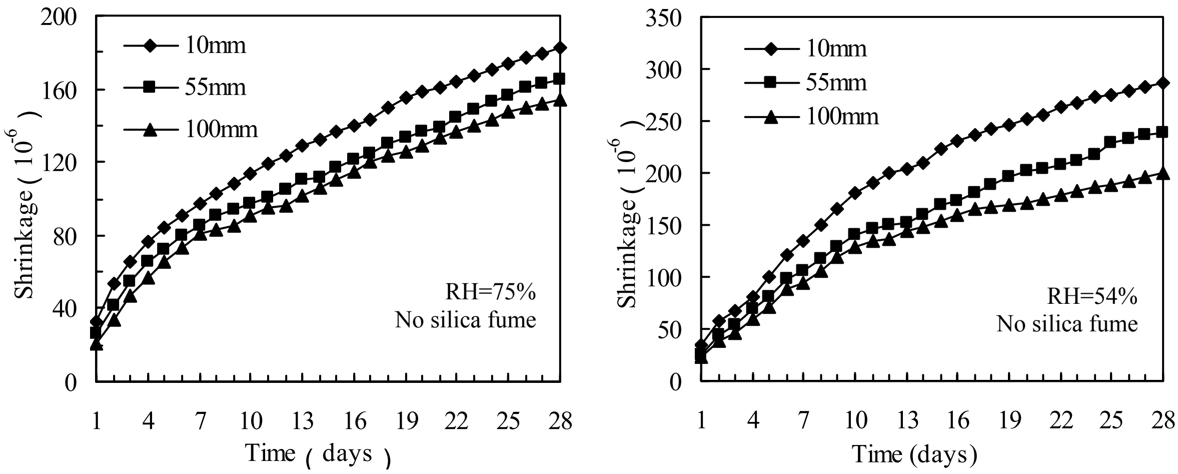
Fig.2 - Device for measuring shrinkage distribution of concrete with one surface exposed to drying condition / *Instalația folosită pentru masurarea contracției în proba de beton cu o suprafață expusă pentru uscare.*

(75%, 54%, and 33%) [15], and similar methods were also been used to measure the concrete shrinkage by other authors [16]. Two specimens were measured for each mixture under every drying condition.On the other hand, the same geometry and size of specimen as for shrinkage test was also prepared to measure internal humidity development in concrete. The specimen was cast with three 10-mm diameter and 100-mm depth holes on one of the end surface, and these holes were located at the same depth as the embedded stubs for shrinkage test and distributed horizontally as shown in Fig.1 (b). The curing, sealing and drying condition was completely the same as for the shrinkage specimen. Every precast hole was covered with a rubber plug to prevent humidity evaporation after demoulding. Relative humidity sensor probe with the same size plug was used to determine the internal humidity in concrete, and it was inserted into the hole immediately after the rubber plug was pulled out and stayed there for more than 10 minutes to obtain a stable value every day after the initial 3 days curing.

3. Results and discussion

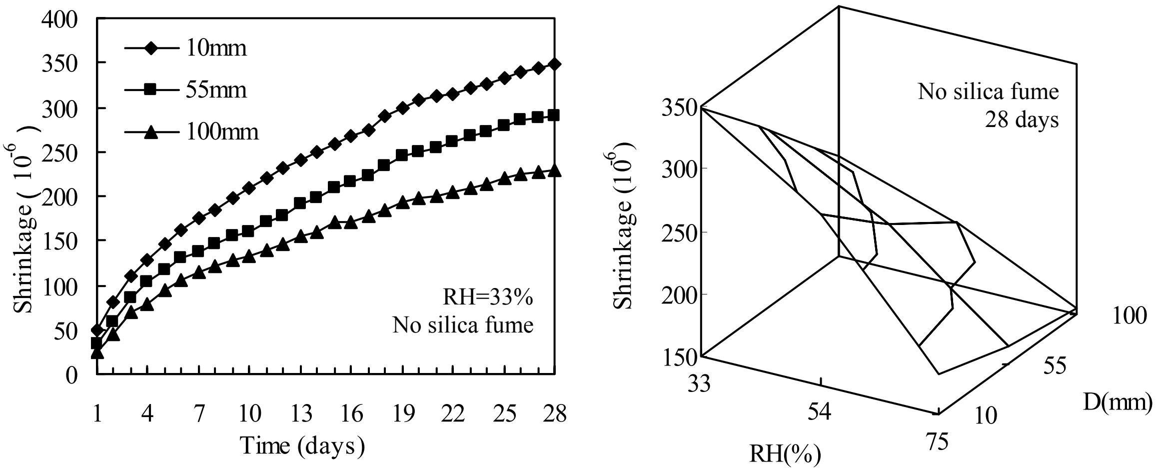
3.1. Shrinkage distribution in concrete specimen

Figure 3 presents the results of shrinkage



(a) Shrinkage development under RH 75%
(a) Evoluția contracției în condiții de RH 75%

(b) Shrinkage development under RH 54%
(b) Evoluția contracției în condții de RH 54%



(c) Shrinkage development under RH 33%
(c) Evoluția contracției în condiții de RH 33%

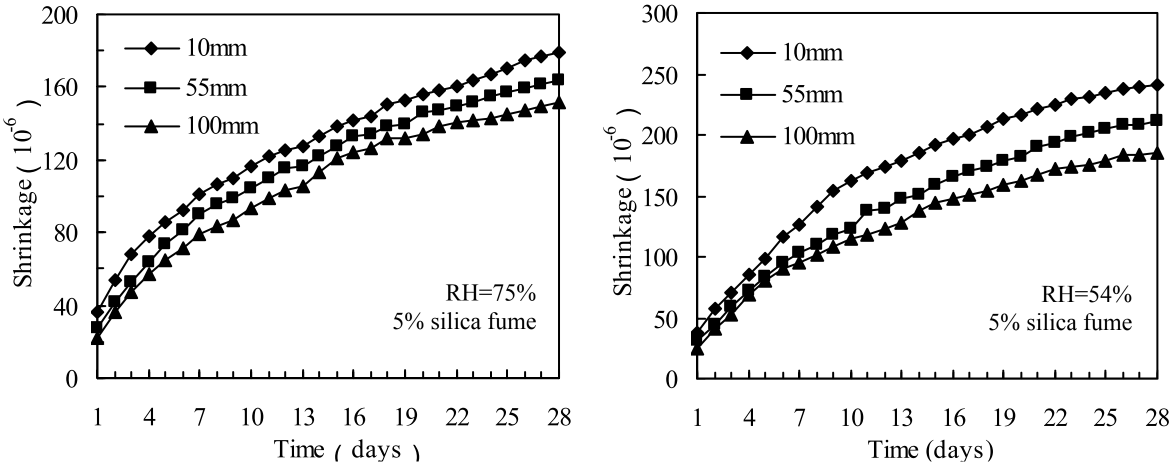
(d) Final shrinkage at 28 days
(d) Contracția finală(remanentă) după 28 zile

Fig. 3 - Shrinkage development in concrete A at different depths from the drying surface
Fenomenul de contracție în betonul A măsurat la diferite distanțe față de suprafața de uscare.

test performed on concrete A exposed to relative humidity levels of 75%, 54%, and 33%. The test was carried out for 28 days after the initial 3 days curing. Shrinkage at every depth in this test is significantly lower than the traditional shrinkage with all the surfaces of specimen exposed to drying condition. It can be seen that the internal shrinkage strain differs obviously according to the depth from exposed surface, and the shrinkage strain is greater at the depth closer to exposed surface of concrete. The shrinkage difference existing among different depths increases with the drying age due to water evaporation from the surface at a higher speed than the speed of water transportation out of the inner concrete. The shrinkage difference between depths of 10 mm and 55 mm is higher than that between depths of 55 mm and 100 mm during the test. It means that a higher shrinkage gradient occurs in the surface zone of concrete exposed the drying condition, and it is partly attributed to the surface shrinkage cracking of actual structures such as pavement.

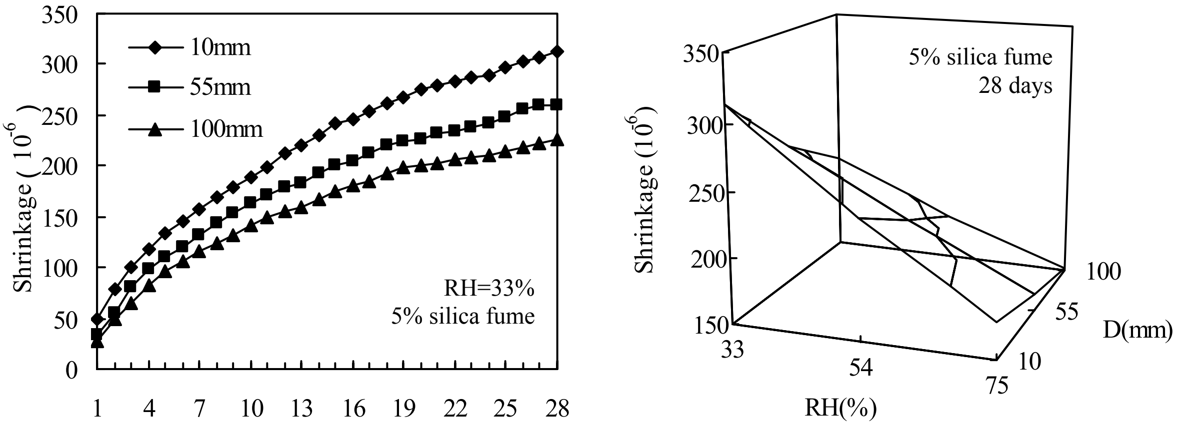
The shrinkage strain at each depth increases with the decreasing relative humidity of environment. The more the shrinkage difference according to depths is, the relative humidity of environment is the lower.

After 28 days of drying, a huge shrinkage difference forms in the concrete specimen as shown in Fig. 3(d). Under the high environmental relative humidity of 75%, the shrinkage at 10 mm is 182×10^{-6}, being 28×10^{-6} higher than the shrinkage at 100 mm (154×10^{-6}). When the relative humidity of exposure condition is as low as 33%, the shrinkage difference between depths of 10 mm (349×10^{-6}) and 100mm (229×10^{-6}) increases to 120×10^{-6} and the shrinkage at 10 mm depth is 59×10^{-6} more than that at 55 mm depth (290×10^{-6}). A self-restrained stress is inevitably caused by such great shrinkage difference. Therefore, the differential drying shrinkage must be considered in the cracking analysis of concrete structures, especially exposed to drying condition with a low relative humidity.



(a) Shrinkage development under RH 75%
(a) Evoluția contracției în condiții de RH 75%

(b) Shrinkage development under RH 54%
(b) Evoluția contracției în condții de RH 54%



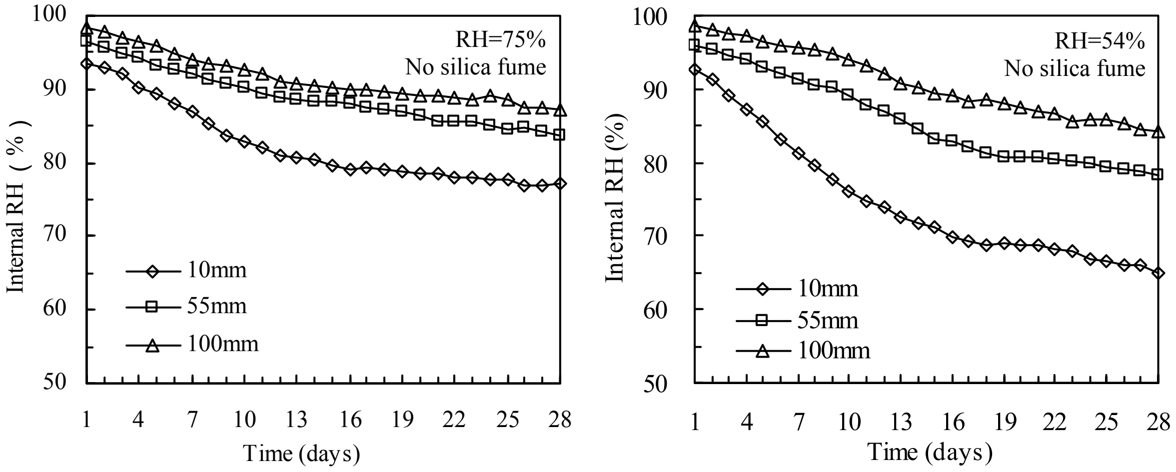
(c) Shrinkage development under RH 33%
(c) Evoluția contracției în condiții de RH 33%

(d) Final shrinkage at 28 days
(d) Contracția finală(remanentă) după 28 zile

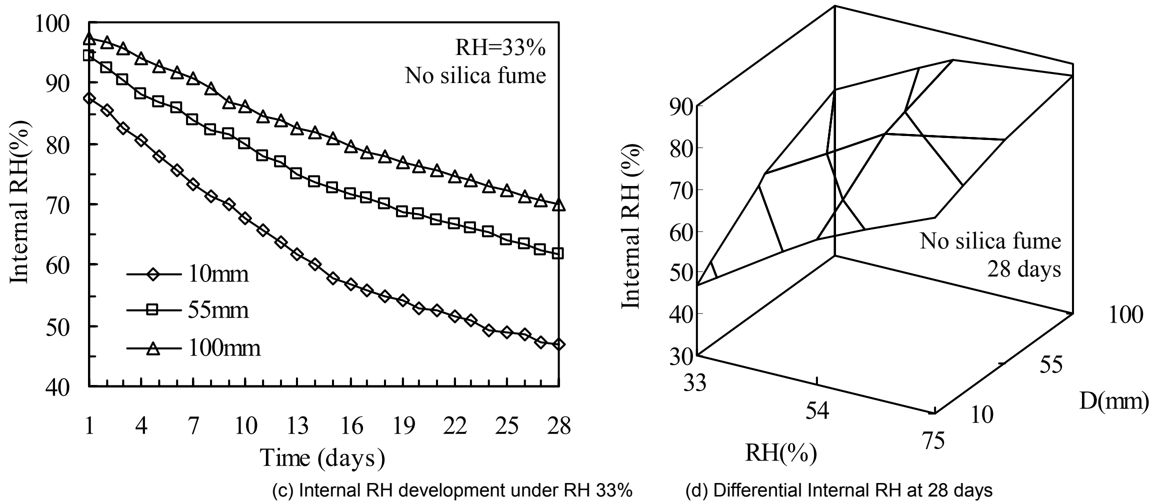
Fig. 4 - Shrinkage development in concrete B at different depths from the drying surface
Fenomenul de contracție în betonul A măsurat la diferite distanțe față de suprafața de uscare.

Differential shrinkage development of concrete B containing 5% silica fume is shown in Fig. 4. As expected, an obvious shrinkage difference is also found among depths from the drying surface. Compared with concrete A, the addition of 5% silica fume reduces the 28 days' shrinkage at 10 mm depth from 182×10^{-6} to 179×10^{-6} under RH 75%, from 288×10^{-6} to 242×10^{-6} under RH 54% and from 349×10^{-6} to 313×10^{-6} under RH 33%. It is well-known that the addition of silica fume increases the autogenous shrinkage of sealed specimen, especially at early ages, due to the high pozzolanic reaction and refinement of pore size [10, 17-18]. Some studies showed that the drying shrinkage of concrete was increased by the high addition of silica fume [19]. Hooton [20] reported that concrete with a low percentage of silica fume didn't show visible increase in shrinkage, whereas concrete with a high percentage replacement of silica fume exhibited considerable increase in shrinkage.

Mazloom [21] found that the drying shrinkage of high-strength concrete decreased with the increasing proportion of silica fume. Basically, the influence of silica fume on drying shrinkage is determined by the balancing of two factors: the increased shrinkage due to the more hydrates especially C-S-H formed in the silica fume mixture, and the reduced shrinkage due to the less water loss induced by the refined pore size distribution and improved microstructure of silica fume mixture. When the first factor is less pronounced than the second factor, the concrete showed a reduced drying shrinkage as found in this paper. On the other hand, there is a much less shrinkage reduction by the addition of silica fume at depths of 55 mm and 100 mm than at depth of 10mm. This can be explained by that the addition of silica fume increases autogenous shrinkage and autogenous shrinkage contributes a higher percentage of total shrinkage in inner position than outer position of concrete specimen.

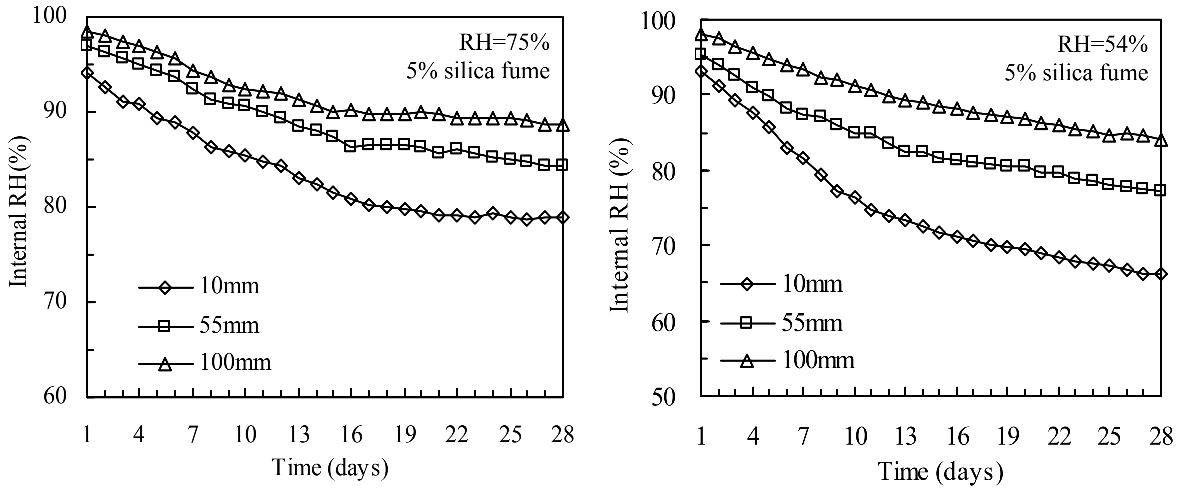


(a) Internal RH development under RH 75% (b) Internal RH development under RH 54%
(a) Evoluția umidității interne (RH 75%) (b) Evoluția umidității interne (RH 54%)

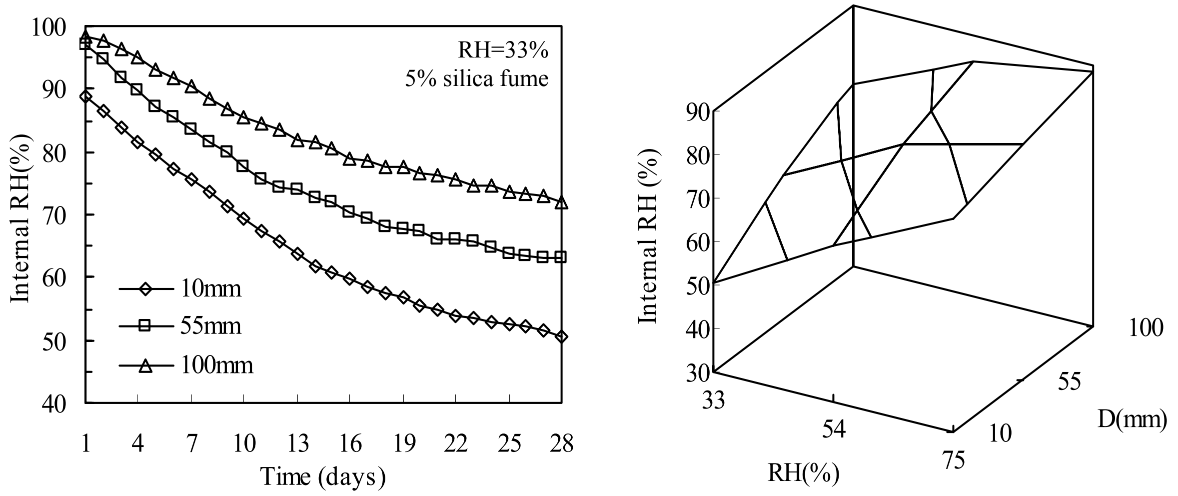


(c) Internal RH development under RH 33% (d) Differential Internal RH at 28 days
(c) Evoluția umidității interne (RH 33%) (d) Umiditatea relativă diferențială după 28 zile

Fig. 5 - Internal RH development in concrete A at different depths from the drying surface
Umiditatea relativă internă în betonul A la diferite adâncimi față de suprafața expusă mediului uscat.



(a) Internal RH development under RH 75% (b) Internal RH development under RH 54%
(a) Umiditatea relativă internă la RH 75% (b) Umiditatea relativă internă la RH 54%



(c) Internal RH development under RH 33% (d) Differential Internal RH at 28 days
(c) Umiditatea relativă internă la RH 33% (d) Umiditatea relativă internă diferențială la 28 de zile

Fig. 6 - Internal RH development in concrete B at different depths from the drying surface
Evoluția umidității relative interne în betonul B la diferite adâncimi față de suprafața expusă mediului de uscare.

As a result, there is a less shrinkage difference between the inner positions (55 mm and 100 mm) and the outer position (10 mm) in concrete B than in concrete A. Based on the above result, the lower self-restrained shrinkage stress occurred in the silica fume concrete, being favorable to the resistance to cracking. However, some researchers found that the cracking tendency of concrete got worse with the addition of silica fume [22], which should be attributed to a higher elastic modulus and lower ductility of silica fume concrete [23]. In addition, the concrete mixture, dosage of silica fume, specimen size, drying condition and other factors should be also considered.

After 28 days of drying, a huge shrinkage difference forms in the concrete specimen as shown in Fig. 4(d). The more the shrinkage difference among various depths is, the relative humidity of environment is the lower. And the influence of relative humidity on the shrinkage difference of concrete containing silica fume is weaker than that of the concrete without silica fume.

This can be explained by the reduced total shrinkage as mentioned above and the lower percentage of drying shrinkage in total shrinkage for silica fume concrete [10]. As a result, the shrinkage difference in silica fume concrete showed a less sensitivity to the outer drying condition (different relative humidity) than the plain concrete.

3.2. *Relative humidity distribution in concrete specimen*

Due to self-desiccation and dissolution of salts in the pore water occurring during the initial curing time [17], the internal RH of concrete is lowered to a little below saturation humidity before testing. After exposure to drying condition, relative humidity at every depth decreases with time as shown in Fig. 5 and Fig. 6 respectively for concrete A and concrete B. The decreasing relative humidity is attributed to both internal self-desiccation and moisture evaporation into drying environment. The decreasing rate of relative humidity at each depth slows down with the drying age due to the reducing moisture difference between concrete and environment, and it is much faster at the outer position of 10 mm depth than at the inner positions of 55 mm and 100 mm depths during the test period, especially in the first 2 weeks. Consequently, an obvious relative humidity gradient forms in the concrete specimen and it becomes more significant with drying time.

The addition of silica fume decreases the relative humidity reduction at depth of 10 mm more than at depths of 55 mm and 100 mm attributing to its preventing moisture loss and accelerating self-desiccation. After 28 days of drying, for concrete A, the relative humidity at depths of 10mm, 55mm and 100mm are 77.3%, 83.8% and 87.1% respectively under RH 75% of drying condition, and become 47%, 61.6% and 70% respectively under RH 33% of drying condition; for concrete B with 5% silica fume, the relative humidity at depths of 10mm, 55mm and 100mm are 78.9%, 84.4% and 88.7% respectively under RH 75% of drying condition, and are 50.4%, 63.1% and 71.9% respectively under RH 33% of drying condition.

The relative humidity gradient in concrete is strengthened by the lower relative humidity of environment and alleviated by the addition of silica fume to a certain degree. The less humidity gradient in silica fume concrete is partly attributed to the less relative humidity reduction in outer concrete due to the increased difficulty of water evaporation from the refined pore structure paste [24] and the more self-desiccation in inner concrete due to the high pozzolanic reaction of silica fume. The influence tendency of drying condition and silica fume incorporation relative humidity distribution in concrete specimen is in agreement with the results of shrinkage test.

3.3 Relationship between shrinkage and internal relative humidity

The relation between shrinkage and relative humidity for concrete A and concrete B exposed to different drying conditions are presented in Fig. 7 and Fig. 8.

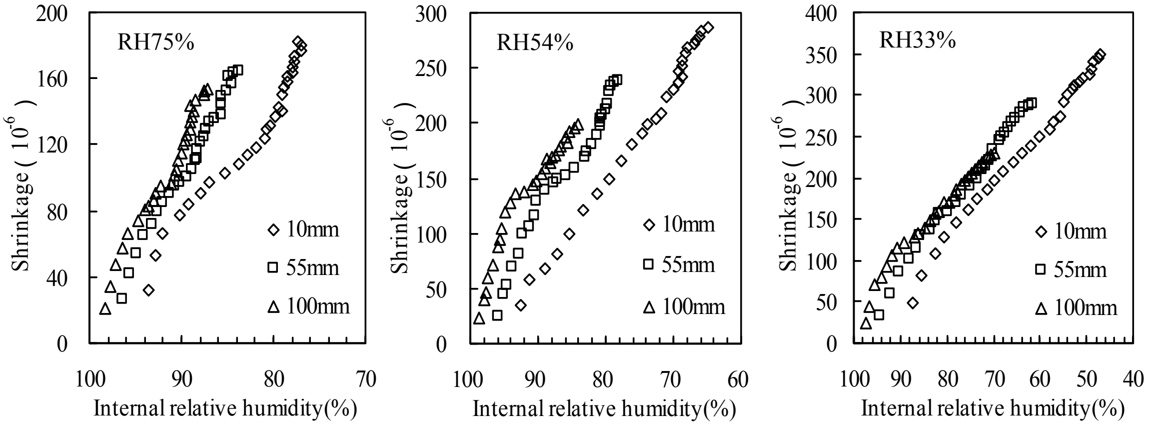


Fig. 7 - Shrinkage vs. internal RH at different depth in concrete A

Evoluția contracției în funcție de umiditatea relativă internă (%) pentru betonul A

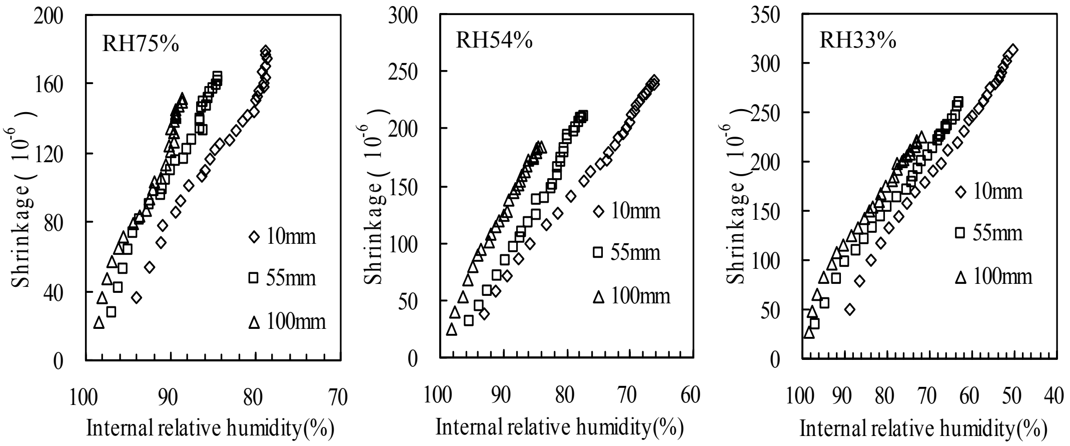


Fig. 8 - Shrinkage vs. internal RH at different depth in concrete B

Evoluția contracției în funcție de umiditatea relativă internă (%) pentru betonul B.

For every depth and every drying condition, it can be seen that the shrinkage increases almost linearly with the decrease of internal relative humidity. For high strength concrete exposed to drying condition in this study, the internal relative humidity reduction is resulted from both inner self-desiccation and environmental drying. For the relative humidity reduction due to either self-desiccation or environmental drying, concrete shrinkage deformation happens in the same way of increasing surface tension of pore water described as Kelvin equation [17]. The relationship between shrinkage and relative humidity can be approximated for the case of high relative humidity (i.e., RH > 50%) as linearly proportional [25]. As a result, the shrinkage strain can be expressed by a constant coefficient and the reduction of relative humidity for every depth and every drying condition. From these 2 Figures, the shrinkage at depths of 55 mm and 100 mm is higher than that at depth of 10 mm for the same reduction of relative humidity for each concrete. It can be explained that shrinkage of the outer layer concrete is restrained by the inner layer concrete and shrinkage of the inner layer concrete is strengthened due to the nonuniform deformation distribution in specimen. Consequently, the position and the structure shape should be also taken into account to predict the actual shrinkage deformation.

4. Conclusions

From the results of this investigation on differential shrinkage of high strength concrete, the following conclusions can be drawn:

1. The internal shrinkage strain differs obviously according to the depth from drying surface, and the shrinkage strain is greater at the depth closer to exposed surface than the inner region of concrete. Such shrinkage difference among different depths increases with the drying time and the decreasing relative humidity of environment. A self-restrained stress is inevitably caused by such great shrinkage difference. Therefore, the differential drying shrinkage must be considered in the cracking analysis of concrete structures, especially exposed to drying condition with a low relative humidity.
2. Due to the reduction of drying shrinkage and increase of autogenous shrinkage of concrete, the addition of silica fume leads to a less shrinkage difference between the inner positions (55 mm and 100 mm) and the outer position (10 mm) in concrete.
3. A relative humidity gradient forms as shrinkage strain in the concrete specimen with one surface exposed to drying condition. At every depth, the more reduction of internal relative humidity results in the higher shrinkage, and their relation can be expressed as a linear equation for every drying condition. However, the increased shrinkage at depth of 55mm and 100 mm is higher than that at depth of 10 mm for the same reduction of relative humidity for every concrete because shrinkage in the outer layer concrete is restrained by the inner layer concrete.

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MANIFESTĂRI ŞTIINŢIFICE / SCIENTIFIC EVENTS

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1st International Congress on Durability of Concrete ICDC), Trondheim, Norway, June 18-21, 2012

This is a new congress series based on the heritage of the former CANMET/ACI Conferences on Durability of concrete as described in the history of these conferences by the Honorary Chair Mohan Malhotra of this congress. The congress is committed to creating an opportunity for professional development, to share and disseminate information, and to foster the continuous advancement of the important field of Concrete Durability.

Every aspect of the congress is intended to make your time here beneficial, professionally and personally. It will function as an arena where colleagues working in every aspect of Concrete Durability can meet, and where you can extend your network with other professionals in your field.

The congress will gather the worlds experts and scientists to present the state of art on durability of existing concrete materials and structures as well as recent developments and emerging technologies for creation of durable and sustainable concrete materials and structures. Thus, ICDC will be an important meeting point for experienced and young scientists alike.

Even though the intention is to bring the ICDC around the world on a regular basis with some years apart, it is a privilege to start out in Trondheim with the 1st one in the new series since it is the "home-town" of both institutions; SINTEF (the Foundation for Industrial and Technical Research) and NTNU (the Norwegian University of Science and Technology).

For Authors: Final papers submitted: 15th Feb. 2012, NB! The papers must be written in English!
Full Registration: 28th May 2012

For Participants: Tentative registration: icdc2012@tekna.no ; http://www.icdc2012.com/

TECHNICAL PROGRAMME

In order to ensure its objectives the congress addresses all factors affecting the durability of concrete structures divided into the following main topics:

- **Durability of sustainable cement and concrete**
- **Durability enhancing concrete admixtures**
- **Additions for enhanced durability of concrete**
- **Concrete deterioration mechanisms**
- **Methodology for testing durability**
- **Treatment of existing concrete structures**
- **Principles of making durable concrete structures**
- **Durability of off-shore concrete structures like**
- **Sustainability**
- **Modelling and calculating durable materials and degradation processes**

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