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Estimation of the structure of air entrained concrete using a flatbed scanner

D. Zalocha, J. Kasperkiewicz *

Institute of Fundamental Technological Research PAS, 21 Swietokrzyska Str., 00-049 Warsaw, Poland

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Abstract

This paper describes the possibilities of estimating the structure of concrete with the help of automatic image analysis using a high-resolution flatbed scanner. Sample preparation techniques and components of the image analysis system are described. Concerning the structure of the entrained air voids system, it was found that the results obtained using a high-resolution flatbed scanner were comparable to those obtained by conventional methods, i.e. using a system equipped with stereomicroscope. The possibility of automatically measuring the paste content in hardened concrete by analysis of plane sections, taking into account information available in RGB histograms, is also presented. A new procedure is proposed for the identification of the distance from the cement paste to periphery of the nearest air void, which enables rapid evaluation of the quality of the air entrainment treatment The procedure also allows some characterization of the aggregate component.

Keywords: Image analysis B; Concrete E; Cement paste D; Air voids

1. Introduction

The existence of a relationship between various structural parameters and properties of a material is one of the basic paradigms in materials science. Quantitative evaluation of the structure enables valuable conclusions to be drawn about the quality, mechanical properties or durability of the material. The aim of the investigations presented in this paper was to establish procedures for appropriate sample preparation and automatic, quantitative estimation of the structure of hardened concrete; in particular of air-entrained concrete. Such estimation is important from the point of view of frost resistance and durability.

It is generally accepted that the air voids structure is a critical parameter of concrete freeze–thaw resistance, at least in the case of a normal strength concrete, (less obvious in case of HPC). The traditional way of determining the air void characteristics of concrete is by microscopic examination as described in standards ASTM C 457 or EN 480-11 [1,2]. As a tool for the estimation the automatic methods of image analysis have become common. The most common source of images for investigation of the quality of air-entrained concrete is a video camera coupled with a microscope. The use of a flatbed scanner in the estimation of air-void characteristics was tried previously without success due to limited resolution of the scanner, [3]. The appearance of new, inexpensive, high-resolution scanners has made possible their application with sufficient accuracy.

The automatic procedures of image analysis systems applied in estimation of the air void parameters are rapid and precise, however, these procedures do not measure the cement paste content of the analyzed surface. According to the model of Powers, referred to in the standards, the paste content is an important parameter required to obtain accurate characteristics of the air void structure and it must be provided by the operator. This paper demonstrates the possibility of high accuracy evaluation of the air voids system using a flatbed scanner with simultaneous measurement of the quantity of cement paste. Additionally the

* Corresponding author. Tel.: +48 22 8261281x310; fax: +48 22 8269815.

E-mail address: jkasper@ippt.gov.pl (J. Kasperkiewicz).

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procedure makes possible certain quantitative evaluation of aggregates arrangement.

2. Description of equipment

Two different systems were compared at the IFTR PAS laboratory for the tests described in the paper. One was composed of image analysis software, and software to control the scanning table, an automatic scanning table, a stereoscopic microscope, a color video camera and a cold light source—"swan neck". The second system was the same image analysis software and a flatbed scanner.

In the first (microscope based) solution the specimen is placed atop the scanning table, which can move along X and Y axes up to 150 mm, with accuracy of 0.1 μm. Magnification of the stereoscopic microscope is between 10× and 63×. Color video camera has three CCD matrices, one matrix for each component of an image in the RGB system. With help of the applied video camera it is possible to capture 24 bits color images at a resolution 768 × 576 pixels, in a rectangular net, or 8 bits grayscale images at the same resolution. To determine the air-void characteristics the magnification was typically 30×, so that a single pixel in the image corresponded to 2.76 μm on the surface of the specimen.

In the second (flatbed scanner based) solution the specimen is placed on the glass top of a flatbed scanner. The scanner used in the tests had an optical resolution of 2400 ppi (points per inch), which means that the smallest point of the image–one pixel–corresponds to 10.6 μm on the specimen. Images obtained from the scanner are recorded in the same 24 bits RGB as in case of the video camera described previously.

Algorithms for measuring the structural parameters have been prepared using the programming language built-in in the image analysis software [4], which makes possible application of morphological filters and various complex image processing operations.

3. Sample preparation technique

The technique of specimen preparation for estimation of the air void parameters in concrete was first developed at DBT Laboratory (Dansk Beton Technik), in Hellerup, where it has been successfully applied for a long time, and it was later modified at the IFTR PAS Laboratory in Warsaw. Concrete specimens of planar dimensions 100 × 100 mm are prepared by cutting, grinding and finally polishing (with help of SiC polishing powders). To avoid defects in observation area the polished surface is inspected with help of a stereomicroscope and proper assessment of the quality demands really experienced operator. The polishing is continued until the surface is free from defects. The next step is coloring of the surface with help of a blue, water resistant marker, which is followed by filling the air voids with zinc paste. Surplus paste is removed using a sharp blade: the surface is cleaned and finally protected using paraffin oil. At the end, the quality of preparation, and especially the accuracy of the air-void filling by the zinc paste is controlled under the microscope. If the quality of the surface is inadequate the whole process must be repeated, as this is one of the most important elements of the preparation. Description of possible defects in the polished surface was given for example by Pleau et al. [5].

The above description concerns the preparation of specimens for microscopic observations. There are certain differences in the sample preparation technique used for estimation of the structural parameters with help of a flatbed scanner. For separation of cement paste regions from the image of the whole concrete sample a special treatment has been worked out at the IFTR PAS laboratory. After the polishing concrete samples are shortly soaked in a blue ink (not painted by a blue marker as in the first solution), which results in cement paste area dyed blue, with the color of a typical aggregate almost unchanged. After dyeing the air voids are filled with white zinc paste as in the first solution. In

Table 1
Comparison of results of measurements of air void parameters obtained using a flatbed scanner and a stereoscopic microscope

No.	Parameters obtained with help of microscope				Parameters obtained with help of scanner			
	$\overline{L}$ (mm)	α (mm^{-1})	A (%)	A_{300} (%)	$\overline{L}$ (mm)	α (mm^{-1})	A (%)	A_{300} (%)
1	0.17	32	4.43	1.72	0.15	31	5.40	2.79
2	0.19	26	4.54	1.51	0.17	28	5.28	2.51
3	0.19	30	4.07	1.79	0.17	32	4.76	2.62
4	0.12	33	5.94	2.58	0.11	33	6.25	3.99
5	0.16	30	4.16	1.92	0.17	27	4.80	2.60
6	0.12	40	4.94	2.55	0.13	36	4.78	2.92
7	0.09	31	7.51	3.09	0.12	27	6.31	3.22
8	0.12	28	6.99	2.81	0.16	26	5.81	2.83
9	0.15	47	2.41	1.05	0.17	42	2.10	1.44
10	0.28	17	5.14	0.86	0.28	18	4.68	1.12
11	0.14	10	14.68	1.03	0.14	11	14.35	1.49
12	0.14	28	6.82	1.83	0.13	27	7.43	2.90

fact, the procedure results in the creation on the polished surface of a blue thin layer on top of the cement paste. The layer forms only on the paste and so avoided are errors due to the misidentification of certain semi-transparent grains of sand (e.g. grains of quartz) as cement paste.

4. Estimation of the air void parameters

Programs to estimate the air void characteristic using both the microscope and the flatbed scanner have been prepared taking into account the new Polish Standard PN EN 480-11 [2]. The Polish Standard recommendations are the same as in the European Standard EN 480-11 and only the linear traverse method is specified. In accordance with this document, the programs perform measurements and calculate all the required air void characteristics:

– spacing factor, $\overline{L}$;
– specific surface, α;
– air content, A;
– content of air voids with diameter less than 0.3 mm, A_{300};
– air void diameter distribution (in form of a distribution table).

A series of observations using both the microscope and the scanner were performed on 12 plane sections of different concrete mixes. Results concerning the four main characteristics of the air voids systems are shown in Table 1. Both sets of data presented in the table in a single row concern always the same surface of the specimen. The accuracy of estimation of the parameters of the air-void system using the microscope, which can be treated as the reference data, was verified previously at an independent laboratory [6].

It can be seen from the Table 1 that using a high-resolution flatbed scanner it is possible to obtain results quite comparable to those obtained using a microscope. The coefficients of correlation obtained between the data from the microscope and from the scanner were about 0.95, with an exception in case of A_{300}, where the coefficient was about 0.85. The differences were not systematic, being both positive and negative, and in all cases they were lower than the expected accuracy related to the natural inhomogeneity of concrete. The differences between the results can be seen in Table 2.

Table 2
Differences between results of measurements of air void parametersobtained using a flatbed scanner and a stereoscopic microscope

	$\overline{L}$	α	A	A_{300}
Maximum difference	0.02	5	1.2	−0.02
Minimum difference	−0.04	−2	−0.97	−1.41
Average difference	−0.0008	1.2	−0.03	−0.64
Correlation coefficient	0.914	0.975	0.971	0.847

To summarize, the only effect of the limited resolution of the scanner can, perhaps, be seen in a slightly lower correlation coefficient in case of the parameter A_{300}. May be this is not a serious problem as even if in the recent standards this parameter is being specified the national standards do not indicate what is the acceptable level of A_{300} for the satisfactory frost resistance of concrete.

5. Automatic measurement of the paste content

Experiments on automatic measurement of the content of cement paste were conducted on the same series of specimens as above. Such measurement is a new idea, which can be realized only using a scanner. The sample preparation procedure leaves the concrete surface with cement paste areas characteristically dyed blue. An example of the histograms is presented in Fig. 1. The diagrams show the relationship between intensity of RGB colors in scale 0–255 (horizontal axis) and number of pixels of a given intensity (vertical axis). Each histogram represents a different channel of RGB image—red, green or blue, respectively. By analyzing the three histograms it is possible to separate the paste from the remaining components. On each histogram it is possible to identify certain peaks corresponding in the image to pixels of the cement paste.

Application of the model suggested by Powers to estimate the air void parameters requires knowledge about the proportion of the paste content in the tested surface [7]. According to this model, the spacing factor is defined in two different ways, depending on the value of the paste/air ratio. In the calculations air voids are approximated by system of spherical bubbles of the same diameter uniformly dispersed in the cement paste.

A special program has been prepared for automatic measurements using the image analysis system mentioned previously (the program operates without any intervention from the operator). Determination of the cement paste content is calculated in the following steps:

– capturing of the image of the surface in 24 bits RBG technology,
– analysis of the histogram of the image,
– thresholding operation,
– measurement of the paste content.

To obtain correct results the threshold operation is made separately on each channel—red, green and blue, which gives three different binary images. For subsequent processing, the image of cement paste used is a logical product of the three binary images (operation: AND). Binarization thresholds are located around the peaks characteristic for cement paste (Fig. 1). The exact positions of the thresholds depend on the statistical parameters of the histograms and, are identified automatically by the system. The threshold ranges are different for each colour channel, for example,

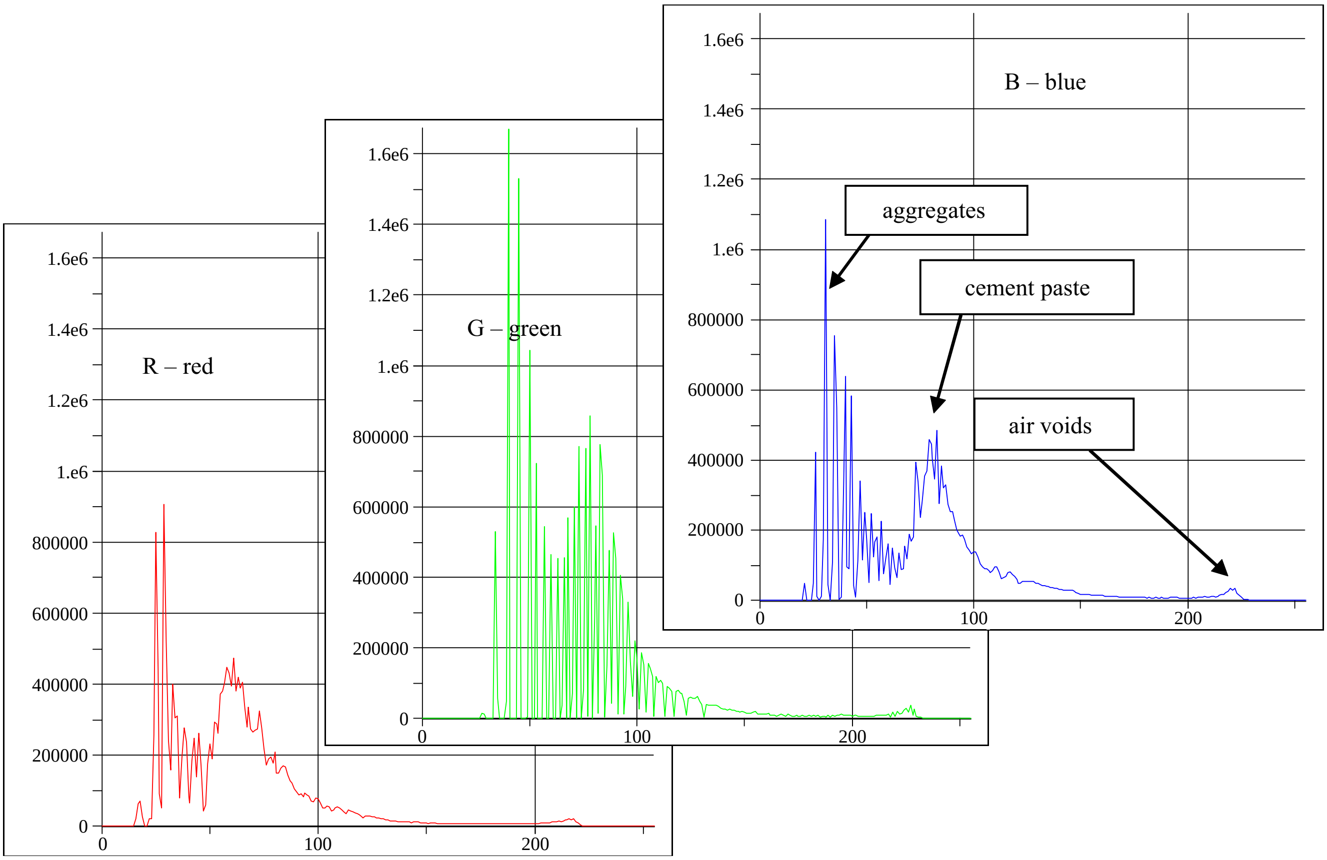

Fig. 1. Histograms of an image of concrete surface in RGB separation. Such information has been used to settle binarization thresholds aimed at identification of the cement paste.

for the blue channel the range of binarization thresholds was found to be equal 20 (difference between the upper and the lower thresholds).

In order to evaluate the effectiveness of the proposed procedure the actual paste content has been measured manually by the point counting method. The measurements were done on 21 plane sections, with samples taken from 12 different concrete mixes. All specimens have been collected from concrete factories. The results of the manual measurements were compared with those obtained applying the image analysis. The comparison is presented in Table 3.

The coefficient of correlation for the results obtained with help of the automatic procedure and the results from the manual measurements was 0.946.

It should be mentioned that the automatic identification of the cement paste is very difficult in case of microscopic observation [8]; at least automatic identification using a microscope was not possible with the samples prepared as described previously.

6. Evaluation of the inhomogeneity of the air entrainment

The value of the spacing factor as proposed by Powers is a mean value for the whole surface under consideration. Applying the routines available in the image analysis system it is possible–on digital images of cement paste with the air voids–to analyze the distribution of distances of points in the cement paste to the periphery of the nearest air void. Finding regions where the distance to the nearest air void is greater than certain acceptable value gives additional information related to the frost resistance of concrete. In the Powers approach there is an inherent assumption that the air entrainment is homogeneous, which often is not true. The proposed approach makes possible a visualization of the effect, and also quantitative estimation of its importance.

The measurement concept presented here is similar to the Phileo factor [9] and the “flow length” by Pleau and Pigeon [10]. By quantifying the volumetric fraction of cement paste within a certain distance from the air void, Philleo extended the approach proposed by Powers. Pleau and Pigeon estimated the distance that freezable water must travel through the cement paste to an air void. The procedure allows the calculation of the volume of a so-called “protected” cement paste (or distribution of *flow lengths*), from measurements directly on the cement paste. All such methods only represent the situation in plane sections, but the two magnitudes–concerning 2D and 3D situation–are naturally related.

Procedures for automatic calculation and graphic presentation of the distances proposed in this paper have been prepared applying functions of geodesic dilation and geo-

Table 3
Comparison of results of paste content measurements on plane sections, obtained by manual point count method and by automatic image analysis

No.	Paste content according to point count method (ZP) [%]	Paste content according to automatic method of image analysis (ZA) [%]	Difference (ZP) – (ZA) [%]	Relative error of the measurement[a] [%]
1	25.8	26.1	−0.3	1.2
2	22.0	23.0	−1	4.5
3	22.0	22.5	−0.5	2.3
4	27.8	27.5	0.3	1.1
5	28.3	28.5	−0.2	0.7
6	27.7	28.8	−1.1	4.0
7	21.0	20.9	0.1	0.5
8	23.7	23.0	0.7	3.0
9	24.5	24.8	−0.3	1.2
10	29.9	29.8	0.1	0.3
11	22.1	22.9	−0.8	3.6
12	22.4	22.8	−0.4	1.8
13	22.2	22.7	−0.5	2.3
14	25.7	25.6	0.1	0.4
15	25.9	25.9	0.0	0.0
16	25.0	24.0	1.0	4.0
17	21.9	21.6	0.3	1.4
18	24.0	24.1	−0.1	0.4
19	25.2	23.3	1.9	7.5
20	24.0	22.1	1.9	7.9
21	24.4	25.1	−0.7	2.9

[a] Error calculated as 100% × |(ZP) − (ZA)|/ZP.

desic distance. Definition of such functions can be found for example in Soille [11]. In consequence of the approach the distance is measured within the cement paste, avoiding the aggregates.

Fig. 2 was obtained by applying the suggested method, the cement paste is characterized by the intensity of gray, depending on the distance to the periphery of a nearest air void. The area fraction of the cement paste within a selected distance from the periphery of air voids can be calculated as a fraction of pixels of a given intensity of gray in the whole image of the cement paste.

In the example image (Fig. 2), it is possible to evaluate the proportion of the area of the cement paste at a distance not more than 0.2 mm to the nearest air void, in relation to the whole matrix area. In this example, this area (lighter shading) is 68% of the total cement paste area; while the remaining 32% of the cement paste area is at the greater distance (dark shading).

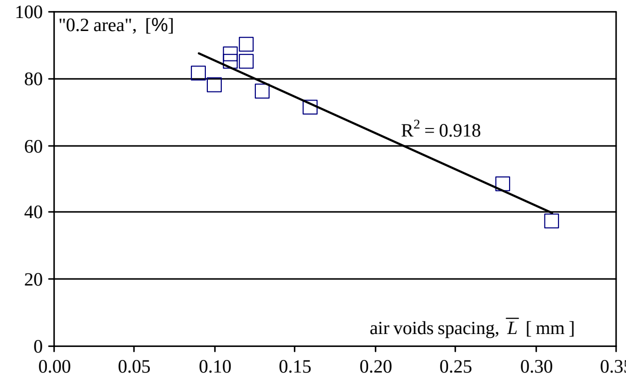

Fig. 3. Relation between the conventional air voids spacing factor, $\overline{L}$, and percentage of area of the cement paste at distance to the nearest air void below the critical value of 0.20 mm.

Even if this is only a 2D representation of the actual 3D situation, such a method of characterization of concrete seems effective, as the concrete was found to be properly protected against the frost when the above mentioned “0.2 area” area (“lighter shading”) was above 60–70%. There is also a good correlation between this new coefficient and the conventional air voids spacing factor ($\overline{L}$), which can be seen in Fig. 3. It should be mentioned that the “0.2 area” factor is not intended to replace the $\overline{L}$ factor, only to better characterize possible inhomogeneity of the air entrainment.

7. Additional possibilities

A natural consequence of the separation of the air voids and the cement paste from the whole image of the concrete surfaces is the possibility to analyze the aggregates. Finally, using a flatbed scanner and the sample preparation technique described above it is also possible to analyze

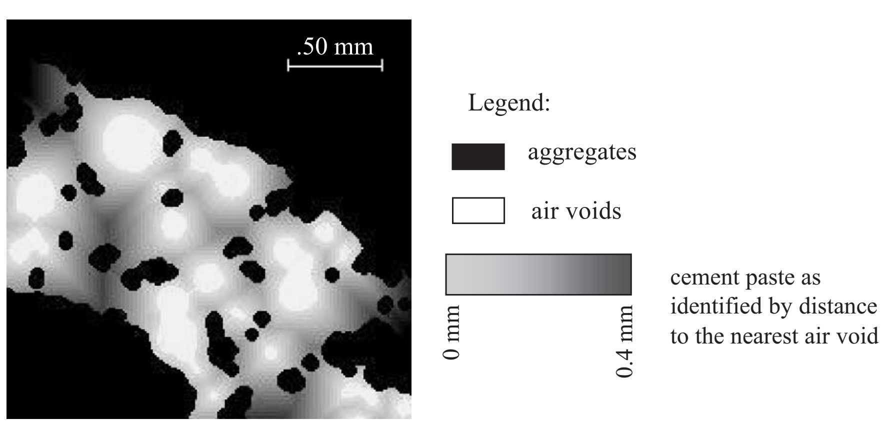

Fig. 2. Presentation of the surface of concrete after isolating the components and evaluating the distances to the nearest air void.

presence of macro cracks and distribution of the entrapped air voids. These kinds of defects, colored white, can be separated in the image by taking into account their stereological shape parameters.

8. Conclusions

Estimation of the air void parameters can effectively be done using a high quality flatbed scanner. An advantage is requirement of appropriate preparation of only one side of the concrete specimen, while when using the conventional set of a stereoscopic microscope, video camera and scanning table it is important to prepare specimens of possibly parallel top and bottom surfaces. Another important advantage is that the cost of the whole image analysis systems using a scanner as the source of images is obviously much lower than the cost of a microscope based system. A final advantage of using the scanner is having a very steady source of light, which in microscopic observations may sometimes cause troubles.

Using the flatbed scanner and a special preparation technique it is possible to automatically measure the paste content on the surface of concrete specimens. Without the intervention of the operator similar measurement is impossible when working with a microscope, and the approach in such case must partly be manual.

Thanks to the possibility to separate the cement paste and the air voids in the image of a concrete surface, it is possible to do a quantitative analysis of areas of cement paste protected to different degree by the air voids for the sake of frost resistance. In the case of really homogeneous concrete the estimation according to the Powers model is sufficient, but in the case of an inhomogeneous material this estimation might be misleading. This is especially important in the case of the exposed layers of a concrete structure. Identification of such non-protected regions allows better conclusions to be drawn about the durability of a given concrete.

It is expected that the application of flatbed scanners will soon become more popular due to increases in resolution of such devices combined with simultaneous decrease of cost of the equipment. When using scanners in the appropriate way it is possible to obtain a good quality images of the whole analyzed surface in relatively short time. Application of special preparation techniques with help of appropriate image analysis systems makes possible automatic characterization of concrete structure.

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