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Effect of internal curing on durability-related properties of high performance concrete

Semion Zhutovsky *, Konstantin Kovler

National Building Research Institute - Faculty of Civil and Environmental Engineering Technion - Israel Institute of Technology, Haifa 32000, Israel

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ABSTRACT

Internal curing of high performance concrete (HPC) by pre-saturated lightweight aggregates is a well-established method of counteracting self-desiccation and autogenous shrinkage. However, by introducing the internal water reservoirs strength and durability properties can be injured. Tests by the widely accepted methods of durability assessment, such as resistance to chloride penetration, air permeability, water absorption, autogenous and drying shrinkage and mass loss, were conducted on HPC mixes made at water to cement ratios in the range of 0.21–0.33. The effect of internal curing on the durability related properties of high-performance concretes as a function of water to cement ratio is reported.

1. Introduction

HPC has become popular due to its superior mechanical and durability properties [1,2]. HPC significantly reduces maintenance costs and enhances service life [3]. Enhanced durability of HPC makes its use attractive in the environments where ordinary concrete would not suffice. The HPC has constantly growing number of applications: marine construction, high-rise buildings, bridge decks and piers, thin-wall shells, airport pavements and many others. However, HPC advancement is hindered by its early-age cracking sensitivity.

HPC made with extremely low w/c ratios is prone to self-desiccation that results in autogenous shrinkage [4–7]. Autogenous shrinkage restrained internally by aggregates and externally by neighboring structural members leads to cracking and even failure [8,9]. Obviously, cracked concrete has reduced mechanical properties and defective durability, which is of particular importance. In order to reduce autogenous shrinkage of HPC and to prevent its early-age cracking it was suggested to introduce into HPC mix pre-saturated LWA [10–12]. Saturated LWA serves as internal water reservoir that supplies internal curing water to counteract self-desiccation [13–16]. This approach was called Internal Curing (IC).

IC attracted widespread research interest and was experimentally proved capable to eliminate or considerably diminish autogenous shrinkage [13–18]. It was demonstrated that it could be successfully applied to obtain improved high performance concrete with reduced sensitivity to cracking [15,19]. Later, IC was extended to utilize additional materials as IC agents. Super Absorbent Polymer (SAP) [20,21], wooden-derived materials [22], and recycled aggregates [23] were reported as appropriate curing agents for IC of HPC.

The function of IC agent is to serve as internal storage for curing water. For this reason, IC agents are usually very porous materials with weak mechanical properties. Introduction of a highly porous weak material into the dense matrix of HPC evidently should alter the superior mechanical and durability characteristics of HPC. The effects of IC on the mechanical properties and durability of HPC and the methods to minimize these effects remain the subject of research interest.

In the most cases, detrimental effect of IC on early-age strength is reported [13–15]. However, the effect of IC on the strength of matured concrete is variable and depends on the IC agent type and content, presence of chemical admixtures and aggregate content. A considerable reduction of elasticity modulus is reported in the literature, when IC was applied even in cases where strength was not reduced [17]. At the same time, it appears that IC has little effect of creep: Schwesinger et al. [17] showed that replacement of 30% and higher of normal weight aggregate by pre-wetted LWA has only a minor influence on creep.

It must be emphasized that not only mechanical properties of materials used for IC affect the mechanical properties of concrete, but furthermore the moisture content of cement paste, which is changed by IC. It is well known that the higher the moisture content of cement paste, the lower is its strength [24]. Thus, keeping concrete in a wet state IC naturally reduces its strength. It should be noted that the effect of moisture content on E-modulus is reverse to its effect on strength, i.e. the higher moisture content, the higher E-modulus. This effect is not taken into account in the most experimental works [13,15,17] and modeling [8,9,20].

HPC is often used just because of its superior durability. The properties most-used in both industry and research to characterize durability of concrete are gas or water permeability, sorptivity [25]

* Corresponding author.
E-mail address: semionz@yahoo.com (S. Zhutovsky).

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and chloride diffusivity. Apparently, introduction of highly porous LWA or large voids of SAP into the dense cement matrix increases the porosity and thus permeability and diffusivity of HPC. However, LWA may have a positive effect on durability as well. First, the cracking due to autogenous shrinkage is eliminated or reduced by IC [7,13]. Second, LWA has an improved elastic compatibility with cement paste that would result in lower microcracking [26]. Third, the improved Interfacial Transition Zone (ITZ) between LWA and cement paste matrix [27,28] would have a positive effect on permeability [29].

In fact, for normal-strength concretes, the performance of Light-Weight Concretes (LWC) in severe environment is reported to be better or at least as good as that of Normal-Weight Concrete (NWC) [11,29]. For high-strength concretes, values of permeability and chloride diffusivity of LWC available in the literature are higher than those of NWC [30]. It has to be noted that in these studies the LWA were used in a dry state and the extra water was added to the mix water to account for 1 h LWA absorption. The effect of partial replacement of normal-weight aggregate by pre-saturated lightweight aggregates was also studied [31]. It appears that higher replacement percentage resulted in lower chloride diffusivities. The size of LWA influenced chloride diffusivity as well, showing lower diffusivity for the finer LWA. A study on mortars with expanded shale aggregate showed that chloride penetration depth was reduced [32] and sorptivity decreased [33] by using LWA for IC. IC improves scaling resistance [34]. A survey of HPC bridge decks provides evidence that IC has beneficial effect on service life as well [35].

The amount, type, particle size and degree of saturation of IC agent all have considerable effect on IC [15,18,36]. Moreover, the IC effectiveness depends on the permeability of the cement paste matrix, and thus on w/c ratio [37]. The effect of IC on durability properties of HPC made at different w/c ratios is extremely important, since w/c ratio is a primary factor that affects concrete durability. A few results on the effect of IC on HPC durability are available for w/c in the range of 0.3–0.4 [32–35]. The current study deals with the effect of IC on sorptivity, air permeability, resistance to chloride penetration, strength, dynamic elasticity modulus and shrinkage of HPC made at w/c of 0.21–0.33, which represent well the range of modern HPC.

2. Materials and methods

2.1. Mix proportions

Concrete mixes with w/c ratios of 0.33, 025, and 0.21 were tested. The mix 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 Blaine fineness of 421.7 m^2/kg and the superplasticizer was of calcium naphthalene sulfonate type (Rheobuild-2000). Internal curing was applied by means of vacuum-saturated LWA—pumice from mount Hekla, Iceland. Only single fraction of pumice sand between 2.36 and 4.75 mm was used. The water absorption of pumice in vacuum after 1 h was 73.1% by weight and specific weight in the oven-dry state was 782 kg/m^3. In order to compensate self-desiccation, the amount of water available for internal curing should be equal to chemical shrinkage [15,8]. For this reason the dosage of LWA incorporated into the concrete mixes 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 ratio at the age of 7 days [38]. Mixes with the same w/c ratio, cement and coarse aggregate content were used as references. The composition of the mixes per 1 m^3 and the measured slump are presented in Table 1 (the weights of all aggregates are oven-dry). The coarse aggregate was crushed dolomite of 2.36 mm < d < 9.5 mm with water absorption capacity 1.5% by weight. The content of coarse aggregate was kept constant 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.

2.2. Testing procedure

2.2.1. Transport properties

Sorptivity was measured according to [39] on cylindrical specimens with diameter of 200 mm and height of 50 mm. Air permeability of HPC was measured on the same cylindrical specimens used for sorptivity. The specimens were cured in sealed conditions at 30 ± 2 °C and then exposed to drying at the ages of 1, 7 and 28 days. Drying was performed in the oven at 60 °C till constant weight, which took usually 7–8 days to achieve. Such moderate drying was chosen in order to avoid cracking during drying. After cooling, Torrent air permeability was measured [40]. Afterwards, the specimens were sealed on the top and sides and placed in a water bath so that the open bottom was constantly submerged in a depth of 3–5 mm. The weight change was recorded and sorptivity was calculated as described in the comprehensive review [41], which suggested a method for estimation of water sorptivity for mortars and concrete and interpretation of the experimental results. The concrete resistance to chloride penetration was measured according to [42]. The minimum number of twin specimens for each type of the test was 3.

2.2.2. Autogenous shrinkage

Autogenous shrinkage was measured on 1000 mm long beam specimens starting from the casting using apparatus similar to that described in [43], but with bigger cross-section (70 × 70 mm). Specimens for autogenous shrinkage were cured in sealed conditions at 30 ± 2 °C.

2.2.3. Total shrinkage and mass loss

Total shrinkage and mass loss were measured on 70 × 70 × 280 mm prisms. The samples were demolded 24 h after casting and stored in a climate-controlled room at a temperature of 20 ± 2 °C and a relative humidity of 50 ± 4%. The length changes were measured using a comparator by a standard procedure described in [44]. For measurement of total shrinkage and mass loss 4 twin specimens were used. The total shrinkage measurements were characterized standard deviation of 5–15% at early ages (2–3 days), and 1–7% at later stages.

2.2.4. Strength and modulus of elasticity

The compressive and splitting strength were measured on 50 mm cubes. The dynamic modulus of elasticity was measured by means of ultrasonic pulse velocity on top surface of the beam specimens with dimensions of 70 × 70 × 280 mm. The resonance ultrasonic transducers

Table 1
Mix proportions (kg/m^3), superplasticizer content and slump.

Mix notation	Cement	Mix water	IC water	Fine aggregate	Coarse aggregate	LWA	Super-plasticizer[a]	Slump, mm
21 L	667	140	40.0	348	1145	54.7	4.2%	104
25 L	600	150	36	396	1145	49.2	3.4%	108
33 L	506	167	30.4	432	1145	41.5	2.6%	152
21	667	140	–	532	1145	–	4.2%	102
25	600	150	–	562	1145	–	3.2%	112
33	506	167	–	572	1145	–	2.6%	164

[a] % by weight of cement.

of 60 kHz were used. Both types of the specimens (cubes and prisms) were demolded at 1 day, and cured in sealed conditions at 30 ± 2 °C. Five and four twin specimens for testing strength and dynamic elasticity modulus, respectively, were used. Standard deviation was 4–10% and 3–7% for splitting and compressive strength respectively. For ultrasonic pulse velocity standard deviation reached maximum of 5% at the time of setting, though at later ages it did not exceed 1%.

3. Results

3.1. Sorptivity

The results of sorptivity tests are presented in Fig. 1. It can be seen that sorptivity of concretes with IC at 1 day is about 20% higher compared with reference concretes for all w/c ratios. Sorptivity slightly reduces with age, while the effect of w/c ratio is pronounced. For concrete with w/c ratio of 0.33, sorptivity of internally cured concrete slightly approaches the sorptivity of the reference and at 28 days it still about 10% higher. For concretes with w/c of 0.25 and 0.21, the difference in sorptivity even increases reaching 44 and 54%, respectively. Thus, it can be clearly seen that IC increases the sorptivity, and this effect is more pronounced for lower w/c ratios.

3.2. Air permeability

Air permeability of concretes without IC remains at the same level, apart from the small reduction in concrete with w/c ratio of 0.33 from 1 to 7 days (Fig. 2). On the other hand, the air permeability of concretes with IC, which is higher than that of the reference at 1 day, reduces considerably with the age and achieves the level of 50–60% lower than reference concrete. The effect of the w/c ratio is noticeable; however the permeability of concretes with w/c ratio of 0.21 and 0.25 is very close.

3.3. Resistance to chloride penetration

The results of accelerated test of concrete resistance to chloride penetration are given in Fig. 3. As evident from the graph, for concrete with w/c ratio of 0.33 the chloride diffusivity is reduced when IC is applied. For concrete with w/c ratio of 0.25 the chloride diffusivity is approximately the same in the reference and internally cured concrete. In concrete with w/c ratio of 0.21 the chloride diffusivity is slightly increased by introduction of LWA. Overall resistance to chloride penetration is sufficiently low considering the fact that no micro-filler was used [30]. The w/c ratio has a distinct effect on the resistance to chlorides penetration in reference mixes. However, this effect is minor in internally cured concretes.

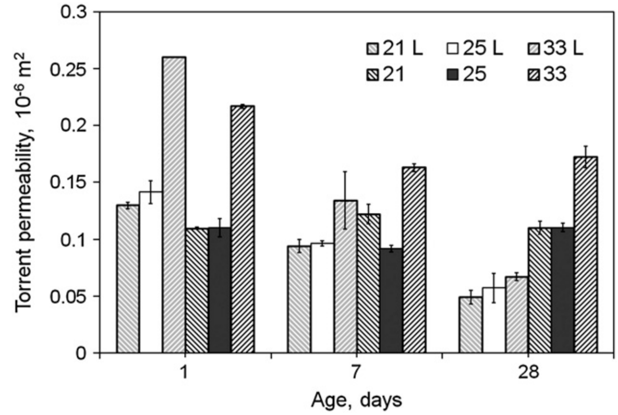

Fig. 2. Air permeability of internally cured concretes vs. references as function of age.

3.4. Total shrinkage and mass loss

The mass loss and total shrinkage are shown in Figs. 4 and 5. Mixes initially containing saturated LWA have consistently higher mass loss. Furthermore, the lower w/c ratio, the lower is the mass loss. For the reference mixes, the lower w/c ratio, the higher is total shrinkage. As observed from the graph, for concrete with w/c ratio of 0.33 and 0.25 the total shrinkage is higher with IC, although the difference is smaller for lower w/c ratio. For concrete with w/c ratio of 0.21 the total shrinkage appears to be slightly reduced by introduction of LWA. Total shrinkage of internally cured mixes relative to that of the reference is shown in Fig. 6.

3.5. Autogenous shrinkage

The autogenous shrinkage data are given in Fig. 7. The beginning of age scale corresponds to the addition of water to the cement, since the measurements of autogenous shrinkage started right after the casting. It can be seen that autogenous shrinkage is completely eliminated by means of internal curing. Practically no autogenous shrinkage was observed even in concrete with all w/c ratio, and even concrete with w/c as low as 0.21 exhibited no autogenous shrinkage.

3.6. Strength and elasticity modulus

The dynamic modulus of elasticity calculated from ultrasonic pulse velocity measurements is shown in Fig. 8. As expected the elasticity modulus is reduced by introduction of porous LWA. The lowest reduction at the age of 28 days was 6.6% at w/c ratio of 0.21. The

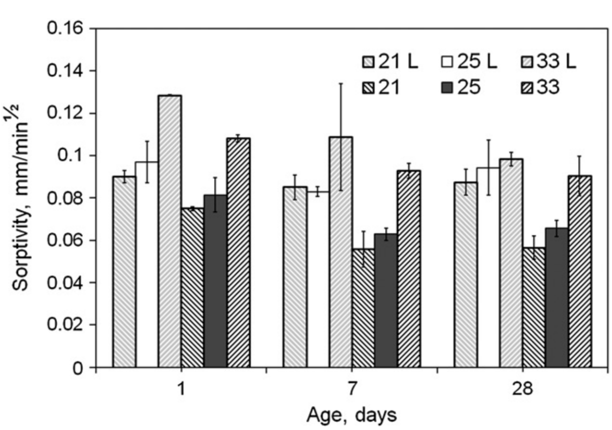

Fig. 1. Sorptivity of internally cured concretes vs. references as function of age.

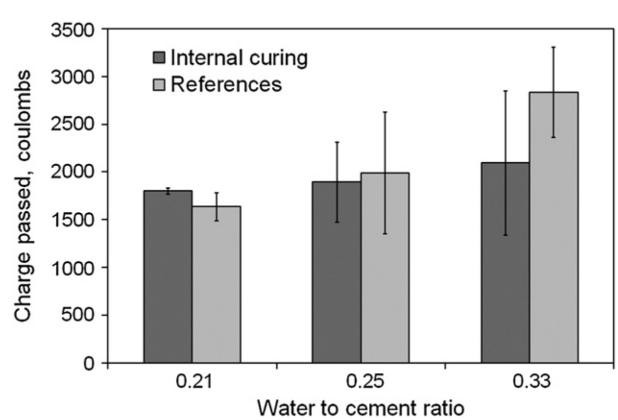

Fig. 3. Resistance to chloride penetration.

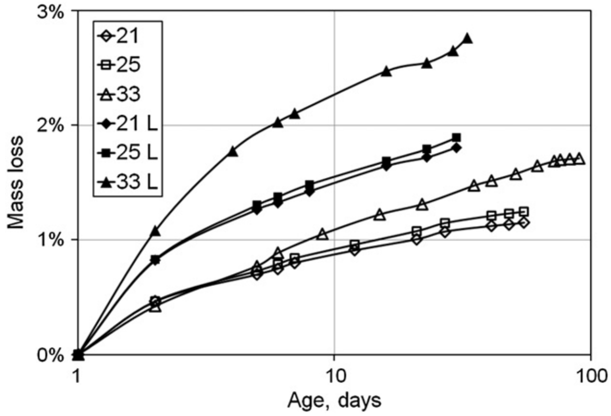

Fig. 4. Mass loss of internally cured concretes vs. references as function of age.

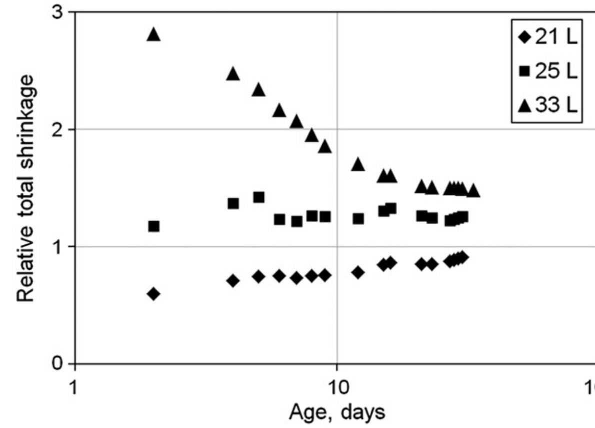

Fig. 6. Total shrinkage of internally cured concretes relative to references as function of age.

reduction of elasticity modulus at w/c ratios of 0.25 and 0.33 was 18.3% and 19.2% respectively. Comparison of dynamic and static moduli for these concretes at the age of 28 days showed that the static modulus is about 65%, 71% and 66% of the dynamic modulus for the C33L, C25L and C21L mixes. Splitting and compressive strength are shown in Figs. 9 and 10 respectively. It can be seen that splitting strength was reduced by 8–11% in internally cured concretes. Compressive strength was almost the same at w/c ratio of 0.33, but reduced by 10% and 4% in mixes with w/c ratio of 0.25 and 0.21 respectively.

4. Discussion

First, it can be seen from the presented results that the effect of IC on durability properties is not necessarily detrimental. In some cases the performance of HPC was even improved by IC. However, the effect of IC was different for HPC made with various w/c ratios.

The sorptivity of HPC was increased by application of IC for all w/c ratios. On the one hand, this could be expected, since the total volume of pores in internally cured concrete was increased by 3–4% in comparison to the reference mixes by addition of the extremely porous LWA. On the other hand, this is in contrary with previously published study on mortars [33]. However, there are significant differences in these two studies that can explain the differences in the results: (i) the LWA used in current study has significantly higher open porosity; (ii) the volumetric content of LWA is higher in mortars; (iii) the possible effect of the percolation of ITZ surrounding normal-weight fine aggregate in mortars [32,33]; (iv) considerably more gentle drying mode used in the study of mortars. The measurements of mass loss were in line with the sorptivity data. The mass loss of internally cured concrete with w/c ratio of 0.33 was twice the reference mass loss. For other w/c ratios, increase of mass loss by IC was less significant, while the mass loss itself for concrete with w/c ratios of 0.25 and 0.21 was very similar. Additional free water added with LWA for IC is obviously the reason for the higher mass loss in internally cured concretes. However, the reduction of matrix permeability with the decrease in w/c ratio results in slightly lower mass low.

Pumice has been proved to be very effective IC agent. As can be seen in Fig. 7, autogenous shrinkage was completely eliminated for concretes with all the tested w/c ratios. In previous studies, LWA typically showed lower efficiency for concretes with lower w/c ratio [15,19]. However, use of more porous LWA with larger open pores in combination with vacuum saturation, which provides maximum degree of saturation, resulted in very effective IC even in concrete with w/c ratio as low as 0.21.

An interesting and unexpected effect of IC on total shrinkage can be seen in Fig. 5. For the reference concretes, a strong dependence of total shrinkage on w/c ratio is observed. The lower w/c ratio, the higher is total shrinkage. This is expected considering the higher cement content in concrete with lower w/c ratios. However, if we consider the total shrinkage of internally cured concretes related to the total shrinkage of reference concretes, it can be seen that for lower w/c ratio relative total shrinkage decreases (Fig. 6). Moreover, for concrete with w/c ratio of 0.21 total shrinkage of internally cured concrete is lower than that of the reference. It seems that lower permeability in conjunction with available internal curing water, which reduces autogenous shrinkage component, lead to reduction of total shrinkage. This is in accordance with the findings published on the reduction of the drying to autogenous shrinkage ratio with reduction of w/c ratio [45]. It is probable that at a later age total shrinkage of internally cured concrete with w/c ratio of 0.21 will reach

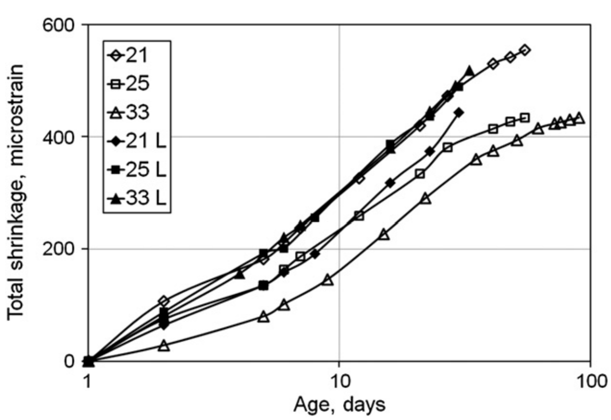

Fig. 5. Total shrinkage of internally cured concretes vs. references as function of age.

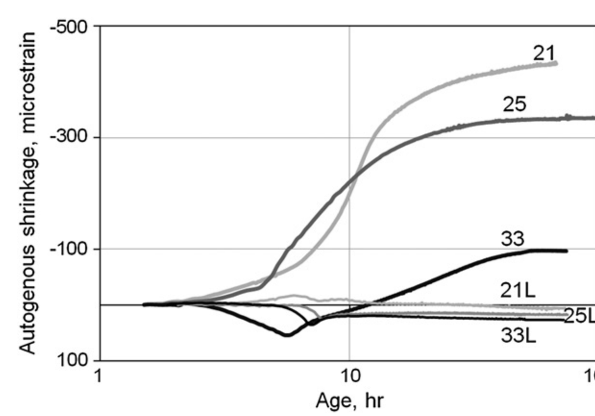

Fig. 7. Autogenous shrinkage of internally cured concretes vs. references as function of age.

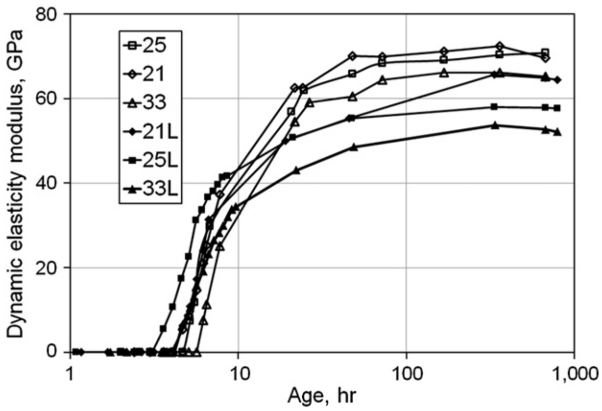

Fig. 8. The dynamic modulus of elasticity of internally cured concretes vs. references as function of age.

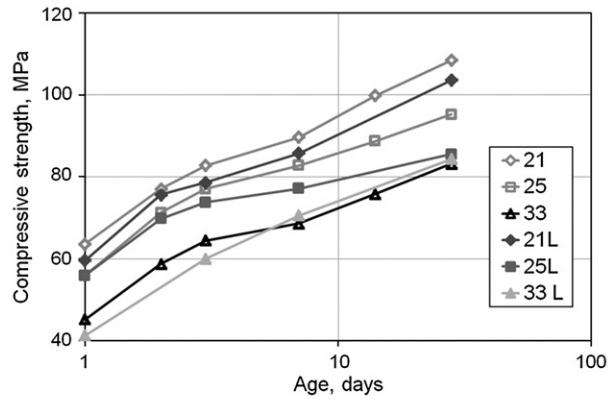

Fig. 10. Compressive strength of internally cured concretes vs. references as function of age.

or even exceed that of the reference, if tendency that has been seen in Fig. 6 will be preserved. However, at early age, when tensile strength is low and risk of cracking is high, total shrinkage at w/c ratio of 0.21 was reduced by IC. The effect of IC on the reduction of total shrinkage is particularly promising, considering the fact that autogenous shrinkage was completely eliminated by IC.

Air permeability, at early age, was increased by IC. However, at later ages, the permeability to air of internally cured concretes reduced and achieved the values below the references. This is most probably the result of enhancement of cement hydration by means of IC, which is reported in the literature [16,32,33]. The effect of IC on resistance to chloride ion penetration varies with w/c ratio. The resistance to chloride penetration of internally cured concrete related to that of the reference made at w/c ratio 0.33 is considerably improved, for w/c ratio of 0.25 it is almost the same, while at w/c ratio of 0.21 it slightly reduced. It appears that at lower w/c ratios the diffusivity of concrete approaches the level of the intrinsic permeability of the cement gel. Reduction of w/c ratio in internally cured concretes does not significantly reduce resistance to chloride penetration. In order to further improve the transport properties of concrete, use of a micro-filler is required. Introduction of silica fume would significantly improve the resistance to chloride penetration. In addition, it appears that when silica fume was used, the detrimental effect of IC on strength was lower, and in some cases even higher strength than in reference mixes was reported [15].

Some sources claim that there is no correlation between the resistance to chloride penetration and water permeability [30]. For this reason, it is interesting to examine the correlation of the resistance to chloride penetration with sorptivity and air permeability. The correlation curves of the resistance to chloride penetration with sorptivity and air permeability are shown in Figs. 11 and 12, respectively. It can be seen that good correlation is obtained between resistance to chlorides penetration and sorptivity of reference mixes. The regression line for internally cured concretes is shifted toward higher sorptivity, although the slopes of the lines are similar. In case of air permeability, the trend is opposite. The line of internally cured concretes is shifted toward the lower air permeability values.

The effect of IC on mechanical properties was detrimental for the most part. The modulus of elasticity was reduced, although the reduction was lower for lower w/c ratio. The reduction of strength was up to 11%, which is considerable for the splitting strength.

It has to be mentioned that the conducted durability tests do not take into account the phenomena of autogenous shrinkage and cracking, which are expected to be higher in the reference mixes. For example, the role of cracking risk reduction by IC is very important and should be considered [35]. Therefore, the positive effect of IC on durability of real concrete structures is going to be more pronounced. Consequently, the standard durability testing procedures should be revised to account for cracking in restrained conditions.

5. Conclusions

It is shown that the effect of internal curing (IC) on transport properties is not necessarily detrimental. In some cases the performance of HPC was even improved by IC. However, the effect of IC was

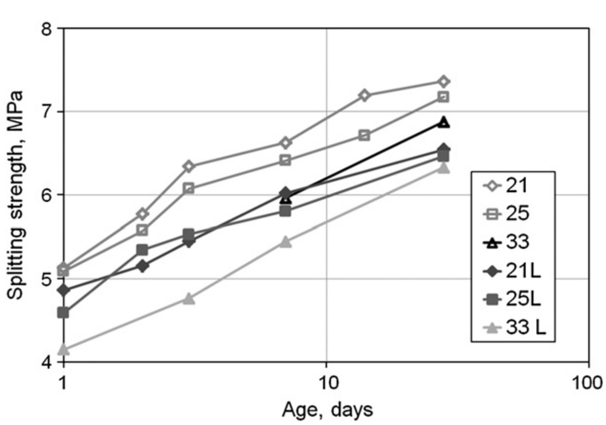

Fig. 9. Splitting strength of internally cured concretes vs. references as function of age.

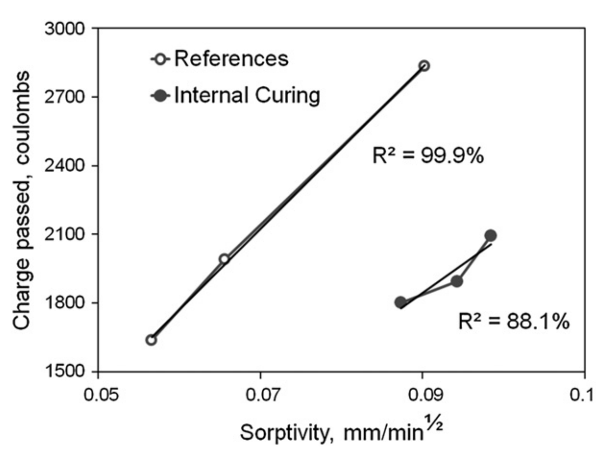

Fig. 11. Resistance of concrete to chloride ion penetration vs. sorptivity.

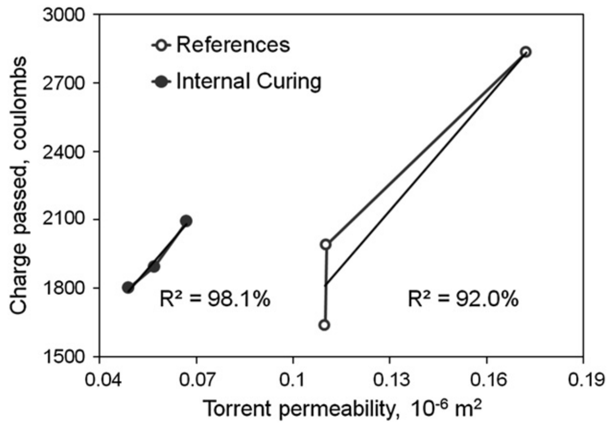

Fig. 12. Resistance of concrete to chloride ion penetration vs. with air permeability.

different for HPC made with various w/c ratios. In addition, the following results have been obtained:

- No serious degradation in durability related properties was revealed.
- Air permeability of HPC was reduced by IC, except at early ages.
- Sorptivity and mass loss were increased by IC, due to the increase of total porosity by 3–4%.
- The effect of IC on resistance to chloride penetration varied with w/c ratio. While for the w/c ratio of 0.33 an improvement was observed, at lower w/c ratios the effect was minor.
- For internally cured concretes reduction of w/c ratio did not result in perceptible improvement of durability. Further research of the effect of IC on concrete durability with a micro-filler is required.
- Reduction of w/c for internally cured HPC had a beneficial effect on drying shrinkage.
- It seems that using pumice which has very high open porosity in combination with vacuum absorption is very effective strategy for elimination of autogenous shrinkage.

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