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Revisiting the protected paste volume concept for internal curing of high-strength concretes

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ABSTRACT

Internal curing of high-strength concrete has been the subject of extensive research for the last decade. The concept of protected paste volume has been one of the most significant theoretical approaches to internal curing. In this paper, the applicability of the protected paste volume concept to internal curing is re-evaluated in view of recent experimental evidence. It is shown, that the concept of protected paste volume and recommendation to limit the spacing factor to approximately 200 μm, cannot be extended to internal curing of high-strength concrete, since the distance of penetration of the internal curing water into the surrounding matrix depends mainly on the availability of internal curing water to the surrounding cementitious matrix. The pore structure of LWA and the size of SAP particles seem to have a marked influence on the availability of internal curing water and thus are factors of greater importance than the spacing factor.

1. Introduction

The popularity of high-strength concrete (HSC) is growing steadily due to its outstanding mechanical and durability characteristics. However, the high early-age cracking sensitivity of HSC limits its application [1–3]. Non-structural cracking of HSC is induced by self-desiccation and autogenous shrinkage [4]. Conventional curing methods are not effective for HSC, since curing water cannot penetrate into low permeability concrete. For this reason, internal curing was proposed [5–7], which implies distributing internal curing water reservoirs inside the concrete. Water-saturated lightweight aggregate (LWA) [8,9], superabsorbent polymers (SAP) [10,11] and other porous materials [12,13] can serve as internal curing water reservoirs. These porous materials used for internal curing are referred to as internal curing agents.

Poor mechanical properties of the porous internal curing agents can have detrimental effect on the mechanical properties of HSC [8,9]. Therefore it was suggested to optimize the size and amount of internal curing agent in accordance with the protected paste volume concept [9]. This concept suggests minimizing the size of internal curing agent particles, so that all the cement paste will lie within a sufficiently small distance from the internal curing agent particle surface, to which the internal curing water could penetrate. In this case the cement paste would be "protected" from self-desiccation. According to this concept "spatial proximity" of internal curing water reservoir to the cement paste matrix is the most important parameter. Implied however is that the reservoir holds sufficient water for curing the paste in the perimeter of its proximity and that all of this water is readily available to penetrate into the surrounding paste.

Recent experimental data demonstrated some discrepancy between the theory and behavior of internally cured HSC. In this paper the results of relevant experimental studies on internal curing are reviewed and the applicability of protected paste volume concept to internal curing is revised. Various engineering parameters for the description of internal curing processes and their suitability as design criteria are discussed.

2. Internal curing

The use of HSC has been expanding due to its superior mechanical and durability properties [14,15]. HSC has its economical benefits, significantly reducing maintenance costs and enhancing service life [16]. Enhanced durability of HSC makes its use very attractive in the environments where ordinary concrete would not suffice. The HSC has had a continuous growing number of applications: marine structures, high-rise buildings, bridge decks and piers, thin-wall shells, airport pavements and many others. However, HSC advancement is hindered by its early-age cracking sensitivity.

HSC made with extremely low w/c ratios is prone to self-desiccation that results in autogenous shrinkage [3,17]. Autogenous shrinkage is restrained internally by aggregates and externally by neighboring structural members, and thus induces tensile stresses which lead to cracking and even fracture [18,19]. Obviously, cracking leads to reduced mechanical properties and impaired durability. In order to reduce autogenous shrinkage of HSC and to prevent its early-age cracking it was suggested to introduce into the HSC mix pre-

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saturated light weight aggregates (LWA) which would serve as internal water reservoirs that would supply internal curing water to counteract self-desiccation [5–7]. This approach was called internal curing (IC).

IC attracted considerable research interest and was experimentally proved to be capable in eliminating or considerably reducing autogenous shrinkage [8,20–23]. It was demonstrated that it could be successfully applied to obtain improved high-strength concrete with reduced sensitivity to cracking [9,24]. Later, IC was extended to utilize additional materials as IC agent. Super-absorbent polymers (SAP) [10,11], wood-derived materials [12], and recycled aggregates [13] were reported as appropriate curing agents for IC of HSC.

The function of IC agent is to serve as internal storage for curing water. Therefore, IC agents are very porous materials with poor mechanical properties. Introduction of highly porous weak material into dense matrix of HSC can have detrimental effects on the superior mechanical properties and durability of HSC. The effects of IC on HSC properties and the ways to minimize these effects remain the focus of considerable research effort.

Detrimental effects of IC on early-age strength have been reported [8,9,22]. However, the effect of IC on strength of matured concrete is variable and depends on the agent type and content, presence of chemical admixtures and aggregate content. A considerable reduction of E-modulus is reported in literature when IC is applied, even in cases where strength was not reduced [20]. It appears that IC has little effect on creep. Schwesinger et al. [20] showed that replacement of 30% and higher of normal weight aggregate by pre-wetted LWA has only a minor influence on creep. Thus, a design procedure, which would optimize the IC agent content, size, type etc., is required in order to counteract negative effects of internal curing and maximize their positive influences.

Complete elimination of autogenous shrinkage may not be necessary. Optimally, only the amount of IC agent, which would be sufficient to reduce cracking risk due to restrained autogenous shrinkage to acceptable level, should be used. This will be economically attractive and will minimize the negative side effects such as adverse influence on rheological, mechanical and durability properties of HSC [11]. For this reason it was suggested to adopt the concept of protected paste volume in order to minimize the amount of IC agent introduced to concrete [25]. According to this concept, smaller particles of IC agent, such as lightweight fine aggregate (LWFA), are beneficial for the effectiveness of IC.

3. The concept of protected paste volume

The concept of protected paste volume takes its origin in the assessment of the effectiveness of frost resistance provided by air entrainment. The protected paste volume is defined as the volume of cement paste "protected" from frost damage by a system of air voids in the cement paste [26]. Each air void is surrounded by a protected shell of cement paste, which Powers called "sphere of influence" [27]. The schematic representation of the spheres of influence for two adjacent air voids is presented in Fig. 1.

This concept implies that the frost resistance of concrete is ensured if the cement paste resides within a sufficiently small distance from the air bubble, which is called "spacing factor". Spacing factors for the voids 1 and 2 are designated L_1 and L_2 in Fig. 1, respectively. It has been demonstrated by numerous researches that for normal-strength concrete spacing factor below 200 μm guarantees frost durability [28–30].

In 1999, Bentz and Snyder [25] suggested to extend the concept of protected paste volume to internal curing. Following this concept, it is assumed that if the cement paste is located within a sufficiently small distance from the surface of the internal curing agent, the cement paste would be protected from self-desiccation and autogenous shrinkage would be mitigated. The spacing factor for internal

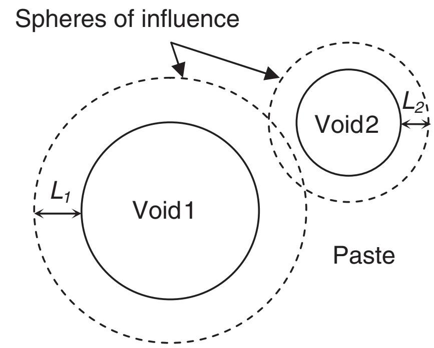

Fig. 1. Schematic representation of the sphere of influence.

curing, or in terms of the paper by Bentz and Snyder "spatial proximity" of internal curing water to cement paste, is controlled by the size of internal curing agent particles. The authors claim that: "As the capillary pore space in the cement paste depercolates during curing, the water transport will be effectively limited to distances on the order of 100 to 200 μm". They also found that "well dispersed system of small saturated LWFA particles would be most beneficial to the curing of field concrete, similar to the case of air voids protecting concrete from damage due to freezing and thawing", which is "in agreement with the protected paste volume concept for air voids, which suggests that a finely dispersed system of small air voids will be superior to one composed of larger air voids at equal air contents".

4. Review of the recent experimental results

Since the internal curing was proposed to counteract the self-desiccation of HSC, there has been a plethora of researches done on this topic. A large number of studies attempted to apply the protected paste volume for internal curing. These works included the efforts to minimize the particle size of internal curing agent and consequently the spacing factor for internal curing, in order to achieve a higher percentage of protected paste volume. They will be critically reviewed here to assess the validity of the protected paste volume concept and resolve the range of parameters which need to be considered to assure full effectiveness of the IC agents.

Lura et al. [22] studied the effect of LWA size on IC efficiency. They compared fine LWA (0–4 mm) with coarse LWA aggregates (4–8 mm and 8–16 mm). The fine LWA performed better, although the difference was minor. Later, the concept of IC by means of saturated LWA was applied with an attempt to optimize it to eliminate autogenous shrinkage with the smallest possible amount of LWA [24,31]. In the course of this work, the grain size of LWA used as curing agent was reduced in order to minimize the paste–aggregate proximity, i.e. the distance to which the IC water should diffuse. The reduction of the grain size down to 4–2 mm was proved beneficial, however further reduction of the grain size resulted in decrease of curing efficiency. Autogenous shrinkage of concretes with size fractions of 2.36–4.75 mm (Pumice2), 1.18–2.36 mm (Pumice1), and 0.6–1.18 mm (Pumice0) of pumice lightweight aggregate containing 20 kg of pre-saturated internal curing water per cubic meter of concrete is presented in Fig. 2. It can be seen that the shrinkage slope and autogenous shrinkage at the age of 7 days are higher for the smaller LWA particles, although their spacing is smaller.

Analysis of the data in [32] suggests that correlation between reduction in the spacing and minimization of autogenous shrinkage does not always exist. In this study, the internal curing efficiency of 0.33 w/c ratio concretes using different types of LWA was undertaken and the results are shown in Fig. 3. The difference between the LWA aggregates was their water absorption capacity (Perlite—450 wt.%,

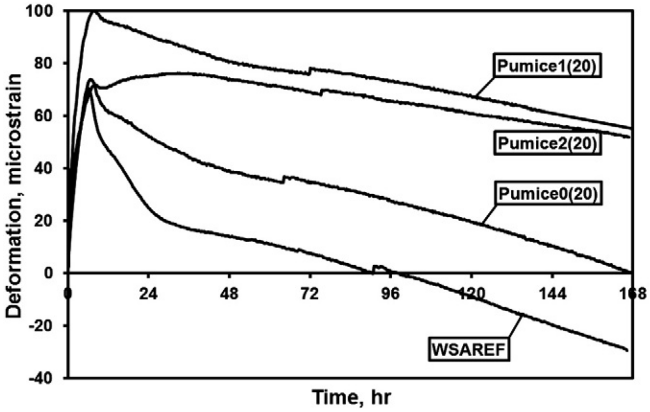

Fig. 2. Effect of grain size on free shrinkage of mixes with w/c ratio 0.33 containing amount of pumice required to counteract self-desiccation [31].

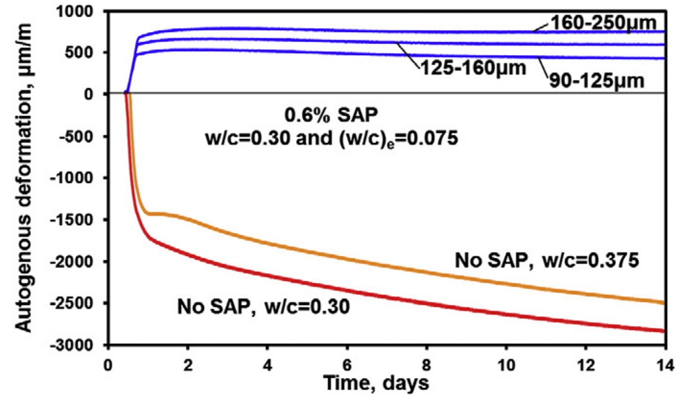

Fig. 4. Linear measurements of autogenous strain of cement pastes with w/c 0.3 and 20% silica fume addition, with no SAP or 0.6% SAP by weight of cement. A paste with w/c 0.375 and 20% silica fume addition is also shown for comparison.
Adopted from [33].

Hekla pumice—70 wt.%, Yali pumice—26.7 wt.%), while the content of the aggregates in each mix was adjusted so that they entrain 20 kg of water per m^3 of concrete, which is theoretically sufficient to avoid self-desiccation. Obviously, the content of LWA with smaller absorption required to meet the requirement for 20 kg/m^3 of water is higher, and thus the spacing between them is smaller. According to the protected paste volume concept their efficiency should be higher. This however is not the case as seen in Fig. 3—the Perlite LWA gave the best performance, exhibited by lack of any autogenous shrinkage after the initial swelling. The Yali pumice with the lowest absorption (and smaller spacing) exhibited the highest autogenous shrinkage after the first swelling.

One would expect that with SAP as IC agent, where almost all of the volume in the particles is water saturated, the system would more closely follow the concept of the protected paste volume, and smaller size SAP particles would yield enhanced efficiency. However, the data for SAP particles in the range of 250 µm down to 45 µm showed just the opposite trend [33,34], as can be seen in Figs. 4, 5 and 6. For the different systems in these figures, the trend was always for an improved efficiency of the bigger SAP particles: they provided higher values of initial swelling, and reduced autogenous shrinkage afterwards.

5. Discussion

The review of the data in the previous section suggests that the spacing concept cannot always account for the efficiency of internal curing systems with regard to reduction in autogenous shrinkage.

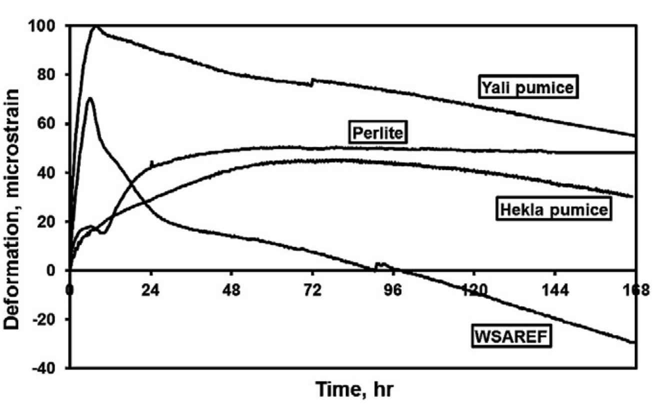

Fig. 3. Effect of LWA type on free shrinkage of mixes with w/c ratio 0.33. LWA fraction is between 1.18 and 2.36 mm.
Adopted from [32].

It has been shown that for both types of IC agents, LWA and SAP, reduction in the spaces between the IC reservoirs does not necessarily result in reduced autogenous shrinkage and even the opposite trend may occur. This apparent discrepancy suggests that other factors need to be considered and they may override the influence of the spacing factor.

One such factor could be the availability of the internal curing water. In the case of LWA, the migration of the internal curing water is dominated by a driving force which is the gradient of capillary pressure between the water in the LWA and the water in the surrounding paste matrix. It can be seen in the data in Figs. 2, 3 and 4 that the smaller LWA particles are characterized by lower absorption, suggesting a finer pore structure of the IC reservoir, and the consequence is a lower driving force for the water to penetrate from the IC reservoir into the surrounding paste matrix. This implies that in the systems studied and reported in Figs. 2, 3 and 4, two competing mechanisms take place upon reduction of the particle size of the LWA: reduction in the spacing factor which should enhance the efficiency, and refinement of the pore structure of the LWA which should result in reduction of the efficiency. The fact that the experimental results indicate reduction in the efficiency upon reduction in the LWA size suggests that the structure of the IC LWA is the more important parameter, and it overrides the spacing factor.

Similar arguments can be made with regard to the influence of the size of the SAP particles (Figs. 4, 5, and 6): in SAP the water is held by van der Waals forces and not by capillary pressure as in LWA. The

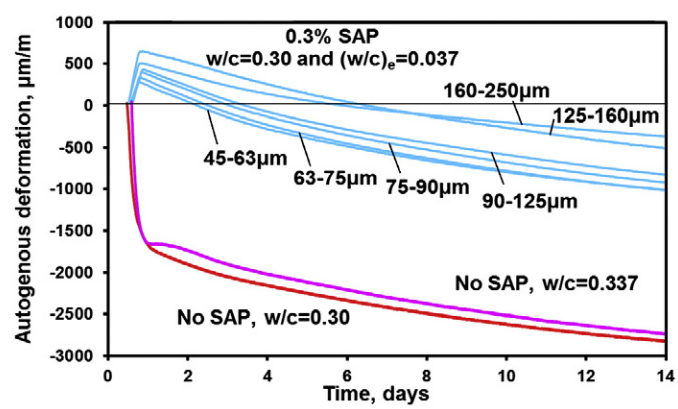

Fig. 5. Linear measurements of autogenous strain of cement pastes with w/c 0.3 and 20% silica fume addition, with no SAP or 0.3% SAP by weight of cement. A paste with w/c 0.337 and 20% silica fume addition is also shown for comparison.
Adopted from [33].

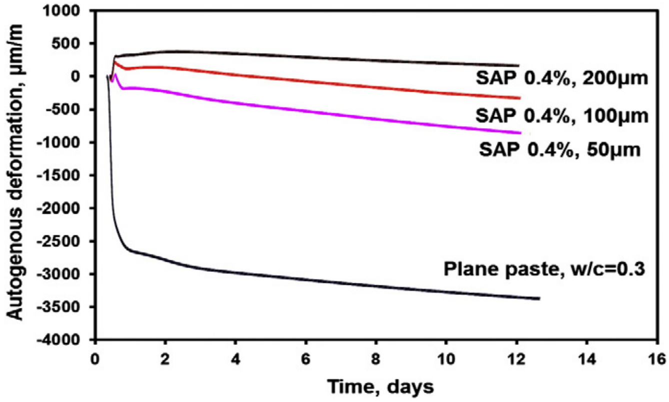

Fig. 6. Autogenous deformation of SF-modified pastes with different sizes of superabsorbent polymer particles. The internal curing water was added to the system according to an absorption capacity of 12.5 ml/g of dry gel. Basic water to cement ratio was of 0.30.
Adopted from [34].

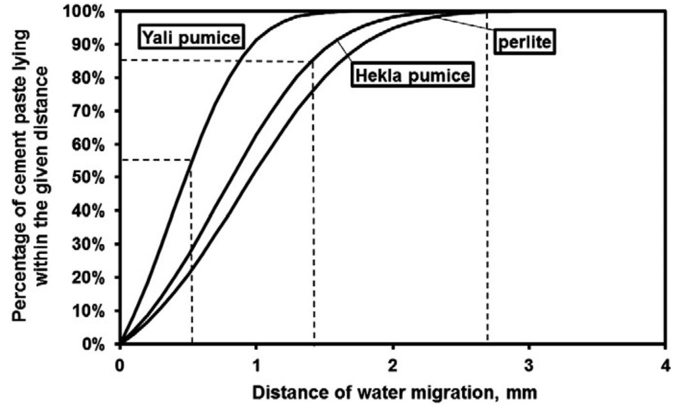

Fig. 8. Assessment of distance of water migration for mixes containing different types of LWA.

water will initially dry out of the particle rapidly, but at a later stage the drying rate is reduced since water has to diffuse through more side-chains which interact with the water molecules by their ionic character [35]. In addition, bigger SAP particles have higher water absorption [34]. Thus, the discharge of water from bigger size SAP particles will take place more readily than in the smaller particles, thus leading to two competing processes when reducing the size of the SAP: higher IC efficiency due to smaller spacing, and reduced efficiency due to a tendency for tighter hold of the water. Since the final outcome is greater efficiency of the bigger SAP particles, it seems that the overriding parameter is the SAP particle structure rather than the spacing factor.

The protected paste volume concept is taken after the modeling of frost resistance and perhaps from there the value of required spacing factor of 200 µm was derived [25] and used thereafter in various references. However, critical review of the literature suggests that the order of magnitude of the spacing factor required for internal curing of HSC is an order of magnitude higher, and is in the range of several millimeters.

Indirect measurements can facilitate the estimation of this spacing parameter by assuming that the percentage of protected paste volume is approximately equal to the percentage of autogenous shrinkage reduction. The calculation of autogenous shrinkage is based on determination of the shrinkage starting after the initial peak of expansion, which usually occurs in IC systems within the first day, in proximity to the final setting time. This portion of the length change curve is a reasonable estimation of the processes generated by self-desiccation which starts immediately after the setting of the cementitious matrix. Although the length change may not be uniform in the paste around the IC agent, the value of the autogenous shrinkage measured may provide an estimate of a weighted average. On this basis one can calculate the distance of water migration [31] by considering calculated curves of the proximity of the paste matrix, i.e. the proportion lying within a given distance from the IC reservoir. An implied assumption in this mode of calculation is that the calculated distance presents a range where there is no shrinkage, and beyond it the autogenous shrinkage is uniform. Thus, the calculated value may be considered as an estimate presenting the “effective value”. As will be shown later, this estimate of the effective value is quite similar to the range of values obtained by new direct measurement techniques of water migration from the IC agent. Proximity curves for the data in Figs. 2 and 3 are shown in Figs. 7 and 8, respectively, and the estimate of the effective distance of water migration is there given based on the values of the relative autogenous shrinkage reduction (which is assumed to be equal to the % of protected paste volume, i.e. the paste lying within sufficiently small distance from the IC reservoir to allow it to be fully migrated by water). The values obtained range from 0.1 to about 3 mm, and they correlate positively with the absorption capacity of the LWA (Fig. 10), and inversely correlated with the reduction in autogenous shrinkage (Fig. 9). The trends in Figs. 9 and 10 support the conclusions reached in the previous section that the overriding parameter controlling the performance of the IC reservoirs is the availability of water to be discharged out of the IC reservoir and not the spacing factor.

The data in Figs. 7 and 8 indicate that the internal curing water can travel to distances of several millimeters. For example, perlite that

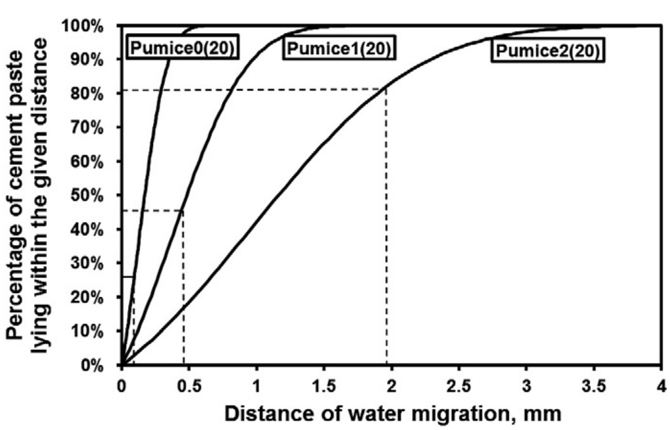

Fig. 7. Assessment of distance of water migration for mixes containing different pumice fractions with w/c ratio of 0.33.

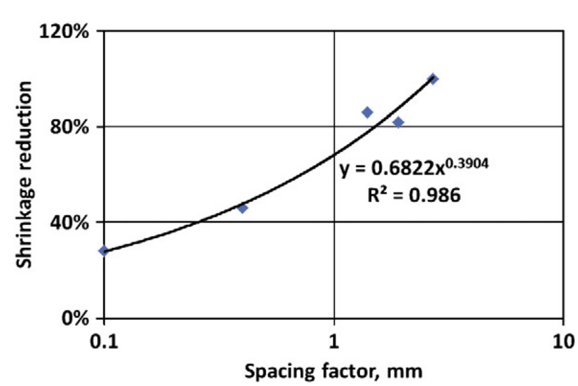

Fig. 9. Correlation of spacing factor and shrinkage reduction.

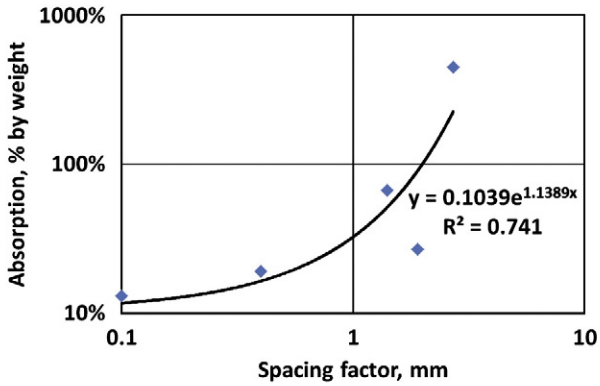

Fig. 10. Correlation of spacing factor and water absorption of LWA.

passed the sieve of 2.36 mm and reminded on the sieve 1.18 mm successfully eliminated any autogenous shrinkage. As shown in Fig. 8, to achieve complete elimination of autogenous shrinkage in this mix, water must penetrate the into cement paste matrix to a distance of at least 2.7 mm.

These calculated values are of the same range obtained in direct measurements. Tests based on X-ray absorption showed that IC water can penetrate into cement paste to a distance of 4 mm from the LWA surface when pumice was used as IC agent [36,37] and to 2 mm when expanded shale aggregate was used [38]. The neutron and X-ray tomography investigation of cement paste internally cured by expanded clay demonstrated that internal curing water was traveling to at least 3 mm [39]. X-ray micro-tomography of mortars internally cured by means of expanded shale confirmed that internal curing water migrates to a distance of about 2 mm [40,41]. Neutron radiography applied to cement paste with saturated expanded shale aggregate indicated water transport distances between 3 and 8 mm [42]. Direct ink penetration test [43] also provides estimates of water travel distance of a millimeter and more (Fig. 11).

The calculations based on autogenous shrinkage analysis as well as the direct water migration measurements indicate that the sphere of influence of the IC agents is on the order of magnitude of few millimeters. Thus there is no reason to attempt to limit the spacing factor to 200 μm as suggested earlier. If the 200 μm value was indeed the valid one then high replacement level of normal-weight aggregate by an internal curing agent would have been required, which is not the case in practice.

The spacing factor of 200 μm stated as a maximum spacing factor for internal curing might have been taken from frost resistance

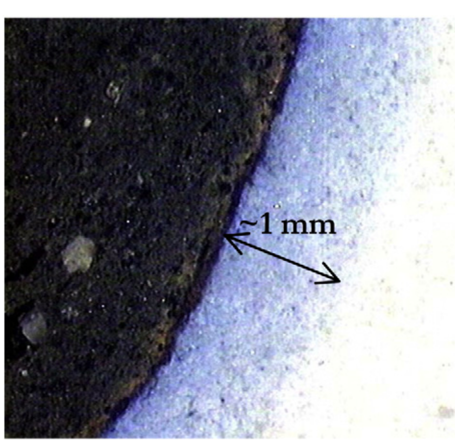

Fig. 11. Blue-ink corona around a Liapor aggregate.
Adopted from [43].

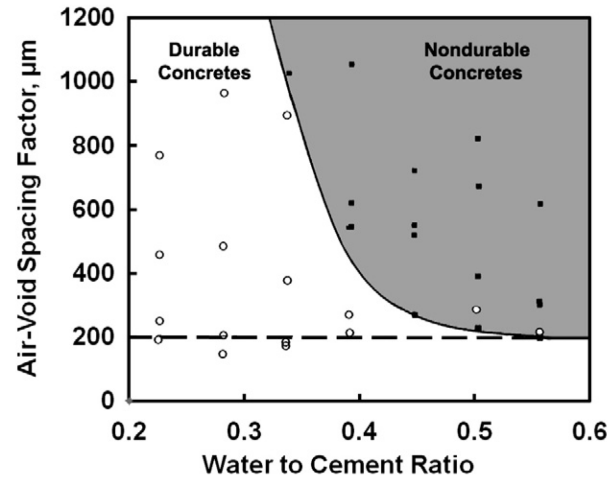

Fig. 12. Air-void spacing vs. w/c ratio for concrete mixtures subjected to 300 rapid freezing and thawing cycles.
Adopted from Okada et al. [44].

requirements. One should note however that the latter value in frost resistance is valid for normal-strength concrete. It is of interest to note that Okada et al. [44] have demonstrated for frost resistance that the spacing factor of 200 μm is not valid for w/c ratios below 0.4 (Fig. 12), which is the range in which IC is applied and studied.

The sphere of influence and the spacing factor certainly have physical meaning for internal curing. However, it cannot be used as design criteria like it is done in frost resistance design.

6. Conclusions

Internal curing has a number of key parameters that influence and control its efficiency. The amount, type and particle size, and degree of saturation of IC agent all have an effect on IC, and in addition to that the permeability of the cement paste matrix, which is a function of the composition of the binder and the w/b ratio. However, the most important parameter seems to be the availability of internal curing water. In order to optimize internal curing of concrete, the water introduced into the internal curing agent has to be readily available to be discharged to the surrounding cementitious matrix. The pore structure of LWA and the size of SAP particles seem to be primarily responsible for the availability of internal curing water and this parameter is of greater significance than the spacing factor.

The concept of protected paste volume and recommendation to limit the spacing factor by approximately 200 μm, which are common requirements for frost resistance of concrete, cannot be extended to internal curing of high-strength concrete. The overriding parameter seems to be the internal structure of the IC agent.

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