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Determination of Parametres of the Air-Void System in Airfield Pavement Concrete Using Computed Tomography

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Abstract. Immediately after completion airfield pavements begin a gradual deterioration that is attribute to several factors. One of the major elements contribute to airfield pavement deterioration is exposure to the environment (freezing-thawing and de-icing salts). Air-voids microstructure in cement-based materials is an important feature related to the freeze-thaw durability of these materials since all the adverse influences are result of potentially harmful ionic fluids and aggressive gas transport through the concrete and the transport properties strongly depend on the morphology of the pores inside the concrete.

For revealing the porous microstructure in airfield pavement concrete X-ray tomography method was used. New and advance methodologies have been developed to determine the basic parameters of air entrainment in concrete (total content of the air, specific surface area of the air-voids system, spacing factor and content of micropores) by summing the distances traversed across a given component along a series of regularly spaced lines in one or more planes intersecting the sample. Using the method mentioned above, to meet requirements of PN-EN 480-11 specification (describes procedure for microscopical determination of air voids characteristics in hardened concrete), the original software was applied – AVCT (Air Void by Computed Tomography) computer programme.

The specimens for CT testing were cylinders extracted by drilling out from the investigated concrete core or cubic specimen. The CT method does not require any special processing of the surface of tested specimen as opposed the common method according to PN-EN 480-11, by which the properly polished section is a prerequisite for obtaining proper results of air voids characterization.

The paper presents the results of the evaluation of air-voids microstructure in concrete conducted with the application of computed tomography method. Exemplary images of distribution and size of air-voids in concrete specimens have been presented. Special attention was paid to obtain effective image resolution.

Keywords: cement concrete, air voids, parameters of air entrainment, X-ray CT.

Conference topic: Sustainable urban development.

Introduction

The major objective in the design and construction of airfield pavement is to provide adequate load-carrying capacity and good ride quality necessary for the safe operation of aircraft under all weather conditions. The presence of contaminants such as snow, ice, or slush on airfield pavements causes hazardous conditions that may contribute to airplane incidents and accidents. These runway surface contaminants should be minimized to maintain safe landing, takeoff, and turnoff operations. Once the ice has bonded to the pavement surface, the airport operators may use approved deicers to melt through the ice pack to break up or weaken the ice bond and use mechanical means, such as plowing.

In common pracice, airfield concrete structures are exposed to different environmental conditions and deteriorate by the coupling effect of different factors (freezing-thawing, deicing chemicals, action of aircraft traffic). Deicing/anti-icing chemicals commonly used on airfields can cause scaling of Portland cement concrete by physical action related to the chemical concentration gradient in the pavement. Deleterious effects on conrete can be reduced, among others, by using air-entraining admixtures, and avioiding applications of chemicals for one year after placement. The proper use of air entrainment, high-quality cementitious materials and aggregates is promising in mitigating frost and the deicer impact on cement concrete. Porosity is one of major component of microstructure that governs several properties, such as permeability, shrinkage, elastic modulus, toughness, and strength.

In order to provide resistance to frost and de-icing agents of airfield pavements, for their construction, the air-entrained concrete is applied. Air voids created by air entrainment and larger voids, created during mixing and placing of concrete are an important components of the concrete structure. Water content and capillary forces in these pores are important to the durability of hardened concrete, subjected to repeated cycles of freezing and thawing, which can cause disintegration of the concrete surfaces layers. The determination of the air-void parameters of cement-based materials is essential in assessing the freeze-thaw durability of those materials.

In practice, parameters of the air-void system are determinated via stereological examination of a polished section using an optical microscope, by means of the linear-traverse method described in PN-EN 480-11 standard, the American standard ASTM C457 allows also the point-count method. In accordance with the definition provided in PN-EN 480-11 standard, the air void constitutes space enclosed by the cement paste, that was filled with air or other gas prior to the setting of the paste. It does not apply to pores of submicroscopic sizes which are characteristic of the hydrated cement paste (gel pores). The assessment of the distribution, size and shape of pores has a decisive influence, among others, on the inference related to concrete durability (Brandt 2010). As a result of the air-entraining agent action, air voids with the sizes from 10 to 1250 μm (optimum < 300 μm) are created. In addition to those mentioned in the concrete structure, there are pores (large pores > 500 μm) resulting from technological reasons (e.g. batch water excess), as well as capillary and gel pores. The pores accidentally created as a result of inappropriate selection of components or incorrect technology of mixing and laying of a concrete mix are harmful due to the strength and tightness of concrete and its frost resistance. The theoretical basis of air entrainment includes the T.C. Powers model, which relates to the cement paste damage as a result of hydraulic pressure exerted by freezing water contained in capillary pores. Due to the impact of frost, the air gaps take the excess of water, which, as a result of its expansion lowers the temperature, and can damage the cement gel microstructure binding. The possibility of the water excess entering to adjacent voids filled with air results in the situation that such damage will not occur

In last years studies have been made to shaw pore sizes and distributions in cement-based materials using X-ray computed tomography method (Rattanasak, Kendall 2005; Assis *et al.* 2009; Kim *et al.* 2012; Kowalska *et al.* 2014; Chalimoniuk, Iwanowski 2016). The experimental findings indicate that the X-ray computed tomography has the potential for an assessment of the freeze-thaw durability of cement-based materials. X-ray computed tomography (CT) imaging is a nondestructive method for obtaining a large number of consecutive sectional images of the internal microstructure of specimens of interest. Tomographic methods provide a mean of obtaining images in three dimentions on materials without any prior preparation such as drying or polishing. To minimize the distortion effects of tomography can be obtain among others, by using of small samples, that is considered a disadvantage of this technique. For example, porosity of cement paste in concrete was determined using cylindrical specimens measuring 25 mm diameter and 50 mm of height (Assis *et al.* 2009). Kwang Yeom Kim (Kim *et al.* 2012) presented an attempt to determine the air-void parameters of three mortars prepared with different air-void content, by implementing the methods designated in ASTM C457 using X-ray CT sectional images. The results of the evaluation of air-voids microstructure in concrete conducted with the application of two methods: microscope image analysis and computed tomography were presented (Kowalska *et al.* 2014; Chalimoniuk, Iwanowski 2016). It was stated that the results concerning the total air content obtained with the use of computed tomography are differ from those received with the use of microscope image analysis – the difference amounts to ca. 0.5 % – 1% (Kowalska *et al.* 2014) and to ca. 2% (Chalimoniuk, Iwanowski 2016).

In this paper special attention was paid to obtain effective image resolution. The original software was applied – AVCT (Air Void by Computed Tomography) computer programme for determination of air voids characteristics in hardened concrete.

Traditional method

The primary method of the concrete structure examination is a qualitative image analysis of its structure, followed by a computer image analysis, which leads to quantitative results (Brandt 2010). By using the stereology laws, it is possible to obtain information about the spatial construction on the basis of flat images achieved on properly prepared surfaces. The flat images, obtained at different depths, make it possible to assess the spatial distribution of tested facilities. The commonly used method for testing the air entrainment structure of hardened concrete is a method that is described in the European PN-EN 480-11 and American ASTM C457 standards. The air void structure testing is based on the so-called traverse method, where observation takes place along measuring lines running in parallel to the original, exposed upper surface. The number of air voids cut with these measuring lines and the length of each pore's chord are recorded. The mathematical analysis of the recorded data enables to describe the air void system using the following parameters: The American standard also provides for the use of a point counting analysis.

The structure of air voids is described with the following parameters (according to PN-EN 480-11):

a) *A total air content* – percentage representation of volume of air voids in the total concrete volume expressed as a volume percentage,
b) *α specific surface of the system of air voids* – a calculated parameter that presents the result of dividing the surface of air voids by their volume; expressed in mm^{-1}. A method used for calculation, the basis of which constitutes average lengths of chords, is suitable for each system of spherical pores.
c) *Spacing factor* $\bar{L}$ – a calculated parameter, which specifies the maximum distance of any point to the slurry from the edge of the air void measured along the slurry, expressed in mm. While calculating this parameter, is is assumed that all the air voids have the same size and are evenly distributed in the slurry, and a model system has the same volume and surface as an actual system.
d) *Air-void size distribution* – a set of calculated values of the number and/or volume of air voids in the hardened

cement paste, with different dimensions, classified into the range of diameters 0–10, 10–20, 2500– ....4000 μm.

e) *The content of A_{300} micropores* – a calculated parameter, which determines the air content in air voids with a diameter to 0.3 mm (300 μm). The value of this parameter is obtained when calculating the distribution of air voids.

The analysis of the system of air voids in the hardened concrete allows to specify the expected frost resistance of the material. It is believed that the structure of occurred voids constitutes effective protection against the harmful effects of frost, if the total air content in concrete is between 4% and 7%, the average distance to the nearest air void (spacing factor) $\bar{L}$ less than 0.20 mm or 0.22 mm, α specific surface of voids in the range of 16–24 mm^{-1}, the minimum air content in voids smaller than 0.3 mm (A_{300}) at least 1.5%, (Brandt 2010).

To apply traditional method it is necessary to prepare polish sections of concrete. The critical feature is to achieve sharp edges on the air voids, seen at the surface of a polished section of concrete. The properly prepared polished section is a prerequisite for obtaining proper results of air void characterisation.

Computed tomography method

The computed tomography (CT) is a type of X-ray spectroscopy which allows to obtain tomographic images (cross sections) of a tested object, and then, to present its spatial image (3D) of multiple flat shots (2D) taken at different positions (Cierniak 2005; Ratajczyk 2011a, 2011b, 2011c). Tomographic images contain information about the location and absorbing characteristics in the object, and they are further used to reconstruct spatial data. Any difference in the material inside the object, change of its density or pores can be imaged and measured. The test involves directing X-ray beam to the tested object, and the recording of its intensity on the other side on the detector (Fig. 1). X-ray as radiation from other ranges of the electromagnetic spectrum can be absorbed and scattered by the matter. As a result of these processes, a radiation beam is subject to attenuation, which is a function of radiation energy, type and thickness of the tested material. The change in the radiation intensity of a parallel radiation beam of the same energy, when passing through the objects, is described by the following relationship:

$$I = I_0 e^{-\mu g}, \tag{1}$$

where: I – radiation intensity after passing through the object; I_o – initial radiation intensity; μ – linear radiation attenuation (absorption) coefficient characteristic for a given material and a specific X radiation wavelength (coefficient determining attenuation of a parallel radiation beam with the cross section of 1 cm^2 while passing through the layer of g thickness); g – tested material thickness.

The tomographic image creation, consists in measuring the absorption of radiation passing through the object. The object's volume is divided into small cells; the so-called voxels (Fig. 1), in which the linear radiation absorption coefficient is the same. The calculation of the distribution of radiation absorption coefficients is performed by the computer. The reconstructed cross-sectional image is a quantitative map of the linear radiation absorption coefficient in voxels included in the scanned layer. The voxel is a unit of 3D spatial image (equivalent to a pixel in 2D image), which corresponds to the diameter of object divided by the number of pixels:

$$V = d / N, \tag{2}$$

where: V – voxel size, d – diameter of object, N – number if pixels.

The voxel size can be characterised with reference to pixel and magnification as a ratio of

$$V = P / M, \tag{3}$$

where P – number of pixels in detector, and

$$M = FDD / FOD, \tag{4}$$

where: FDD – distance between X-ray source and detector, FOD – distance between X-ray source and object.

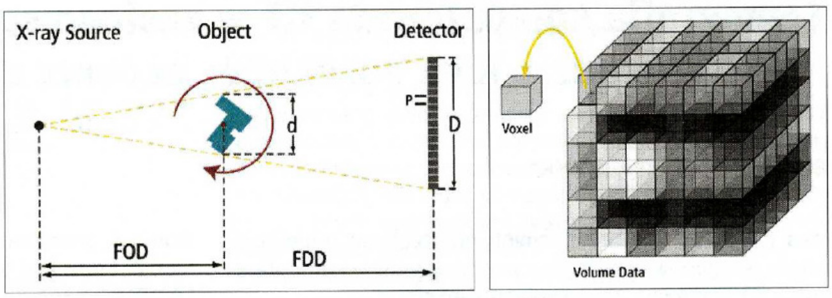

Fig. 1. Some parameters characterising CT tomography (Ratajczyk 2011a)

The main scanner's components include, (Cierniak 2005): X-ray tube and its power supply, the positioning system of a measured element which usually consists of a measuring turntable and a linear guide, as well as the system of detectors, often in the form of a matrix (panel, board). The detection system may consist of a single scanning element, a linear system of elements or a surface system of scanning elements. The X-ray tube is a source of X-ray which, passing through the object and reaching the detectors (Fig. 1), carries information about the object's structure. The information is obtained in the form of a series of shots, the so-called projections. The projection is a name for an image produced on the screen by the impacting X-ray after passing through the tested object. The array of detectors makes it possible to change the values of projections, expressed in the radiation intensity, to electrical values.

Examination

Testing concrete

Cement concrete for airfield pavements (class C35/45) was used for testing. Concrete mix was taken during paving construction at buiding site. The concrete composition was: Portland cement CEM I 42.5 ($\leq$ 0,60 % Na_2O_{eq}) – 395 kg/m^3, sand 0/2 – 500 kg/m^3, granite aggregate 2/8 – 340 kg/m^3, 8/16 – 425 kg/m^3, 16/22.5 – 525 kg/m^3, plasticizer BASF BV18 – 1.7 kg/m^3, air-entrainment admixture BASF LP75 – 0.10 kg/m^3, water-cement ratio w/c = 0.38. The requirements for concrete composition and the constituents are describe in Polish defense standard NO-17-A204. Concrete meets requirements for fresh and hardened concrete specified in the standard. As to durability in accordance to the standard maximum value of mass loss after 200 cycles of freezing-thawing should be less than 4.9%, maximum compressive strenght loss – 19%, maximum amount of scaled material after 56 cycles of freezing-thawing (samples poured of water or deicing chemicals) is 0.01 kg/m^2.

Test samples' execution

Concrete cubes with sides of 10 cm and 15 cm are standard samples for assessing the characteristics of the air voids in the hardened concrete. In order to optimise the obtained images and ensure the required resolution, cores with a diameter of 10 mm are extracting from the cubes using a pistol diamond drill. The cores are taken at a different distance from the trowelled face (Fig. 2). Exemplary cores were presented in Fig. 3.

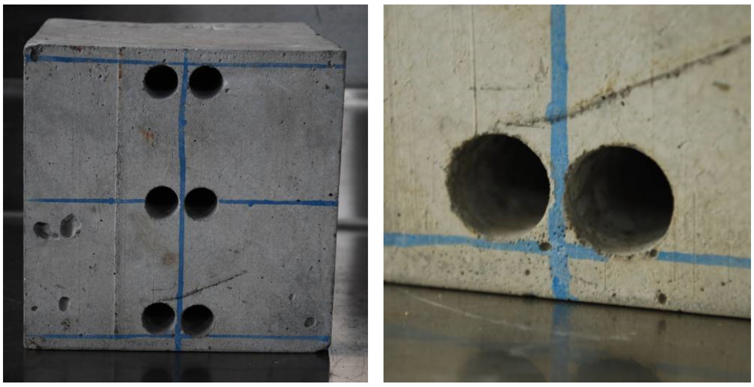

Fig. 2. The way of collecting cores from concrete samples

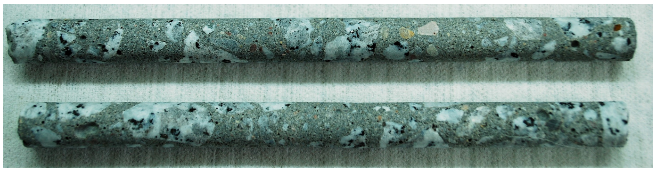

Fig. 3. Exemplary cores collected for CT tests

X-raying a sample and image processing

The testing of collected concrete samples included CT tests, a digital image analysis with the use of developed AVCT programme (Air Voids by Computed Tomography) and marking the characteristics of air voids in concrete. The tests of samples were carried out with the use of v/tome/x m CT scanner by GE company, equipped with a panel detector and a projection system using a cone-shaped X-ray beam.

The CT scanner is equipped with a lamp with the power of 300 kV and the second one for nanotomography with the power of 180 kV and the resolution of 0.5 μm. In the carried out test, the examined object was on the turntable in relation to immovable elements: lamp and detector. By using a spatial X-ray beam and the panel detector, after the object's full rotation of 360º, a complete image of the entire object was obtained. The final imaging accuracy depends on the number of projections implemented for a complete rotation. The image reconstruction on a graphics station was performed with the use of the datosx programme by GE company (Fig. 4, Fig. 5).

These samples were tested using the following CT parameters: voltage 200 kV, current – 200 µA, projections on 360 – 1440, filters: 0.5 mm Cu + 0.5 mm Sn, 2048x2048 px. panel detector.

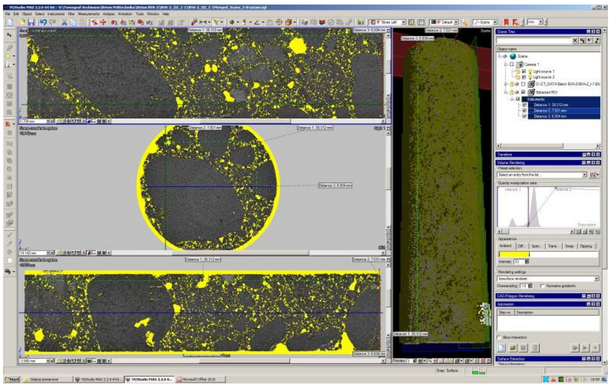

Fig. 4. View of the sample in the VGStudio MAX programme

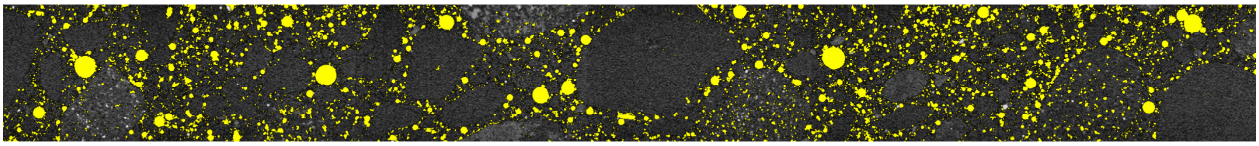

Fig. 5. View of the sample scan

Image analysis

The AFIT conducts the analysis of the obtained images, constituting the shot holes' flat sections, from the CT scanner for determination of the air pores' characteristics according to the requirements of the PN-EN 480-11 standard using the **AVCT** (Air Void by Computed Tomography) computer programme, in which the results are obtained on the basis of measurements of air voids' chords on the observed samples' sections (in accordance with the standard test). The structure of air voids is described with the following parameters:

– air's total content:

$$A = \frac{T_a \cdot 100}{T_{tot}}, \tag{5}$$

where: T_a – total lenght of chords, T_{tot} – total lenght of traverse line;

– specific surface area of the air voids:

$$\alpha = \frac{4 \cdot N}{T_a}, \tag{6}$$

where: T_a – total lenght of chords, N – number of voids cuts by traverse line;

– distribution ratio:

$$\overline{L} = \frac{3 \cdot \left[1{,}4(1+R)^{1/3} - 1\right]}{\alpha}; \tag{7}$$

or

$$\overline{L} = \frac{P \cdot T_{tot}}{400 \cdot N}, \tag{8}$$

where: a – specific surface area of the air pores, R – ratio of paste/air, P – paste volume, T_{tot} – total lenght of traverse line, N – number of voids cuts by traverse line.

The screenshot from the AVCT programme for processing data obtained with the use of CT method was presented in Fig. 6.

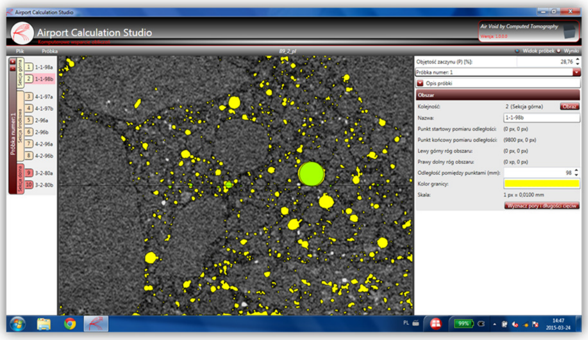

Fig. 6. Developed programme for processing data obtained with the use of CT method – screenshot

Measurement

Following the standard PN-EN 480-11, the total length of a traverse line is assumed to be at least 1200 mm, for one concrete specimen. Some analyses were undertaken in terms of total lenght of traverse lines. Results obtained for air-void content and micropores content depend upon the lenght of traverse, as shown in Fig. 7. The range of parameters becomes higher by approx. 0.15 %. as the lenght increases from 1290 mm to 1500 mm and 1700 mm.

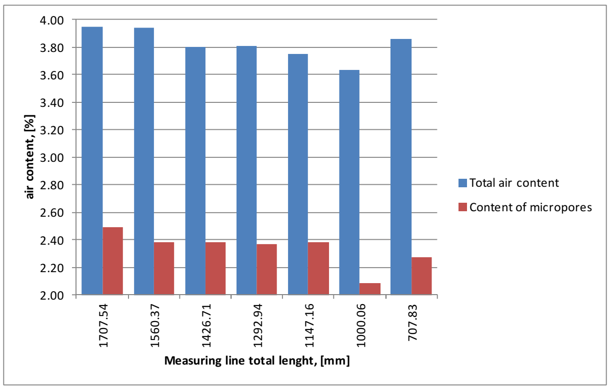

Fig. 7. Total air-void content vs. total lenght of traverse lines

Using cores of diametr 1 cm it is possible to obtain resolution 2915 dpi (the size of one pixel was about 8.7 µm). However, such a resolution is not sufficient to accurately determine the amounts of pores in the first class (0–10 µm) in accordance to PN-EN 480-11, which critically affects the quantification of other air-void parameters. Working on obtaing higher resolution the testing cores were cut for four parts along the longitudinal axis and measured again to estimate only the content of A_{300} micropores, especially in the first classes (size 1–100 µm). The resolution increased to 7690 dpi (1 px = 3.3 µm) – Fig. 8. These data allowed for deriving other parameters obtained with a prior procedure.

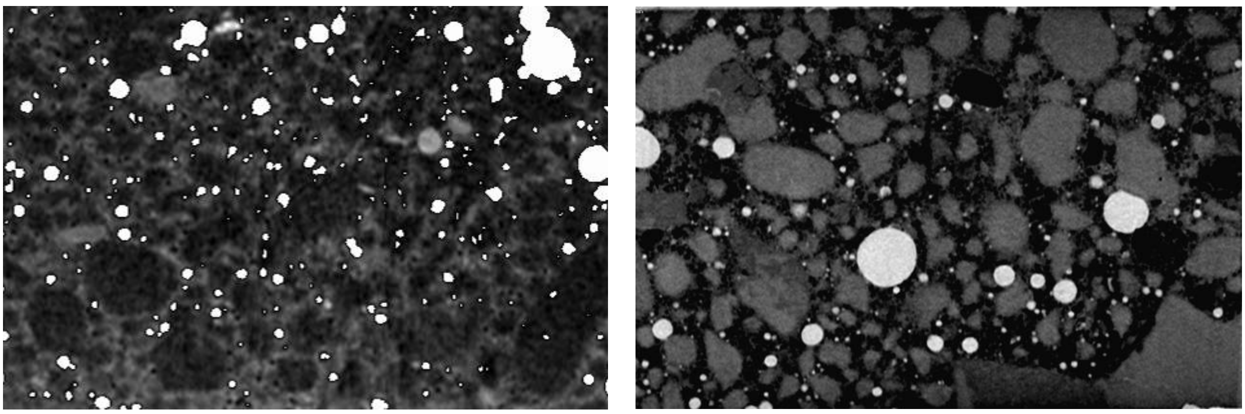

Fig. 8. View of the sample scan before and after enhancement of resolution of CT images

In Table 1 and Table 2, the test results obtained for cores taken from two cubes (marked I and II) with the use of CT method before (No. I-1, I-2, II-1, II-2) and after resolution enhancement (No. I-1A, I-2A, II-1A, II-2A) were compared. Samples marked I-1 and I-2 (II-1 and II-2) represents cores taken in two perpendicular directions of the cubes. Air voids size distribution before and after resolution enhacement are shown in Fig. 9–12. The results obtained with the use of an improved procedure are higer by approx. 1% in relation to total air content and content to micropores, and higher by approx. 20 mm^{-1} in relation to specific surface of air voids, and lower by approx. 0,1 mm in relation to the distribution ratio, in comparison with the results obtained before enhancement of CT images. The results confirmed the data presented by Kowalska (Kowalska *et al.* 2014) showed that the total air content obtained with the traditional method is higher by approx. 1% than parameters obtained by a method with the use of CT method and the proprietary software.

Table 1. Results of marking the characteristics of air voids in hardened concrete

Parameter		Unit	Requirement	Computed tomography method (CT)			
				I-1	I-1A	I-2	I-2A
Slurry volume	P	[%]	–	24.7	24.7	24.7	24.7
Measuring line total length	T_{tot}	[mm]	–	1280.09	1280.09	1296.12	1296.12
Total length of chords per pores	T_a	[mm]	–	51.4	63.82	53.17	65.59
Total air content	A	[%]	4–7	4.02	4.99	4.10	5.06
Total number of measured chords	N	–	–	364	795	373	798
Specific surface of air voids	α	[mm^{-1}]	16–24	28.33	49.85	28.06	48.69
The ratio of slurry/air	R	–	–	6.15	4.95	6.02	4.88
Distribution ratio	L	[mm]	≤ 0.20	0.18	0.09	0.18	0.09
Content of micropores	A_{300}	[%]	≥ 1.5	2.55	3.35	2.53	3.32

Table 2. Results of marking the characteristics of air voids in hardened concrete

Parameter		Unit	Requirement	Computed tomography method (CT)			
				II-1	II-1A	II-2	II-2A
Slurry volume	P	[%]	–	24.7	24.7	24.7	24.7
Measuring line total length	T_{tot}	[mm]	–	1257.56	1257.56	1282.39	1282.39
Total length of chords per pores	T_a	[mm]	–	41.78	57.44	40.92	55.47
Total air content	A	[%]	4 – 7	3.32	4.57	3.19	4.33
Total number of measured chords	N	–	–	258	721	279	731
Specific surface of air voids	α	[mm^{-1}]	16–24	24.70	50.23	27.27	52.68
The ratio of slurry/air	R	–	–	7.43	5.41	7.74	5.71
Distribution ratio	L	[mm]	≤ 0.20	0.22	0.10	0.21	0.09
Content of micropores	A_{300}	[%]	≥ 1.5	1.49	2.48	1.72	2.62

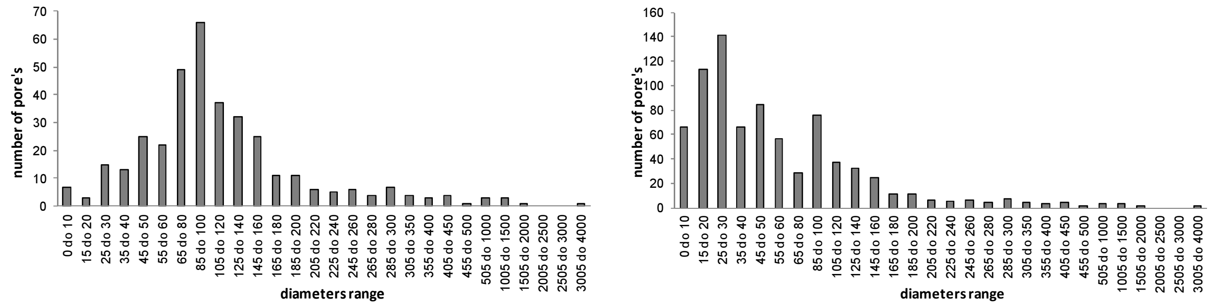

Fig. 9. Air voids size distribution before and after resolution enhacement, sample I-1 and I-1A

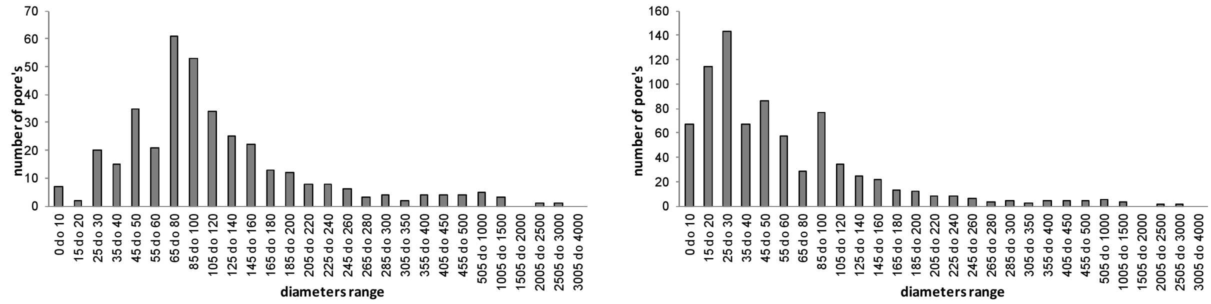

Fig. 10. Air voids size distribution before and after resolution enhacement, sample I-2 and I-2A

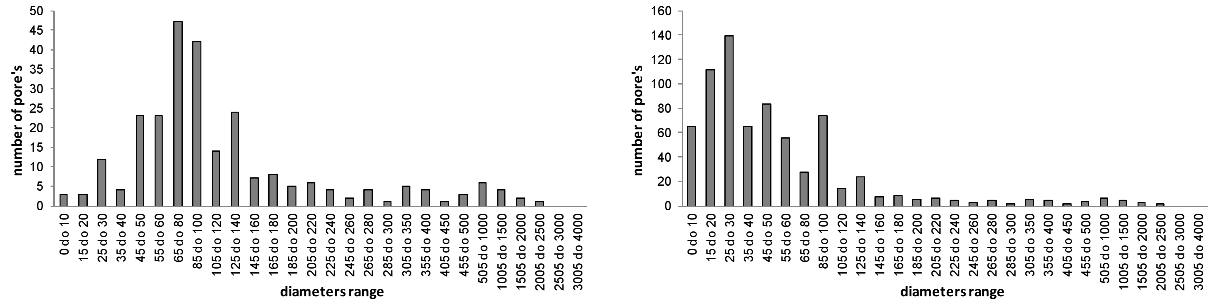

Fig. 11. Air voids size distribution before and after resolution enhacement, sample II-1 and II-1A

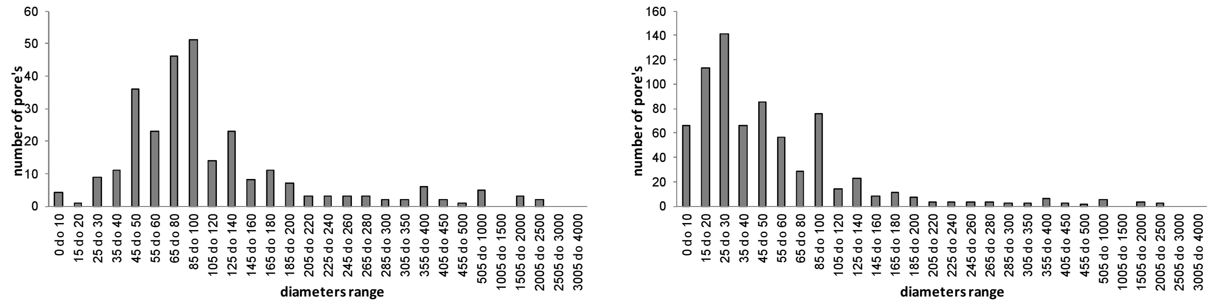

Fig. 12. Air voids size distribution before and after resolution enhacement, sample II-2 and II-2A

Conclusions

The parameters of the air-void system of hardened concrete determined by the procedure described in PN-EN 480-11 are as accurate as the correctly prepared test sample. X-ray Computed Tomography offers the possibility to estimate air-void parameters avoiding specialised equipment for preparing samples (lapping, polishing, additional preparation to obtain sharp edges of air-voids) and excessive time required for preparation of a tested specimen. As compared to conventional testing method the use of CT metod reduces the influence od human factor on the result.

The experimental investigation of conrete was conducted using CT method with implementation the way of determination of parameters characterising the system of air voids specified in PN-EN 480-11 standard.

The test results of airfield pavement concrete samples obtained with the use of X-ray CT sectional images and the developed software to analyse images and to determine the air-void parameters are presented in the paper. An attempt to improve resolution of CT images was taken. The total air content and content to micropores values obtained via to the proposed procedure are more compatible with the previously published data of test results achieved with the traditional method.

It is ancipitated that improvements in the resolution of the procedure applied X-ray CT images will provide possibilities for the determining of air-void parameters of airfield pavements concrete. However, the size of core specimens taking from laboratory samples (cubes or cores extracted from finished construction) and aggregate size used for concrete mix can affect the results and need to be taken into consideration.

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