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Image analysis as a tool for estimation of air void characteristics in hardened concrete: example of application and accuracy studies

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A special application of automatic image analysis to evaluation of air void characteristics is presented. Sample preparation technique, components of the image analysis system and programs for automated processing of the data according to the new Polish Standard PN EN 480-11 are described. The resulting the system is also discussed. Application of a flatbed scanner to effective estimation of the air void parameters is proposed.

Key words: *image analysis, concrete, air void structure, frost resistance, accuracy.*

1. Introduction

Image analysis is a relatively new tool for characterization of the structure of concrete. When humans see and recognize something their brains perform a complex and complicated image analysis. In recent decades investigations are aimed at transferring this process to machines. In this paper we present a special application of an automatic image analysis system. In the description included are all the steps of the image analysis: image acquiring, image processing and the measurements.

Destructive action of frost in hardened concrete is connected with extension of water in low temperature. Limited possibility of water molecules migration results in considerable tensile stresses and as an effect certain disintegration of the microstructure of the material. Process of degradation proceeds mainly in the hardened cement paste. It is known that air entrainment of concrete improves its frost resistance. Possibility of water to move to nearby located air voids decreases the probability of the destruction of material. However, the air content alone is not a sufficient parameter to characterize the air void structure. Important is the air void distribution and this was found to be characterized by the parameters of spacing factor and specific surface of the air voids.

According to ASTM C457 Standard, the spacing factor is defined as a useful index related to the maximum distance from a point in the cement paste to periphery of the nearest air void. Specific surface is defined as the surface area of the air voids per unit of volume of air voids in hardened concrete; it is usually expressed in $[mm^2/mm^3]$ [1]. The idea of measuring of the spacing factor based on the models by Powers was first published in 1949, cf. [2]. According to the concept of Powers, the spacing factor is defined in two different ways dependent on the paste/air ratio, see Fig. 1.

It is generally expected that normal concrete will be frost resistant when the spacing factor is below 0.20 mm, the specific surface being at the same

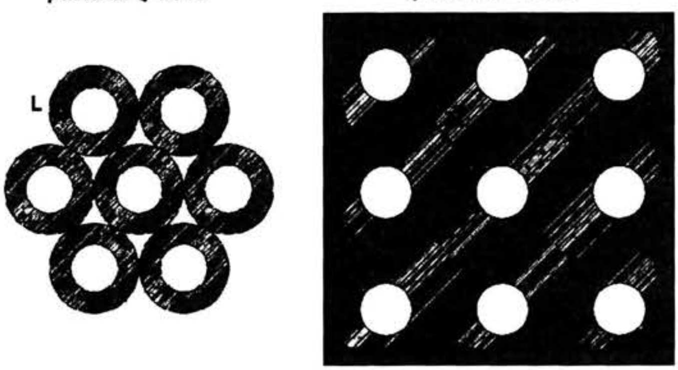

FIGURE 1. Schematic illustration of the models assumed by Powers in calculation of the spacing factor.

TABLE 1. Suggestions of maximum admissible spacing factor in case of high performance concrete, after [4].

W/C ratio	Recommended average spacing factor	Permitted maximum spacing factor	Waiver
> 0.40	230 μm	260 μm (for scaling resistance)	300 cycles ASTM C666 50 cycles ACTM C672
0.35-0.40	350 μm	400 μm (for scaling resistance)	300 cycles ASTM C666 50 cycles ACTM C672
0.30-0.35	450 μm	550 μm	500 cycles ASTM C666
< 0.30	No data, it is acceptable to use the criteria provided above		

time greater than $16\,\mathrm{mm}^{-1}$ [3]. The limits are different in case of modern high performance concretes (HPC), where they depend on the w/c ratio. Suggestions of maximum admissible spacing factor in HPC are shown in Table 1 [4].

2. Description of the Polish Standard PN EN 480-11

Worldwide accepted procedure of characterization of the air void structure is the ASTM Standard C457 [1]. There was no equivalent in Poland of the ASTM Standard until the Polish Committee for Standardization has filled in the gap by introducing the European Standard EN 480-11, as the Polish Standard PN EN 480-11 [5]. There are some differences between European and ASTM Standard. According to the Polish Standard for estimation of the air voids structure applied is only the linear traverse method. Along a traverse measured are the lengths of chords intersecting the air voids and the number of such chords. Total length of the traverse should be at least 1200 mm on each concrete sample. Two samples of concrete should be used for characterization of pore structure. European Standards do not provide possibility to apply the modified point count method that was described in the ASTM Standard.

Spacing factor is calculated in the same way as in ASTM C457, but symbols have been changed:

$$\bar{L} = \begin{cases} \dfrac{P\,T_{\mathrm{tot}}}{400N}, & \text{for } R \leqslant 4.342, \\ \dfrac{3}{\alpha}\left[1.4\,(1+R)^{1/3} - 1\right], & \text{for } R > 4.342, \end{cases}$$

$$\alpha = \frac{4\,N}{T_a}, \qquad A = \frac{100\,T_a}{T_{\mathrm{tot}}}, \qquad R = \frac{P}{A}.$$

The meaning of the symbols is:

R – paste/air ratio;

P – content of the cement paste in hardened concrete: the standard recommends to take this value from the mix design [%]; there is no indication concerning the procedure in case such information is unavailable;

T_{tot}– total length of the linear traverse [mm];

T_a– total length of the chords in the air voids [mm];

A – total air content [%];

N – number of chords in the air voids.

According to the new Polish Standard, the air void system can be evaluated by means of an appropriate image analysis system. This pertains also to a setup composed of high quality video camera, a stereomicroscope and an automatic scanning table. By applying an automatic procedure it is possible to avoid errors due to human operators and to increase the speed of test.

3. Sample preparation technique

Sample preparation technique, which is used at the IFTR laboratory, was transferred from DBT (Dansk Beton Technik) laboratory in Hellerup, where it has been successfully used for a long time. According to this technique a rectangular sample of concrete of planar dimensions 100×100 mm is polished with the help of polishing powders (SiC). The following gradations are used: P320, P600 and P1200. After polishing and before acceptance of the preparation the surface is inspected with the help of a stereomicroscope to avoid surface defects like small pullouts, broken voids edges etc., see Figs. 2-4.

The polishing is continued until the surface is possibly free from defects, and then the sample of concrete is ready for further of preparation. The next step is colouring of the surface with the help of a blue, water resistant marker, and then filling the air voids by zinc paste. Surplus of the paste is removed using a sharp blade. Finally surface is cleaned using paraffin oil. At the end, the quality of preparation, especially the accuracy of the air void filling by the zinc paste is controlled again under the microscope. If the quality of the surface is poor the whole treatment has to be repeated. There is an important

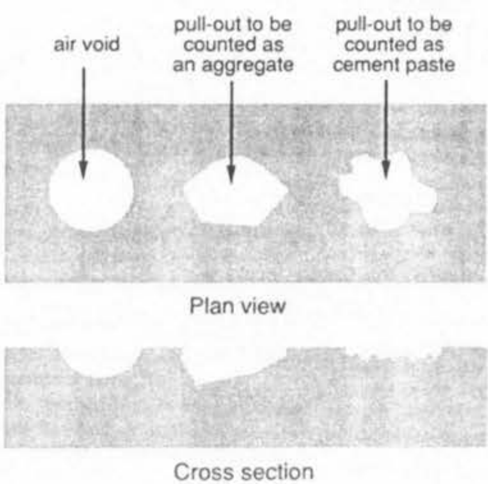

FIGURE 2. Schematic differentiation between air voids and pullouts that might be interpreted as air voids, after [6].

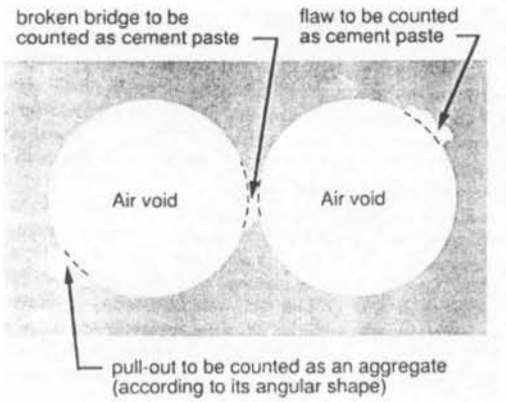

FIGURE 3. Schematic illustration of pullouts around air voids, after [6].

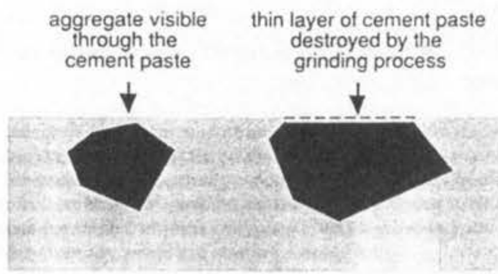

FIGURE 4. Schematic illustration of effects of aggregates located underneath the surface, after [6].

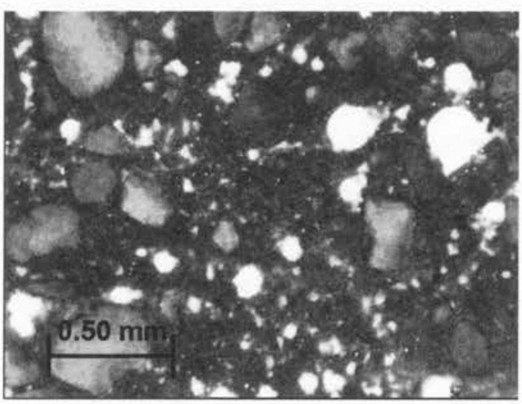

FIGURE 5. Image of prepared concrete sample of poor quality.

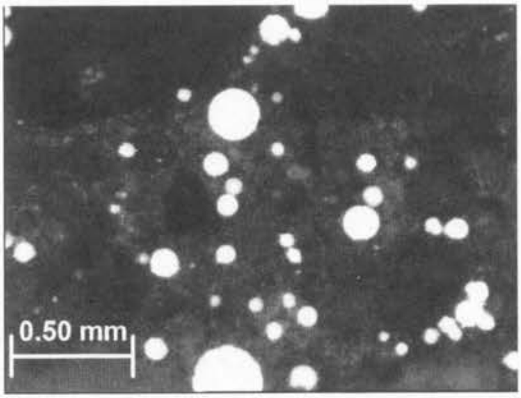

FIGURE 6. Image of prepared concrete sample of good quality.

element of expertise (Figs. 5 and 6). The measurements should be performed only on very carefully prepared specimens. This seems to be the main point to assure precision of the measurements.

4. System description

At the IFTR laboratory the system used for the automated image analysis is composed of:

- image analysis software Image Pro Plus,
- software Scope Pro to control the scanning table,
- automatic scanning table Marzhauser Scan 150 × 150,
- stereomicroscope Nikon SMZ 800,
- colour video camera Sony DXC 950P,
- cold light "swan neck" Precoptic,
- ultraviolet ring lamp Stocker & Yale.

The software is operated from the Dell Workstation 620. The scanning table can move along X and Y axes up to 150 mm with accuracy of 0.1 μm. Magnifications of the stereomicroscope are between 10× and 63×. Colour video camera has three CCD matrices, one matrix for each component of an image in the RGB system. With the help of this video camera it is possible to capture 24 bits colour images in the RGB system by resolution 768 × 576 pixels in rectangular net, or 8 bits gray scale images by the same resolution 768 × 576 pixels.

With the help of the present system it is possible to analyze in real time images up to 100 MB.

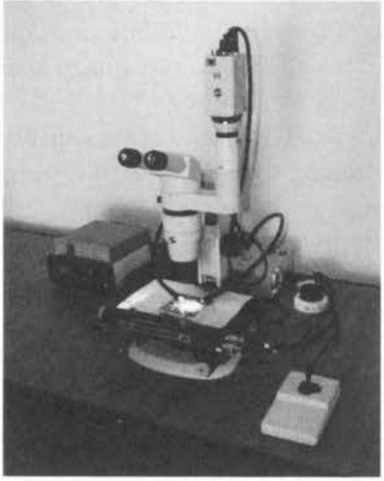

FIGURE 7. Image analysis stand.

In presented procedure, to determine the air void characteristics the magnification 30× is used; it means that 1 pixel in the image corresponds to 2.76 μm in the real sample.

5. Description of the program for automated air void analysis

Special program for automated air void analysis has been prepared according to specification in the new Polish Standard PN EN 480-11. The Polish standard conditions are the same as in the European Standard EN 480-11. In accordance with this document the program calculates all air void characteristics:

- spacing factor $\bar{L}$,
- specific surface α,
- air content A,
- content of air voids with diameter less than 0.3 mm A_{300},
- air void diameters distribution (a distribution table).

This program prepared in Image Pro Plus allows to control the table, the camera and to process of the images.

The procedure is as follows. Properly prepared concrete sample is fixed on the scanning table, and the next stage is initiated by moving to the start point position to start capturing images. In one course 38 single frames are captured and the frames are tiled to form one image. In such a way we obtain an image that represents 1.56×79.5 mm band of concrete sample surface. Size of the image is large, since 566×28804 pixels correspond to 49 MB of the computer memory. This 24 bits colour image is converted to 8 bits gray scale image.

The next step is a threshold. The aim of this operation is the identification of the air voids and obtaining a black and white binary image. At the end of this operation the binary image strip displays with the white air voids against the black background (Fig. 8(a)).

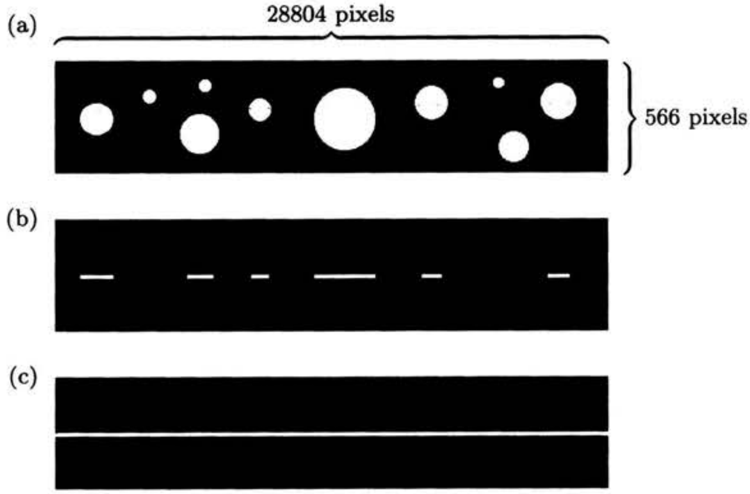

FIGURE 8. Process of generation of chords in air void image: (a) binary image of air voids A, (b) image of the linear traverse T, (c) image of chords in air voids as a product of logical operation $A \cap T$.

On this image realized is a logical operation "AND" with the image of a linear traverse, see Fig. 8(b). Finally, we obtain the image of chords in air voids, see Fig. 8(c). Measurements of length and number of the chords correspond to applying the linear traverse air void analysis method. The program described strictly corresponds to the procedures used in both the Polish and European Standard.

6. Accuracy studies

Program of special investigations have been realized and pertains to the determination of effects of the level of threshold of the image analysis system and of the light intensity. Sample of concrete with known parameters of the air void system was tested using various threshold levels, intensity of light and different positions of the linear traverse. The results received were compared in order to find the best settings of the system.

The threshold is the operation used to binary conversion of the image. In the present case it is the level of discrimination of the air voids from the background of the image. The relation between various parameters of air voids structure and the level of threshold was found to be close to linear (see Figs. 9-11). Tests were made on the same image of concrete sample. Of course, it is an expected result because modification of the threshold changes apparent diameter of an air void on binary image, see Fig. 8(a). However, changing threshold level by ± 5 degrees of gray value results only in changes of the measured spacing factor below 0.01 mm, of the specific surface below $2\,\mathrm{mm}^{-1}$, and of the air content below 0.5%. These changes

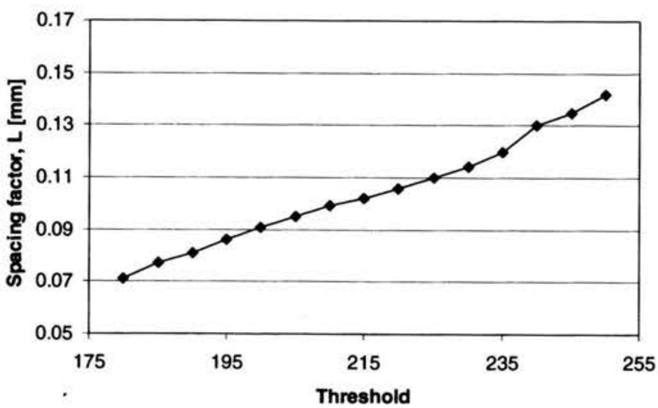

FIGURE 9. Relationship between the threshold level and the spacing factor $\bar{L}$.

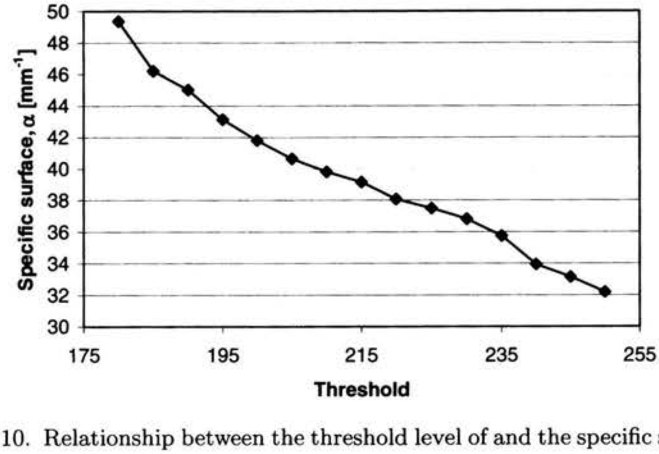

FIGURE 10. Relationship between the threshold level of and the specific surface α.

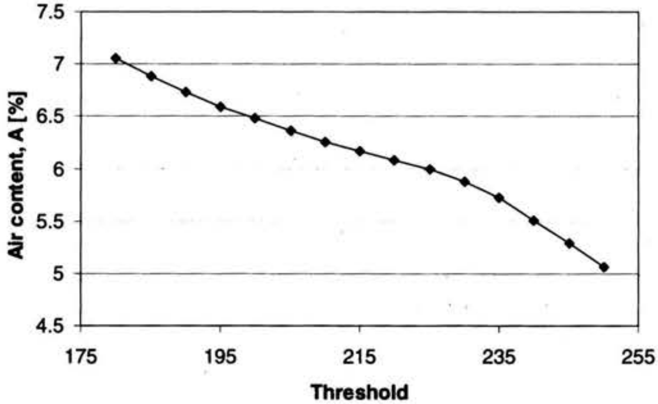

FIGURE 11. Relationship between the threshold level and the air content A.

are lower than the expected accuracy of the whole system, when applied evaluating concrete.

A more important factor seems to be the intensity of light. For the analysis of the effects of the intensity of light prepared was a kind of a standard black surface, being actually a fragment of floppy disk. The intensity of light was measured as a mean grey value of image of such standard. Relationship between the parameters of air voids and the intensity of light is shown in Figs. 12 and 13.

Also the sensitivity of results with respect to the position of the linear traverse was tested. The differences observed between the tests results at the

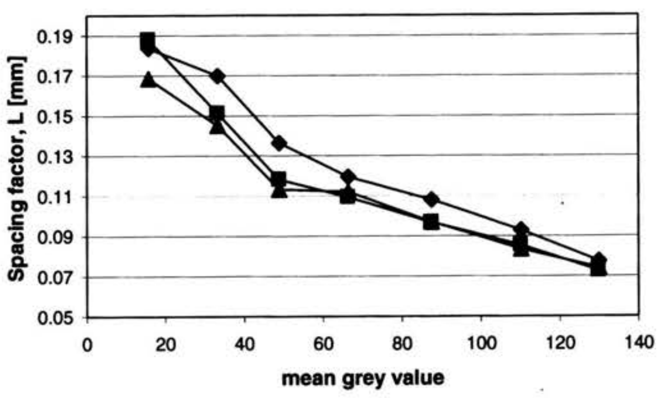

FIGURE 12. Relationship between mean gray value on the standard and the spacing factor $\bar{L}$.

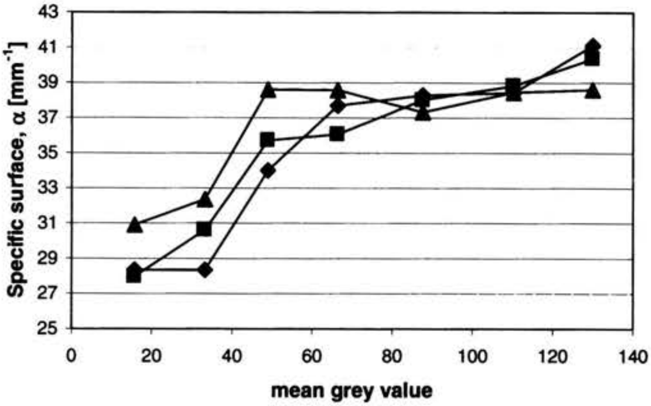

FIGURE 13. Relationship between mean gray value on the standard and the specific surface α.

traverse line being shifted by about 0.6 mm are shown in Figs. 12 and 13. Each line on the graph represents different position of the linear traverse.

Differences between values of the specific surface (α) depending on position of the linear traverse are up to $6\,\text{mm}^{-1}$, and between values of the spacing factor ($\bar{L}$) are up to 0.2 mm. This means that similar level of differences between consecutive measurements on the same sample of concrete might be expected in practical situations.

A structure of known parameters has been analyzed at various settings. Expected air void characteristics were obtained at the level of threshold 225 and for intensity of light between 50-90 as characterized by standard mean gray value. The conclusion is that the use of the described settings is in general appropriate for receiving correct test results.

7. Shape of objects analysis and its effect on the results

The consequence of filling voids by zinc paste is that some features emerge in the sample image. These are the features of objects like cracks, air voids inside coarse aggregate grains or damages of the paste surface, see Fig. 14. These objects will produce errors during automatic measurement of the air voids structure. In traditional way of preparation for automatic measurement such objects have to be painted by a black marker. This is a labour-consuming process and results are usually not satisfactory. The aim of investigation was to discover rules describing the misleading objects with the help of the shape factors in order to filter them later from the image of concrete sample.

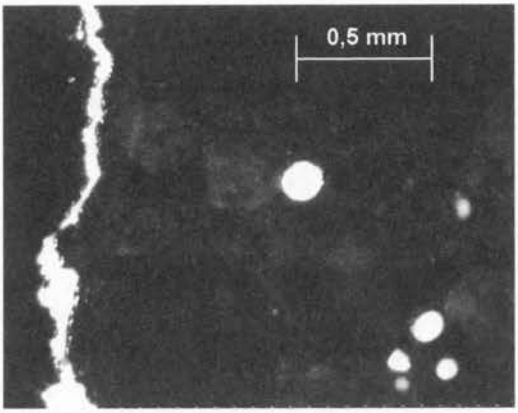

FIGURE 14. Picture of concrete sample with crack and entrained air voids.

In ASTM and European standards an air void is defined as "a small space enclosed by cement paste in concrete and occupied by air". This term does not refer to capillary porosity and to submicroscopic pores. The term includes also both the entrapped and the entrained air voids [1, 5]. Differentiation between entrapped and entrained air voids was introduced by ASTM C125 Standard. In accordance with this document an entrapped air void is characteristically 1 mm or more, and of irregular shape; an entrained air void is typically between 10 and 1000 μm in diameter and is spherical or nearly so, cf. [8].

To find some rules describing the "incorrect" objects shape factors were measured with the help of the image analysis system. Machine learning methods and data filtration procedures were used. A database consisting of 2504 records was prepared. Of those, 1776 records (marked by "T") correspond to regular air entrained voids, 186 objects (marked "N") are positively not the entrained air voids, and 542 objects (marked "?") were classified as uncertain. This classification was done by an expert. Various shape factors can be measured automatically with the help of image analysis system Image Pro Plus. A single record concerns one object, that is a simply connected region in the binary image, (black and white image). The feature is described by attributes. The attributes are:

- *Area* – the area of measured object, A,
- *Aspect* – the ratio between major and minor axis of ellipse equivalent to object, As,
- *Area/Box* – the ratio between area of object and area of its bounding box, A_B,

- *Box X/Y* – the ratio between width and height of object's bounding box, X_Y,
- *Radius Ratio* – the ratio between maximum and minimum distance between object's centroid and outline, R_R,
- *Roundness* – the shape factor defined as perimeter$^2/(\pi$ Area), Ro,
- *Per-Area* – the ratio of area of object to total area of image or AOI (Area of Interest), P_A,
- *Size (width)* – the Feret diameter along minor axis of object, W,
- *Fractal Dim.* – the fractal dimension of the object's outline, F_D.

Before the analysis all the data in the database were unified so that there are two digits after decimal point.

During the experiment special emphasis was put on rules describing the objects not being air entrained air voids. Machine learning programs AQ19 and See5 were used. Examples of generated rules are shown in Tables 3 and 4. The rules are presented in the form of conjunctions.

The meaning of the symbols used in Tables 3 and 4:

C – total number of records satisfying the rule from whole database,

N – number of correctly detected objects, not being entrained air voids,

T – number of not correctly detected objects, being entrained air voids,

? – number of not correctly detected objects, classified as uncertain.

The precision of the rule is defined as $\frac{N}{C} \cdot 100\,\%$.

Rules generated by programs AQ19 and See5 did not allow (with the only help of simple filtration) to remove automatically erroneous objects from image without removing simultaneously many properly entrained air voids. However, the analysis of the test results allowed to find the rule describing some incorrect objects, mainly cracks. Using data filtration in MS Excel this rule has been fixed to range: R_R > 3700, Ro > 3500, W < 200. In physical magnitude this rule corresponds to the range: Radius Ratio > 3.7, Roundness > 3.5, Width < 0.2 mm.

For confirmation of precision of the accepted rule tests were done on the air void structure on concrete samples after object filtration. Objects with shape factors matching the obtained rule were removed from the image. Also tests have been performed with manually removed misleading objects from the image. Examples of results are included in Table 5.

In the case of a good quality of concrete sample influence of the incorrect objects on the test results is small (see sample No. 3 in Table 5). If quality of material is poor, however, the influence the incorrect objects increase, see sample no. 2 in Table 5.

TABLE 2. Example of a few records from prepared database (the values have been unified by multiplying).

No.	A	As	A_B	X_Y	R_R	Ro	P_A	W	F_D	T_N
725	68.57	100.00	1000.00	1000.00	7.47	1000.00	5.52	5.52	0.00	N
726	76.19	163.30	833.33	1333.33	10.08	1000.00	6.13	6.35	0.00	N
727	30.47	100.00	1000.00	1000.00	5.20	1000.00	2.45	2.76	0.00	N
728	30.47	100.00	1000.00	1000.00	5.20	1000.00	2.45	2.76	0.00	N
729	1356.33	109.08	741.67	937.50	1384.77	1057.14	109.10	39.55	1063.00	T
730	1310.61	199.71	651.52	1833.33	5662.39	2685.26	105.50	30.33	1232.79	T
731	6751.17	101.51	668.17	1147.06	1304.67	1341.78	543.40	95.98	1088.31	T
732	1112.49	108.05	802.20	928.57	1247.49	1000.00	89.50	34.18	1063.07	T
733	3916.59	109.34	706.04	1076.92	1351.08	1094.58	315.20	69.58	1047.37	T

TABLE 3. Examples of rules generated by program AQ19.

No.	Rule	Number of records				Precision of the rule [%]
		C	N	T	?	
1	[A = 83.81 ... 921.99] [As > 126.64] [R_R > 2391.77] [W > 3.42] [F_D < 1228.28]	243	40	142	61	16.5
2	[A = 1847.80 ... 9905.78] [As > 150.24] [R_R > 2795.76] [W > 32.70] [F_D < 1110.11]	23	9	13	1	39.1

TABLE 4. Examples of rules generated by program See5.

No.	Rule	Number of records				Precision of the rule [%]
		C	N	T	?	
1	A > 76.19; As > 201.87; Ro ⩽ 1037.78; W ⩽ 5.86	8	4	1	3	50.0
2	A ⩽ 9433.35; X_Y ⩽ 1291.67; R_R > 2823.96; R_R ⩽ 3206.43; Ro > 1256.5; Ro ⩽ 2614.84	7	6	1	0	85.7

TABLE 5. Examples of results of estimation air void parameters using object filtration.

No. of sample			1	2	3
Measurement without object filtration	A	[%]	3.05	1.89	6.01
	$\bar{L}$	[mm]	0.136	0.160	0.106
	α	[mm^{-1}]	45.6	47.7	38.6
Measurement with manual object filtration	A	[%]	2.83	1.69	5.94
	$\bar{L}$	[mm]	0.153	0.197	0.115
	α	[mm^{-1}]	41.7	40.8	36.1
Measurement with automatic object filtration using shape factors	A	[%]	3.00	1.84	5.91
	$\bar{L}$	[mm]	0.139	0.171	0.111
	α	[mm^{-1}]	44.7	45.3	37.5

The filtration procedure presented above allows to remove from the image mainly cracks, objects frequently occurring in practical situations and producing errors during automatic measurement of air void parameters.

8. Application of high-resolution flatbed scanner

Primary source of images in estimation of the air void characteristics in concrete is nowadays a video camera coupled with microscope. Application of flatbed scanners in estimation of air void characteristics was not successful because of small resolution of scanners [7]. Appearance of new inexpensive, high-resolution scanners allows thinking about elimination of this obstacle.

In the IFTR laboratory the scanner Microtek ScanMaker 5600 with optical resolution up to 2400 points per inch is used. The smallest point of image – pixel – corresponds to 10.6 μm of length. The program to estimate the air void characteristics using the flatbed scanner has been recently prepared according to the specification in the Polish Standard PN EN 480-11, cf. [5]. Examples of results of estimation air void characteristics using the microscope and the scanner are shown in Table 6.

TABLE 6. Comparison of test results of evaluation air void parameters using microscope and flatbed scanner.

No.	Source of images	Spacing factor $\bar{L}$ [mm]	Specific surface α [mm^{-1}]	Air content A [%]
1	microscope and video camera	0.12	33	5.94
	flatbed scanner	0.11	35	5.69
2	microscope and video camera	0.12	32	4.89
	flatbed scanner	0.12	28	6.57
3	microscope and video camera	0.16	30	4.16
	flatbed scanner	0.16	25	5.45
4	microscope and video camera	0.15	47	2.41
	flatbed scanner	0.16	47	1.96
5	microscope and video camera	0.12	40	4.94
	flatbed scanner	0.13	37	4.42

Using a high-resolution flatbed scanner it is possible to obtain results comparable to the test results from the microscope. Advantages of applying of the scanner are permanent source of light and necessity of preparation only one side of concrete sample. Source of light type "swan neck", used in the system installed at the IFTR laboratory, requires permanent adjusting to the correct value. Capturing of images with the help of stereomicroscope, video camera and scanning table requires specimens with parallel top and bottom sides of the samples.

9. Experiments with application of a flatbed scanner

At IFTR laboratory tests on separation of the cement paste from the image of concrete surface were realized, and on automated measurement of the content of cement paste. To this end polished concrete samples were soaked in blue ink. In the consequence of the sample preparation the concrete surface is obtained with a distinguishable blue areas of the cement paste. By analyzing the histogram of the image of the so prepared concrete sample it is easer to separate the paste from the whole image. In images of the air voids and cement paste it is possible to analyze distribution of distances from the cement paste to the nearest air void.

The value of the spacing factor as modeled by Powers [2] is the mean value for the whole surface under consideration. Finding regions on the concrete surface, where the distance to the nearest air voids is greater than certain acceptable value, will give more information about frost resistance of concrete.

In Fig. 15 the cement paste is characterized by the intensity of gray depending on the distance to the nearest air void.

These experiments will be continued.

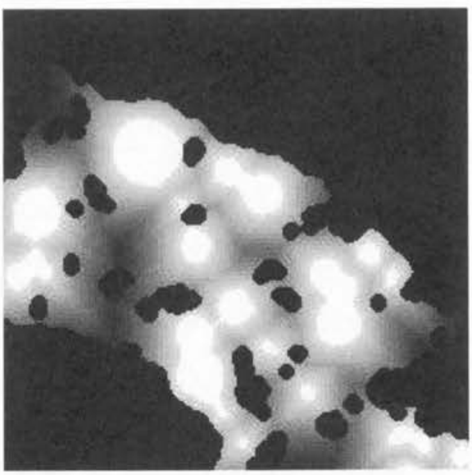

FIGURE 15. Image of aggregates, cement paste and air voids.

10. Conclusions

In view of developing the national roads system, improving the infrastructure and producing new concretes in Poland, introduction of new methods for quality control and quality assurance, like the methods described in this paper, is really important.

Image analysis system is a perfect tool for estimation of the structure of concrete. As a source of image a digital camera, a flatbed scanner or a video camera can be used. In the image analysis very important is the quality of sample preparation. Only high quality preparation of the samples can be used in the estimation of the structural parameters, like air void system parameters. Poor treatment of samples is a main source of errors.

Evaluating the air void parameters some defects of the surface image can be eliminated using object filtration by shape factors. Automatic image analysis requires permanent conditions of exposure in order to ensure repeatability of measurements. It requires control of settings of the system. By using image analysis system, as described in the paper, it is possible to obtain satisfactory results for automatic measurement of air void structure. This system right now is ready for quality control of industrial concretes. The estimation of the air void parameters can effectively be performed by using a high quality flatbed scanner.

Acknowledgements

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