CRACKING POTENTIAL OF INTERNALLY CURED CONCRETE MADE AT VARIOUS WATER TO CEMENT RATIOS

Semion Zhutovsky and Konstantin Kovler

National Building Research Institute, Technion – Israel Institute of Technology, 32000 Haifa, Israel, e-mail: nbri@technion.ac.il

Abstract: Internal curing technology has been developed to counteract the autogenous shrinkage of high-performance concretes and to reduce its cracking sensitivity. In literature, the total shrinkage of internally cured concrete is reported almost unchanged after exposure to drying. On the other hand, the range of water to cement ratios studied is quite narrow. Thus, the effect of water to cement ratio on total shrinkage and cracking potential of internally cured concrete attracts considerable interest. In this research, the restrained drying shrinkage of concrete with water to cement ratios of 0.33, 0.25 and 0.21, internally cured by means of water-saturated light-weight aggregate (pumice) was studied. In parallel, strength, free drying shrinkage and mass loss of the same concrete mixes were tested. The experimental results demonstrate that water to cement ratio has considerable impact on cracking potential of internally cured concrete.

Keywords: Cracking potential, high-performance concrete, internal curing, shrinkage, water to cement ratio

BIOGRAPHY

Dr. Semion Zhutovsky is a research fellow in the National Building Research Institute (NBRI) – Faculty of Civil and Environmental Engineering, Technion – Israel Institute of Technology. Dr. Zhutovsky published 11 papers in international leading peer-refereed journals. He is a member of the International Union of Laboratories and Experts in Construction Materials, Systems and Structures (RILEM) and American Concrete Institute (ACI). His research interests are cement hydration, internal curing, high-performance cementitious materials and durability.

Prof. Konstantin Kovler is Head, Department of Building Materials, Performance and Technology, NBRI – Faculty of Civil and Environmental Engineering, Technion. He edited 6 books and authored 6 patents, 220 technical publications and 18 book chapters. Chairs 5 committees in Israeli Standards Institution. He is RILEM Fellow and ACI member. His research interests include high-performance cementitious materials, radioactivity of building materials, uses of chemical admixtures, gypsum, pozzolanic materials, fibers, natural stone and industrial by-products in construction.

1 INTRODUCTION

High-performance concrete (HPC) has been continuously gaining popularity due to its superior mechanical and durability properties [1, 2]. However, HPC has its own drawbacks. Due to extremely low water to binder ratio (W/C) and low permeability, traditional curing methods fail to supply curing water into the internal core of structural element made of HPC and it exhibits self-desiccation and autogenous shrinkage, which lead to cracking [3]. Cracking sensitivity of HPC due to autogenous shrinkage is referred by some researchers and practitioners as the Achilles heel of HPC [4]. Internal curing has been developed as the technology that is intended to provide a solution for the early-age cracking sensitivity of HPC [4, 5]. It implies the introduction into a concrete mixture of highly absorptive material that is able to prevent reduction of relative humidity and generation of capillary pressure inside the cementitious matrix. Internal curing is able to provide curing water from inside of the element, reduce or even eliminate completely autogenous shrinkage of sealed high-performance concrete specimens in the lab [5-8].

However, the concrete structures are usually exposed at a construction site to drying conditions at an early stage. Drying of concrete may start at ages of one or several days after the end of curing or, in most cases, right after demolding. Several researchers noted that after the exposure to drying conditions internally cured high-performance concrete exhibits higher drying shrinkage, therefore internal curing does not reduce the total shrinkage of high-performance concrete [9-11]. In other words, internally cured high-performance concrete still can crack in the period of drying.

The experimental data on drying shrinkage of internally cured high-performance concrete available in the literature are obtained mainly for concrete mixes made of water to cement ratio above 0.3. This paper comes to extend these data for lower water to cement ratios. Autogenous and drying shrinkage of concretes with water to binder ratio of 0.33, 0.25 and 0.21 were measured. The experimental results provide the evidence that for internally cured concretes with water to cement as low as 0.21, drying shrinkage can be significantly reduced. This means that internal curing can be very beneficial for reducing cracking potential of concretes with extremely low water to cement ratios.

2 MATERIAL AND METHODS

2.1 Materials

Concrete mixtures with W/C of 0.33, 025, and 0.21 were studied. The mixture compositions were adjusted with superplasticizing admixture in order to keep the slump in the range of 110-160 mm. The cement type was CEM I 52.5N with a Blaine fineness of 421.7 m^2/kg and the superplasticizer (SP) was of calcium naphthalene sulphonate type. Internal curing was applied by means of vacuum-saturated LWA – pumice from mount Hekla, Iceland. Only a single fraction of pumice sand with particle size between 2.36 and 4.75 mm was used. The water absorption of pumice under vacuum after 1 hour was 73.1% by weight and specific weight in the oven-dry state was 782 kg/m^3.

In order to eliminate self-desiccation, the amount of water available for internal curing should be equal to chemical shrinkage [12]. For this reason the dosage of LWA incorporated into the concrete mixtures was adjusted to contain the amount of absorbed water for IC, which was equal to the experimentally measured chemical shrinkage of cement paste with the same W/C at the age of 7 days [13].

Mixtures with the same W/C, and contents of cement and coarse aggregate were used as references. The proportions of the mixtures per cubic meter are presented in **Table 1**. All weights of aggregates that are given in **Table 1** are oven-dry weights. The coarse aggregate was crushed dolomite with the grain size between 2.36 mm and 9.5 mm. The water absorption capacity of coarse aggregate was 1.5% by weight. The content of coarse aggregate was kept constant in all mixtures in order to exclude its effect on concrete properties. The fine aggregate was natural sea sand with grain size below 0.6 mm and water absorption capacity 0.4% by weight.

Table 1: Mixture proportions [kg/m^3]

Mixture notation	Cement	Mixing water	Internal curing water	Fine aggreg.	Coarse aggreg.	LWA	SP*
21	667	140	-	532	1145	-	4.2%
25	600	150	-	562	1145	-	3.2%
33	506	167	-	572	1145	-	2.6%
21 L	667	140	40.0	348	1145	54.7	4.2%
25 L	600	150	36.0	396	1145	49.2	3.4%
33 L	506	167	30.4	432	1145	41.5	2.6%

* Superplasticizer content is given by cement weight percent

2.2 Methods

The potential for cracking was determined by means of restrained ring tests following the standard procedure of ASTM C1581-04 [14]. The specimens were demolded and exposed to drying at one day in a controlled environment of 50±4% RH and 20±2°C. The measurements included continuous monitoring of the strain developed in the steel ring. The results of the ring tests were obtained in terms of strain-time curves. The strain measured is the one in the restraining steel, using which one can calculate the stress in the concrete according to equation reported by See et al. [15]. Cracking was identified by a sharp drop in the strain. The net-time-to-cracking and stress-rate-at-cracking criteria were evaluated and classified according to the prescription of the standard [14]. The strain curves obtained in the tests are omitted, and only the values of two standard criteria of cracking potential and their classifications are presented in this paper.

The compressive and splitting tensile strength were measured on cubes with the edge length of 50 mm. The samples for strength tests were cured at the temperature of 20°C and 50% of relative humidity, which corresponds to the curing conditions of ring specimens for the standard test of cracking sensitivity according to ASTM C1581-04. This standard test is based on simulating restrained shrinkage in concrete rings cast around the inner steel ring. The measurements included continuous monitoring of the strain developed in the steel ring. The results of the ring tests were obtained in terms of strain-time curves. Cracking was identified by a sharp sudden decline in the strain. The strain measured is the one in the restraining steel, and from it one can calculate the stress in the concrete $\sigma_t(t)$ following the equation reported by See et al. [15]:

$$\sigma_t(t) = E_s \varepsilon_s(t) \frac{r_{ic} h_s}{r_{is} h_c} \qquad (1)$$

$\varepsilon_s(t)$ - elastic strain in steel ring at time t;
E_s - modulus of elasticity of steel ring;
r_{is} - internal radius of steel ring;
r_{ic} - internal radius of concrete ring;
h_s - thickness of steel ring;
h_c - thickness of concrete ring.

The ASTM C1581-04 standard suggests two criteria upon which the cracking potential (or cracking sensitivity) is determined. One of the criteria is the net time of cracking in the ring test (time from the initiation of drying), and the other one is the stress rate at cracking, which is calculated by a special procedure outlined in the standard. The ASTM C1581-04 classification is presented in **Table 2**.

Table 2: Cracking sensitivity classification according to ASTM C1581-04

Cracking sensitivity	Time to cracking, t_{cr} (days)	Stress rate, S (MPa/day)
High	$t_{cr} \leq 7$	$S \geq 0.34$
Moderate-High	$7 < t_{cr} \leq 14$	$0.17 \leq S < 0.34$
Moderate-Low	$14 < t_{cr} \leq 28$	$0.10 \leq S < 0.17$
Low	$t_{cr} > 28$	$S < 0.10$

3 RESULTS AND DISCUSSION

Cracking usually occurred at the time when the stress curve crossed the tensile splitting strength, as shown in **Figure 1** for concrete made at W/C=0.33 internally cured using LWA.

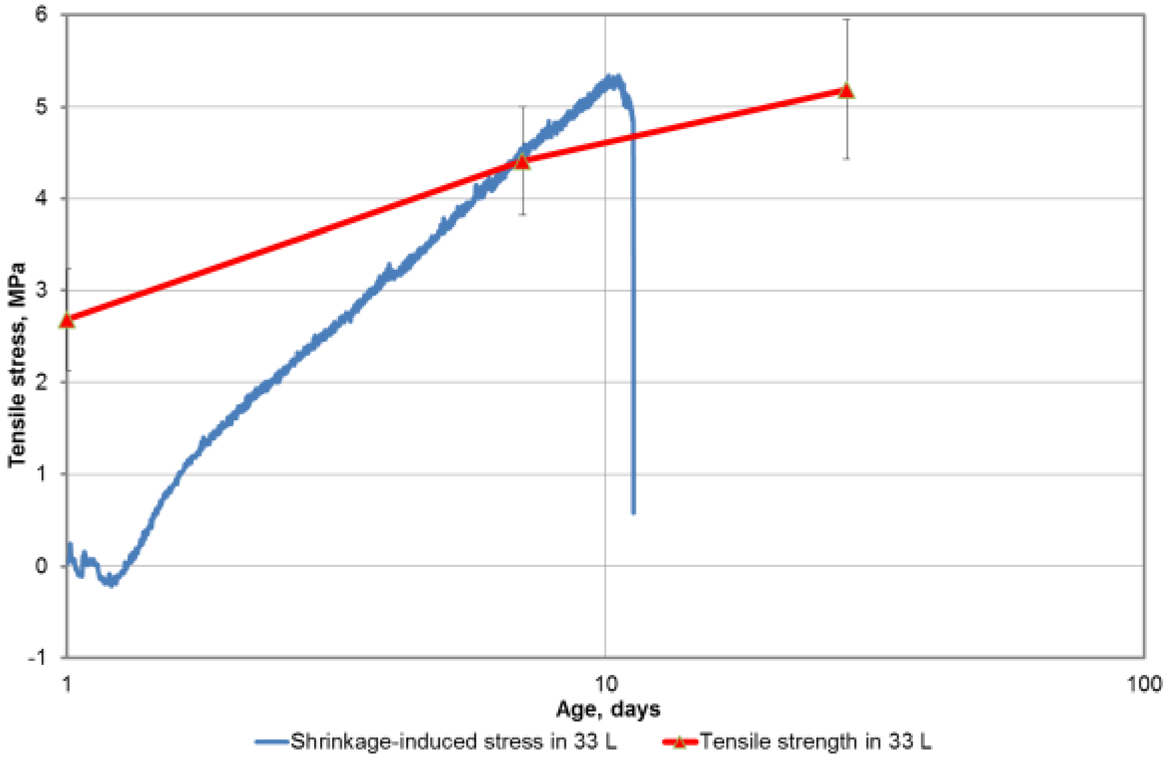

Figure 1: Typical results of the development of shrinkage-induced stress in concrete ring and tensile splitting strength determined in the age of 1, 7 and 28 days (for the case of concrete made at W/C = 0.33 internally cured with LWA).

Cracking potential of concretes with W/C of 0.33, 0.25, and 0.21 according to both net-time-to-cracking and stress-rate-at-cracking criteria is shown in **Figure 2**. It is apparent that the reduction of W/C results in a considerable increase in cracking potential by both standard criteria, according to ASTM C1581-04. This trend readily demonstrates the cracking sensitivity problematic of HPC. In **Figure 2**, the effect of internal curing on the cracking sensitivity of concrete can be clearly recognized. It can be seen that, for a W/C of 0.33, the potential for cracking was nearly unaffected by internal curing. However, for concrete mixtures with lower W/C, of 0.25 and 0.21, the potential-for-cracking classification was successfully reduced from high to low by both standard criteria - of net-time-to-cracking and stress-rate-at-cracking.

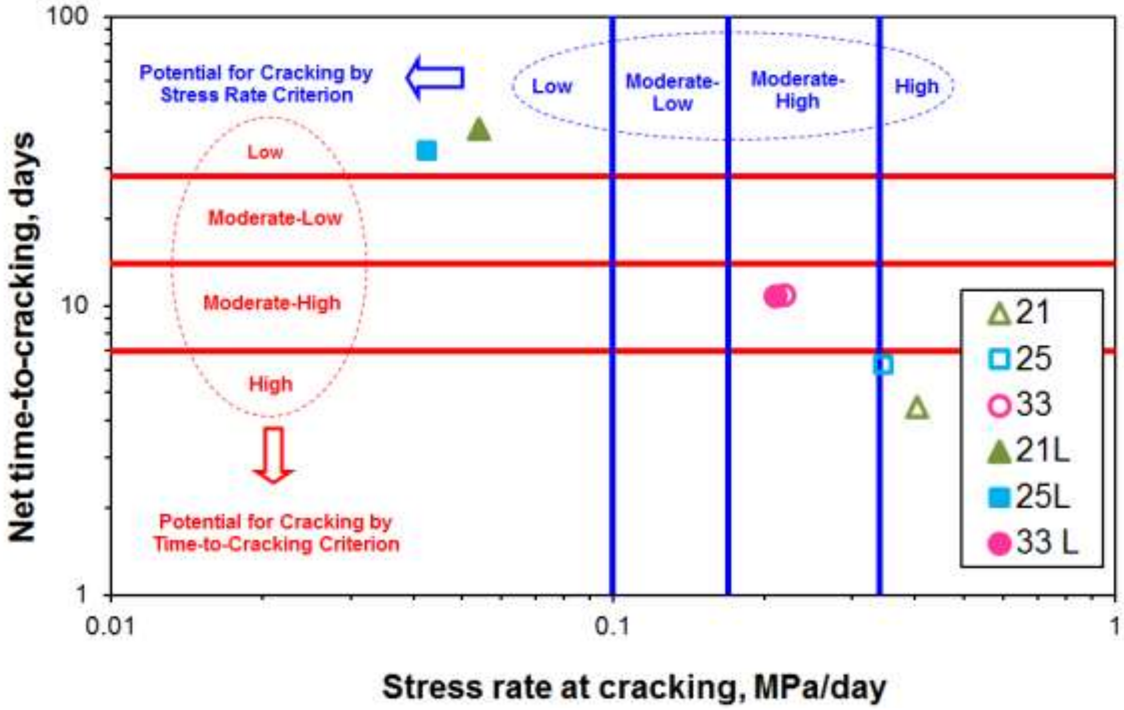

Figure 2: Effect of internal curing on cracking sensitivity of concrete mixtures made at W/C of 0.33, 0.25 and 0.21.

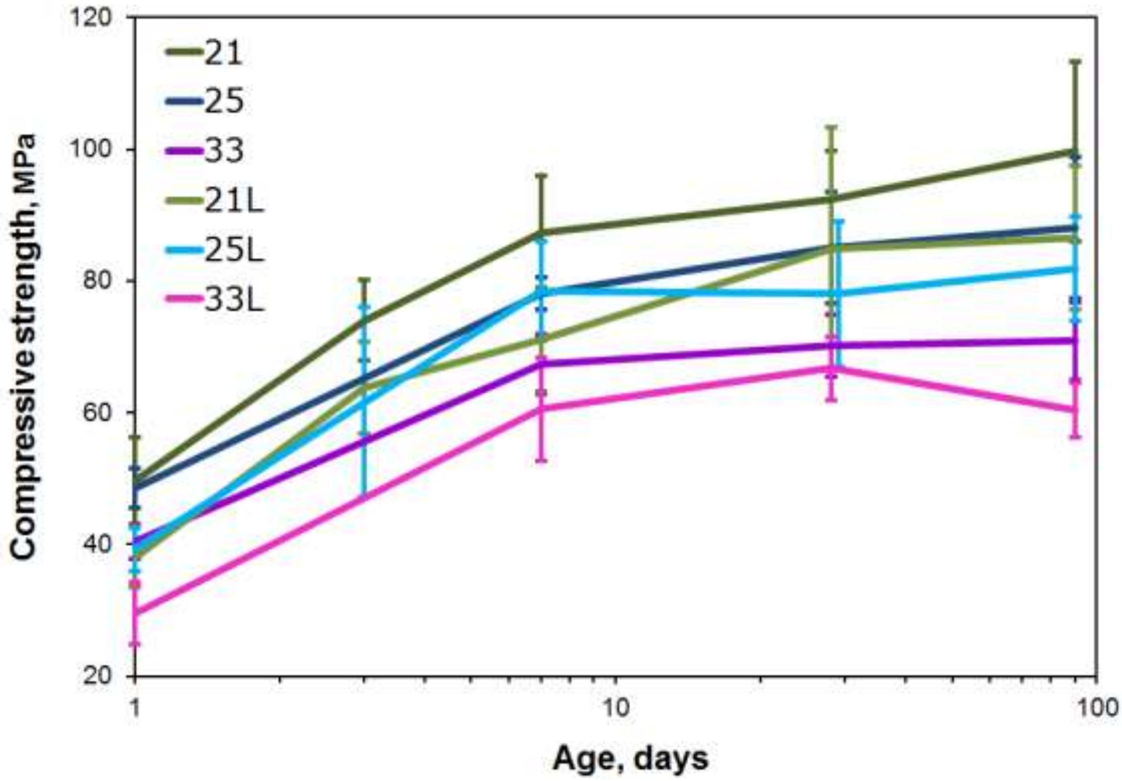

Figure 3: Effect of internal curing on the compressive strength of concrete mixtures made at W/C of 0.33, 0.25, and 0.21.

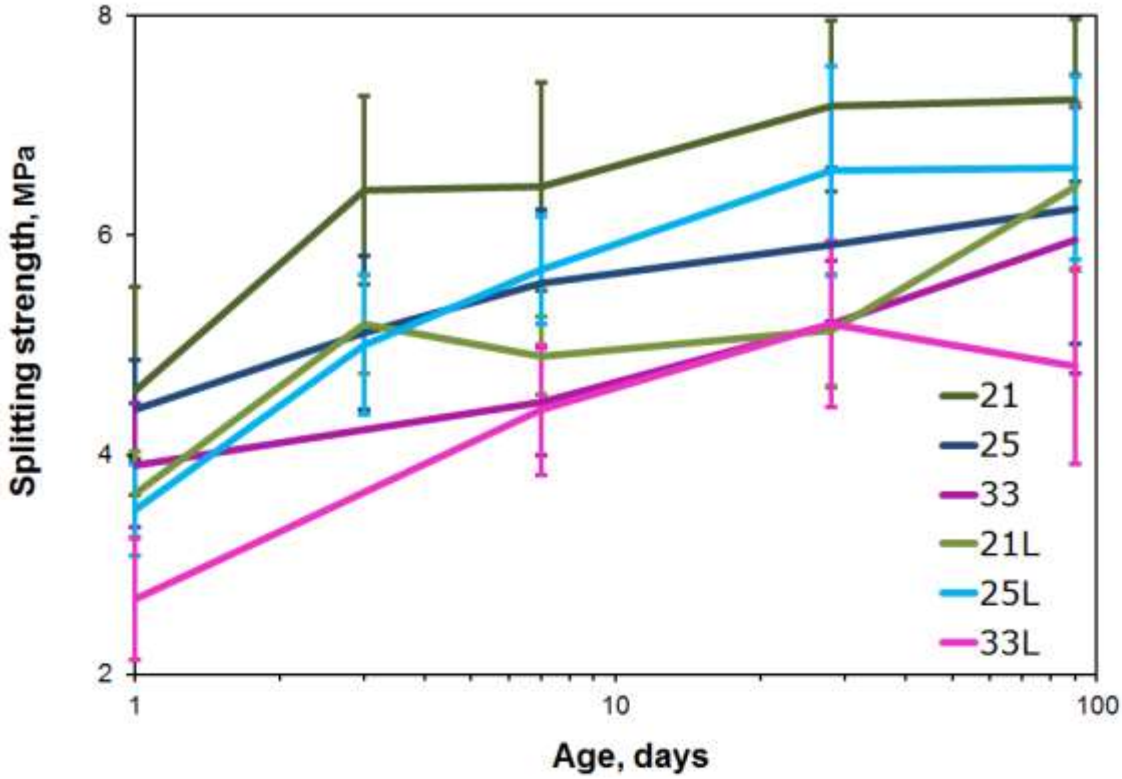

Figure 4: Effect of internal curing on the splitting tensile strength of concrete mixtures made at W/C of 0.33, 0.25, and 0.21.

Compressive strength of reference and internally cured concretes with W/C of 0.33, 0.25, and 0.21 is presented in **Figure 3**. It can be seen that compressive strength is slightly reduced by the introduction of saturated LWA as internal curing agent; however, the strength reduction becomes lower with the concrete age. At the age of 1 day the reduction of compressive strength was 19-27% for various W/C. At the age of 28 days the loss of compressive strength of internally cured concrete in comparison to reference concrete was less than 9% for all the mixtures. Moreover, at the age 90 days the compressive strength loss slightly increased for W/C of 0.33 and 0.21.

Tensile strength plays a crucial role in cracking sensitivity of concrete. The effect of internal curing on the splitting tensile strength of concretes with W/C of 0.33, 0.25, and 0.21 is shown in **Figure 4**. The loss of splitting tensile strength as a result of the internal curing application is significant at an early age. At the age of 1 day, the splitting tensile strength of internally cured concrete was lower than the strength of the reference concrete by about 20% for concretes made at W/C of 0.25 and 0.21, and by approximately 27% for concrete with W/C of 0.33. However, at later ages the difference in splitting tensile strength between the internally cured and reference concrete seems to be insignificant.

The concrete potential for cracking is determined by a bundle of its properties. These include shrinkage, creep and tensile strength. The subtle difference in tensile strength cannot explain the significant differences in cracking sensitivity of internally cured concretes that are observed in **Figure 2**. According to the experimental data found in the literature [16], the variation in creep of concrete mixtures cannot be significant enough to provide satisfactory reasoning for these differences in the cracking potential. The different effect of internal curing on the cracking sensitivity of concrete made at different W/C ratios may be explained by the fact that the contribution of autogenous shrinkage to the total shrinkage increases with the reduction of W/C [17]. Indeed, in concretes made with W/C above 0.3 more than 50% of total shrinkage is due to drying shrinkage, which increases by internal curing. However, in concretes with much lower

W/C, most of the shrinkage will be comprised of autogenous shrinkage, which can be successfully reduced by internal curing. Thus, the potential of cracking of internally cured concrete can be effectively controlled by the reduction of W/C.

The limited length of the current conference paper does not allow to provide a detailed information about the time dependences of autogenous shrinkage, drying shrinkage and mass loss due to drying. However, the main observations from the experimental study can be formulated as follows:

1. The drying shrinkage of concrete with W/C ratio of 0.33 was increased by incorporation of internal curing.
2. For concrete with W/C ratio of 0.25, the total free shrinkage was practically unaffected.
3. For concrete with W/C ratio of 0.21, the total free shrinkage was decreased by incorporation of internal curing.

Thus, with the reduction of W/C ratio, the detrimental effect of internal curing decreases until it vanishes at W/C ratio of 0.25, and eventually turns into a positive influence at W/C ratio of 0.21.

The mass loss of internally cured concrete was found higher than the mass loss of the reference concrete, although the difference between them slightly decreased with the reduction of W/C ratio.

The drying at the environmental conditions used for restrained ring test conducted according to the ASTM C1581-04 started at early age of 24 hours, i.e. the tested concrete received insufficient curing. For this reason, additional drying shrinkage tests were carried out on the specimens cured at sealed conditions for 3 days. The specimens used for this drying shrinkage test series were, in fact, the same ones that were used for autogenous shrinkage measurements, but exposed to a drying at the age of 72 hours. The tests were conducted at the environmental relative humidity of 35% and temperature of 30 °C. These environmental conditions are best matched to the hot climate conditions in Israel. In addition, the hot and dry climate conditions are favourable, because they intensified drying shrinkage of the material, accelerated the test, and allowed to obtain the results within a shorter period.

The study of the effect of internal curing on the total free shrinkage of concretes with W/C ratios of 0.33, 0.25 and 0.21 under 30 °C and relative humidity of 35% showed that the total free shrinkage of the reference concrete mixtures increased with the reduction of W/C ratio, while, for internally cured concretes, the opposite trend was observed. These data support the results of the restrained ring test, which showed that the cracking sensitivity is reduced by internal curing at low W/C ratios.

Besides, W/C was also found to have a significant effect on the ability of internal curing to promote a higher degree of cement hydration [18].

For concretes with moderate-low W/C, in the range of 0.3-0.4, hybrid curing, which is a combination of internal curing and shrinkage reducing admixtures, may be beneficial [19].

4 SUMMARY AND CONCLUSION

The most important goal of the application of internal curing technology is the reduction of cracking sensitivity of HPC. The effect of internal curing on potential to cracking of concrete was experimentally studied using the procedure of the standard test method (ASTM C1581-04, 2004). The use of internally cured concrete with lower W/C was shown beneficial from the cracking sensitivity point of view. The main finding of this work is that the cracking potential of internally cured concrete decreases by the reduction of W/C. The reduction of W/C in conjunction with internal curing significantly decreases the potential for cracking.

ACKNOWLEDGEMENTS

The authors are thankful to Prof. Arnon Bentur for the valuable comments and help.

REFERENCES

[1] P.C. Aïtcin, “High-Performance Concrete”, E&FN SPON, 1998.

[2] K. Kovler, O.M. Jensen, (eds.): “RILEM Report 41 "Internal Curing of Concrete", RILEM Publ. S.A.R.L., Bagneux, France, 2007.

[3] K. Kovler, S. Zhutovsky, “Overview and future trends of shrinkage research”, Materials and Structures 39 (2006) 827-847.

[4] K. Kovler, O.M. Jensen, “Novel technologies of concrete curing”, Concrete International 27 (2005) 39-42.

[5] S. Zhutovsky, K. Kovler, A. Bentur, “Revisiting the protected paste volume concept for internal curing of high-strength concretes”, Cement and Concrete Research. 41 (2011) 981–986.

[6] S. Zhutovsky, K. Kovler, A. Bentur, “Influence of cement paste matrix properties on the autogenous curing of high-performance concrete”, Cement & Concrete Composites 26 (2004) 499–507.

[7] S. Zhutovsky, K. Kovler, A. Bentur, "Efficiency of lightweight aggregates for internal curing of high strength concrete to eliminate autogenous shrinkage", Materials and Structures 35 (2002) 97-101.

[8] S. Zhutovsky, K. Kovler, "Effect of internal curing on durability-related properties of high performance concrete”, Cement and Concrete Research 42 (2012) 20-26.

[9] K. van Breugel, H. Outwerk, J. de Vries, “Effect of Mixture Composition and Size Effect on Shrinkage of High Strength Concrete”, in V. Baroghel-Bouny and P. C. Aitcin (eds.), International RILEM Workshop on Shrinkage of Concrete, Paris, France, 2000. pp. 161-177.

[10] P. Lura, K. van Breugel, I. Maruyama, “Autogenous And Drying Shrinkage of High-Strength Lightweight Aggregate Concrete At Early Ages – The Effect of Specimen Size”, in: A. Bentur, K. Kovler (eds.), RILEM International Conference on Early Age Cracking in Cementitious Systems, Haifa, Israel, 2001, pp. 337-344.

[11] I. Maruyama, R. Sato, “A trial of reducing autogenous shrinkage by recycled aggregate”, in: B. Persson, D. Bentz, L.-O. Nilsson (eds.), 4-th International Seminar on Self-Desiccation and Its Importance in Concrete Technology, Gaithersburg, Maryland, USA, 2005, p. 264-270.

[12] D. P. Bentz, K. A. Snyder, “Protected paste volume in concrete: Extension to internal curing using saturated lightweight fine aggregate”, Cement & Concrete Research 29 (1999) 1863-1867.

[13] S. Zhutovsky, K. Kovler, “Chemical shrinkage of high-strength / high-performance cementitious materials”, International Review of Civil Engineering 1 (2010) 110-118.

[14] ASTM C1581-04, “Standard Test Method for Determining Age at Cracking and Induced Tensile Stress Characteristics of Mortar and Concrete under Restrained Shrinkage”, American Society for Testing and Materials, 2004.

[15] H. T. See, E. K. Attiogbe, M. A. Miltenberger, “Shrinkage Cracking Characteristics of Concrete Using Ring Specimens”, ACI Materials Journal 100 (2003) 239-245.

[16] P. Schwesinger, G. Sickert, “Reducing Shrinkage in HPC by Internal Curing by Using Pre-soaked LWA”, in: H. Mihashi (ed.), International Workshop on Control of Cracking in Early-Age Concrete, Tohoku University, Japan, 2000, p. 313-318.

[17] E. Tazawa, S. Miyazawa, “Experimental Study on Mechanism of Autogenous Shrinkage of Concrete”, Cement and Concrete Research 25 (1995), 1633-1638.

[18] S. Zhutovsky, K. Kovler, “Hydration kinetics of high-performance cementitious systems under different curing conditions”, Materials and Structures 46 (2013) 1599-1611.
[19] S. Zhutovsky, K. Kovler, A. Bentur, “Effect of hybrid curing on cracking potential of high-performance concrete”, Cement and Concrete Research 54 (2013) 36-42.