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A METHOD OF ANALYZING POROSITY STRUCTURE IN AIR-ENTRAINED CONCRETE

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Abstract

Important characteristics which substantially affect the system of air pores that protect concrete from cyclic freezing and thawing are the pore size distribution and number of air voids. The pore distribution is measured with the standard factor L based on the Powers model, in which considerable simplifications are assumed. The Philleo factor which determines the percentage content of protected paste located at a distance S from the edge of the nearest air void provides a better solution. Developing the concept put forward by Philleo, the PPV (paste protected volume) index was proposed. PPV is the ratio of the volume of the paste protected by air pores, at the assumption that S=200 μm, to the total paste volume. It accounts not only for sizes and number of air voids, but also for aggregate grains often disregarded in analyses. The task to determine four phases for real concrete is extremely difficult, therefore an approach in which an idealised image of concrete grain structure generated on the basis of a numerical model was used. The results obtained from image analysis were compared with standard spacing factor L and with the parameters developed by Philleo and Attiogbe. The analyses conducted by the authors shows that accounting for aggregate grains in calculations substantially affects the assessment of the quality of the air pore structure.

Streszczenie

Rozkład wielkości pustek powietrznych oraz ich ilość są ważnymi charakterystykami, które mają znaczący wpływ na system porów powietrznych zabezpieczających trwałość betonu przed cyklicznym zamrażaniem-rozmrażaniem. Charakterystyk tych nie uwzględnia normowy wskaźnik rozmieszczenia porów L określany w oparciu o model Powersa, który zakłada istotne uproszczenia. Lepszym rozwiązaniem jest np. wskaźnik Philleo, który określa procent zaczynu chronionego przez pory powietrzne, czyli znajdującego się w odległości S od najbliższej pustki powietrznej. Rozwijając koncepcję Philleo zaproponowano wskaźnik PPV, który stanowi stosunek powierzchni obszarów zaczynu chronionego przez pory powietrzne, przy założeniu S=200 μm, do całkowitej powierzchni zaczynu. Wskaźnik PPV uwzględnia nie tylko liczbę oraz rozkład wielkości porów powietrznych ale również rozkład wielkości ziaren kruszywa, co w wielu analizach jest pomijane. Ponieważ wyznaczenie czterech faz betonu jest rzeczą bardzo trudną dla rzeczywistych zgładów, postanowiono posłużyć się modelem numerycznym. Model ten umożliwia wygenerowanie struktury ziarnistej betonu napowietrzonego z uwzględnieniem założonych rozkładów wielkości porów powietrznych oraz wielkości ziaren kruszywa. Wyniki otrzymane na podstawie analizy obrazu numerycznego zostały porównane z normowym wskaźnikiem rozmieszczenia porów L oraz ze wskaźnikami Philleo i Attiogbe. Badania przeprowadzone przez autorów pokazują, że uwzględnienie obecności ziaren kruszywa w obliczeniach znacząco wpływa na ocenę jakości struktury porów powietrznych.

Keywords: **Air-entrained concrete; Distribution of air pore sizes; Distribution of aggregate grain sizes; Numerical model; Protected paste.**

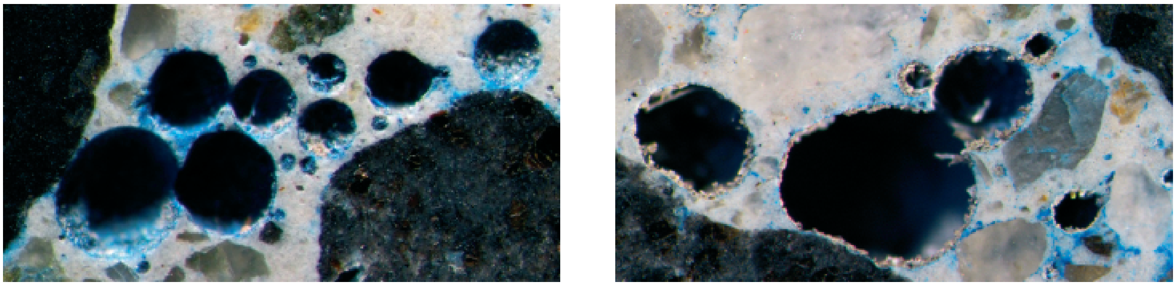

Figure 1.
View of complex pore arrangements in air-entrained concrete

1. INTRODUCTION

A basic method that protects concrete against the adverse action of frost, water and de-icing salts is air-entrainment and it has been known for over 70 years. This technology involves introducing a surfactant into the concrete mix. The air-entraining agent makes it possible to form and evenly disperse small air bubbles in the concrete when the components are mixed. The system of small air voids protects concrete from damage caused by an increase in the volume of freezing water. Appropriate spacing of air voids in hardened cement paste significantly reduces the distance to be travelled by water that is not frozen yet, from a random point inside the hardened cement paste to the nearest air void [1]. It is essential to provide a time-stable system of small air bubbles, which are located close enough to one another, at the lowest possible total air content to ensure freeze-thaw resistance. The standard PN-EN 480-11 [2] or ASTM C 457 [3] presents the method of determining the parameters of air pore structure, which is described by the following parameters: total air content A, specific surface of air pore system α, spacing factor L and micropore content A_{300}. The standard [2] specifies the determination of the pore structure parameters on the basis of the Powers model assuming that all bubbles have the same diameter and are distributed in cube corners. Thus, spacing factor L corresponds to a half of the cube diagonal. Unlike in traditionally air-entrained concrete, in modern concrete technology cement, additives and admixtures are combined, which often causes problems related to obtaining the time-stable pore system. The effects of air-entrainment may differ due to the action of many factors, including: the mix consistency and temperature, mixing time, transport time, type of the concrete mix placing and compacting [4]. Substantial air losses occur when the concrete mix is pumped (approx. 1-1.5%), and also vibrated [4]. Some characteristics of the aggregate grains, especially of sand (roughness, number and shape of grains) [5], which are often unaccounted for, can also affect air-entrainment. Taking into account a large number of factors that affect the quality of air-entrainment, it may happen that air-entraining agents will not generate the required pore structure. The systems of air pores may be not fine enough, or they may not be stable in time [6]. As a result, the actual image of the pores can significantly diverge from the Powers model because of the pore shape and spacing. Fig. 1 shows the irregular spacing of air pores in the concrete.

The Powers model does not account for the distribution of air pore sizes in the concrete. It is therefore necessary to develop a model that will take into account the diversity of pore diameters and pore non-uniform spacing in the cement paste to more accurately describe the actual structure of air bubbles, and thus to better determine concrete freeze-thaw resistance. Other options concerning the description of air pore structure were proposed by Philleo [7], Attiogbe [8], Shanshan et al. [9] or Elsen et al. [10]. In accordance with Philleo, each air bubble protects the paste area around it, which has the width of S, from the detrimental frost action. It is the random distribution of air voids but not their total volume in the paste that plays an important role. The air void spacing factor S*, proposed by Philleo, is based on the logarithmic distribution. While using the gamma distribution, Attiogbe determined the parameter F, which like factor S*, gives the volume of the paste potentially protected by air bubbles. Unlike the standard factor L, both S* and F account for the randomness of air void size and spacing in the paste, and also for their actual number. Shortcomings in estimating the spacing factor L result in the lack of a consistent correlation between L and the freeze-thaw resistance results. The conclusions drawn from analyses by Attiogbe [11] indicate that the parameter F is

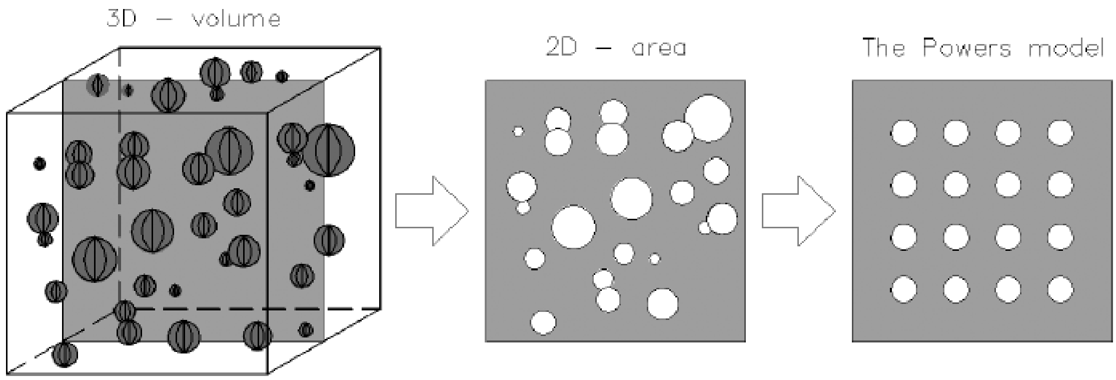

Figure 2.
Measurement of air pore characteristics on the basis of the 2D analysis

better related to the results of freeze-thaw tests when compared with the air bubble standard spacing factor L. All dependences used to compute the spacing factor L disregard the role of aggregate in the concrete. It is assumed that spaces between aggregate grains are large enough to accommodate an appropriate number of air bubbles, as a result, only the paste – air system is considered. Diamond et al. [12] claim that the aggregate presence may, however, substantially affect the spacing of air bubbles.

The numerical model developed in the present study takes into account the aggregate – paste – air system. On the basis of the results obtained for this model, the PPV index is computed and, further, compared with the results produced with the standard method and also those in accordance with Philleo and Attiogbe.

2. NUMERICAL MODEL OF AIR-ENTRAINED CONCRETE POROSITY

The investigations aimed to describe the characteristics of the air-entrained concrete structure parameters on the basis of 2D analysis while taking into account the actual pore distribution. The manner of taking measurements of pore characteristics is presented in Fig. 2.

To perform 2D analysis, it is necessary to have concrete image, which contains four separate phases: aggregate, paste, air and rings of the paste protected by air voids. The structure of real concrete does not show sufficient contrast, consequently, it is difficult to differentiate individual phases. In their investigations, the authors conducted an initial experiment, which involved the development of the model that would make it possible to generate a simplified image of the concrete grain structure, in which the four basic phases could be differentiated. The method of generating and randomly distributing grain structures has been used for years. Yet, it is applied to concrete fracture mechanics, but not to the analysis of concrete air pore structure [13, 14, 15]. To develop the model, Matlab software and Image Pro Plus software for the image automatic analysis method were used. It was assumed that both aggregate particles and air pores are round and they cannot coalesce. The data entered into the program include: percentage content of aggregate, air and paste, the aggregate grading curve, air pore diameter distribution and the thickness the surrounding layer S. The manner of image generation and making calculations is shown in Fig. 5. First, aggregate grain sizes are randomly generated in accordance with the aggregate grading curve (Fig. 3), then, those are randomly distributed in the paste area of 100 x 120 mm (Fig. 5a, dark blue).

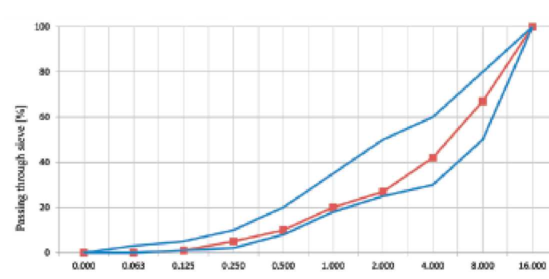

Figure 3.
Exemplary aggregate grading curve together with boundary curves

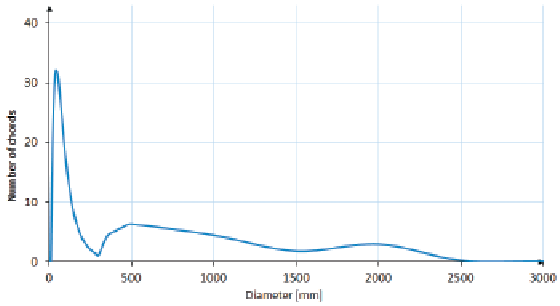

Figure 4.
Exemplary distribution of air pore sizes

In the next step, air pores are randomly distributed (Fig. 5c, yellow) among aggregate grains. The pore diameters are generated in accordance with the assumed distribution of pore sizes (Fig. 4).

Next, surrounds, 0.200 mm in thickness, are produced around air bubbles (Fig. 5d, white). Then, air and aggregate (in accordance with Fig. 5c) are subtracted from image 5d leaving, in Fig. 5e, the area of protected paste (white) and the paste area, which remains unprotected (light blue). The final outcome, namely image 5f, makes it possible to compute the percentage ratio of the protected paste area (white) to the total paste area (white + light blue).

The generated image of concrete structure also makes it possible to determine the standard parameters of air pore structure, and the parameters in accordance with Philleo and Attiogbe. The randomness in generating the sizes of air bubbles and aggregate particles, and also their random distribution in the paste results in the fact that the data entered into the program do not differ much from the output data.

3. EXPERIMENTAL RESULTS AND THEIR ANALYSIS

The paper presents the investigations that were conducted in two stages. Stage I involves the comparison of parameters determined for concretes on the basis of microscopy measurements on the sections with the results obtained from the analysis of the numerical model. Stage II provides the analysis of the results

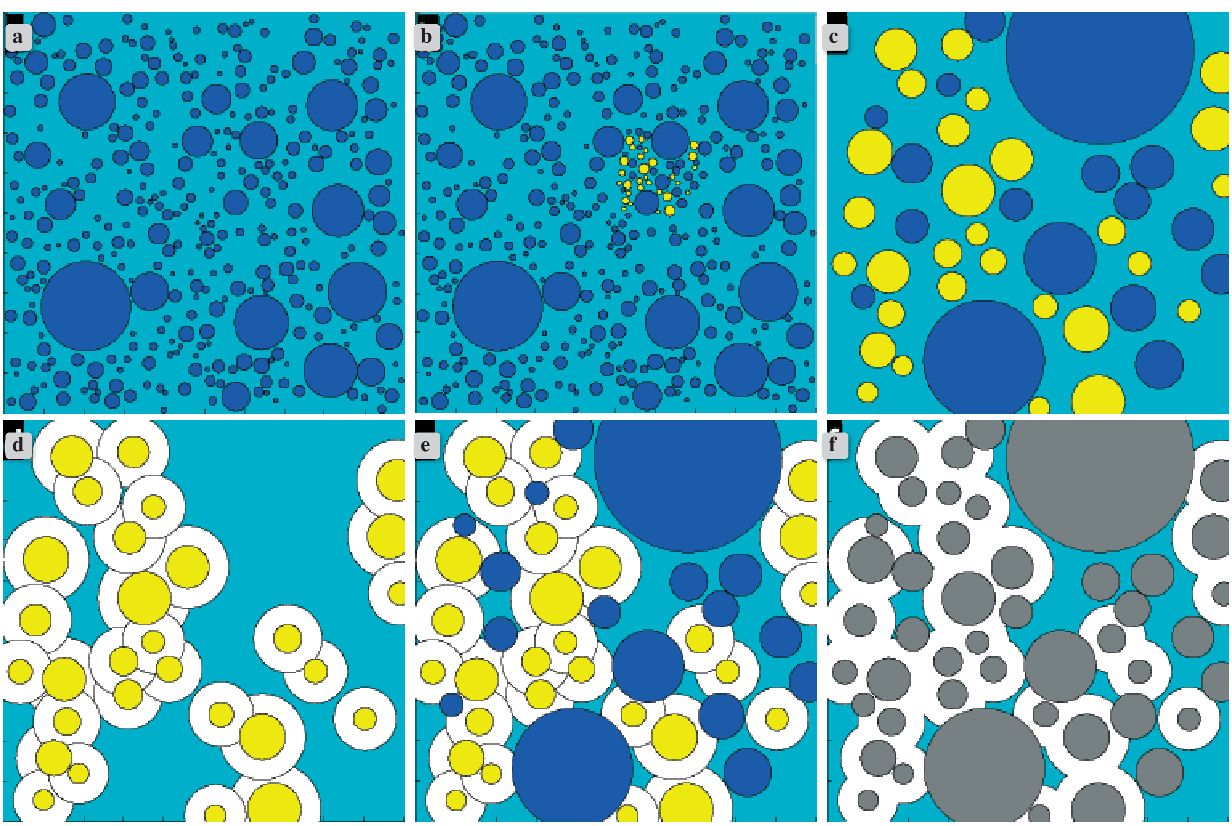

Figure 5.
Image generation: a) spacing of aggregate particles in the paste, b) addition of air voids in the selected area, c)air and aggregate in the analysed area d) imposing rings of protected paste around air voids, e) all four phases accounted for, f) protected paste (white) and unprotected paste (light blue)

Table 1.
Comparison of results for real concretes with those obtained from the numerical model

Parameter		**Concrete**					
		B1		**B2**		**B3**	
		measurement	**model**	**measurement**	**model**	**measurement**	**model**
Standard parameters	P [%]	26.79	25.,88	29.05	28.55	26.40	26.,07
	A [%]	6.44	5.67	2.06	2.19	3.92	3.62
	N	381	423	149	184	370	255
	α [mm^{-1}]	9.81	12.97	23.31	14.59	15.24	12.25
	L [mm]	0.424	0.343	0.318	0.488	0.348	0.447
	A_{300} [%]	0.96	0.40	0.59	0.43	0.82	0.59
PPV [%]		-	53	-	26	-	27
S* [%]		96	97	94	94	96	97
F [%]		100	100	53	57	100	98

Table 2.
Parameters of the air pore structure obtained from the numerical model

Parameter		**Concrete model**				
		M1	**M2**	**M3**	**M4**	**M5**
Standard parameters	P [%]	28.43	28.41	28.39	28.37	28.41
	A [%]	3.35	3.29	3.21	3.24	3.04
	N	193	285	363	422	466
	α [mm^{-1}]	10.01	15.06	19.67	22.63	26.66
	L [mm]	0.588	0.394	0.305	0.264	0.231
	A_{300} [%]	0.26	0.70	1.22	1.50	1.93
PPV [%]		40	59	72	81	85
S* [%]		96	96	96	96	97
F [%]		84	83	81	82	77

from the numerical model for five concretes with constant aggregate grading, constant pore size distribution, similar content of aggregate (67.96÷67.98%), paste (28.37÷28.43%) and air (3.61÷3.67%), but with different content of micropores A_{300} (0.26÷1.93%).

The results of tests on concretes in Stage I are presented in Table 1. The data show that standard results obtained for both cases are similar. Because of substantial difficulties in differentiating four basic concrete phases on the surfaces of real sections, it is not possible to determine their key parameter, namely PPV.

The results obtained from the numerical model for five 5 concretes in Stage II are presented in Table 2. With an increase in the number of micro-pores A_{300}, the pore spacing factor L decreases, and the percentage of the protected paste grows. The results obtained on the basis of the numerical model confirm the current state of knowledge on properly air-entrained, freeze-thaw resistant concretes [8]. At higher content of micropores A_{300}, convergence between the PPV, and S and F is better, while at low fraction of fine pores in the total air content, a discrepancy between those parameters grows.

Initial analyses, carried out both in Stage I and II, show that taking into account aggregate grating has a considerable effect on the results of the air pore structure assessment. In a majority of cases, the value of the PPV index clearly deviates from the values of the parameters S* and F, determined on the basis of the total air and paste content, and the number of bubbles.

4. CONCLUSIONS

There are a lot of doubts and concerns with respect to the method of determining the pore structure parameters and to the congruence of thus obtained results with freeze-thaw resistance measurements when the approach specified in the standard based on the Powers model is used. In the study, a method of determination of the PPV (paste protected volume) index was proposed (PPV is a development of the concept put forward by Philleo). The parameter PPV is determined on the basis of images generated from the numerical model of concrete grain structure. The model makes possible generating images that differentiate four basic concrete phases. The data entered into the program include: the percentage content of aggregate, air and paste, the aggregate grading curve, air pore diameter distribution and the thickness the surround S. On the basis of analyses, it can be concluded that, in most cases, the value of PPV index clearly deviates from the values of the parameters proposed by Philleo and Attiogbe. The investigations presented in the study show that taking into account the aggregate-paste-air system produces results that are substantially different from those obtained for the paste-air system. The proposed in the study method of 2D analysis of the porosity structure in air-entrained concretes will make it possible to more accurately describe the dependencies holding in the system and to obtain a better correlation between the parameters and freeze-thaw resistance results. To conduct investigations of this kind, it is necessary to solve problems related to the differentiation of individual phases in real section samples by colouring and contrasting them, so that it will be possible to determine the PPV index. The problem sets up a barrier to the development of this analysis method.

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