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Automated air void analysis on hardened concrete Results of a European intercomparison testing program

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Abstract

This paper presents the results of a European round robin test on air void analysis on hardened concrete (SMT-EC-research project — Contract No. SMT4-CT95-2006). Thirteen laboratories in Europe from seven countries participated in the intercomparison test of which seven used a manual method and six an automated measurement system. The results indicate that the results obtained with measuring methods using image analysis (IA) techniques all statistically lie in the group of all measurement results. The automated methods can be problematic when a high amount of porous sand grains is present in the concrete. A second disadvantage of these automated methods is that it is not possible with the current methods being used to measure the paste content of the sample.

Keywords: Image analysis; Concrete; Air void analysis

1. Introduction

It is generally recognised that the air void structure of concrete is a critical parameter for the durability of concrete subjected to frost/thaw action and deicing salts. An air void analysis is the only method available on hardened concrete to evaluate the air void structure of concrete. Traditionally, the air void system is characterised and assessed in terms of the total air content and the spacing factor of the air bubbles as defined by Powers [1]. More recently, the micro air content (A300) has been recognised to be also an important factor [2]. For ordinary concrete, a great number of test results are available which document the correlation between the frost/thaw resistance of the concrete and the spacing factor of the air bubbles, whereby a spacing factor of about 0.200 mm seems to guarantee a good frost resistance [3]. General relationships of the different parameters of the air void system and the parameters having an influence on the stability of the air void system have been extensively investigated, especially at Laval University — Quebec [4]. More detailed information about the different measurement methods can be found in Elsen et al. [5].

Automated methods for air void analysis using image analysis (IA) techniques improve the existing methods by reducing the measurement time from 4–6 h manually to 10–30 min. Area and diameter measurements can be performed using these automated measurements making it possible to quantify the spacing between the air voids more precisely. Limited information although is available concerning the precision of the air void measurement methods. Most articles that have been published about the precision of air void analysis measurements including results from interlaboratory measurements present only data obtained microscopically using the traditional manual methods, e.g., Langan and Ward [6], Pleau et al. [7] and Sommer [8].

A limited number of experimental results of air void measurements using automated systems have been published by individual laboratories [9,10]. Automated systems use automated traverse methods or IA methods. The calculations in the former case do not differ from the manual linear-traverse method because both methods measure the individual chord lengths. The latter methods using IA techniques are not only capable of measuring chord lengths but also diameters, section areas and the perimeters of the air voids.

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Table 1
Comparison between EN480-11 and ASTM C457-90

Parameter	EN480-11	ASTM C457-90
Method	Linear-traverse method	A: linear-traverse method B: modified point-count method
Area (max. aggregate 31.5 or 37.5 mm, respectively)	150 mm^2	155 mm^2 (=24 $in.^2$)
Number of specimens	2	≥ 1
Length of traverse line (max. aggregate 31.5 or 37.5 mm, respectively)	≥ 2400 mm	≥ 2540 mm (=100 in.)
Magnification of the microscope	100 × ± 10 ×	50 × to about 125 ×
Air void size distribution	yes	no
Micro air content	yes	no

A comparison of the automated method vs. traditional manual method has been published by Ohta [11], who found a reduction of measurement time with 83–88% and a reduction of the coefficient of variance of the measurement of 75% using an automated method.

2. Standardisation and measurement methods

The air void system (ASTM C457-90, EN480-11) is most often characterised and assessed in terms of the total air content, the micro air content, the specific surface and the spacing factor of the air bubbles.

2.1. Total air content (physical parameter), symbol A%

The total air content is the proportion of volume of air voids to the total volume of concrete, expressed as a percentage by volume.

2.2. Micro air content (physical parameter), symbol A300

The micro air content is defined as the air content of air voids of 0.3 mm diameter or less.

2.3. Specific surface (physical parameter), symbol α

The specific surface is a calculated parameter representing the total surface of all voids divided by the total volume of voids (mm^{-1}).

2.4. Spacing factor (hypothetical parameter), $\bar{L}$

The spacing factor is defined by Powers [1] as a parameter related to the maximum distance of any point in the cement paste from the periphery of an air void.

if $p/A \leq 4.342 \quad L = p/(A\alpha)$

Table 2
Summary of results of measurements of round robin test

Laboratory	C01	C02	C03	C04	C05	C06	C07	C08	C09	C10	C11	C12	C13
Method used	A	R	P	A	A	R	R	P	P	R	A	A	A
Sample													
Air content (vol.%)													
1	2.4	2.6	3.1	3.6	2.5	3.0	3.0	3.4	2.6	1.7	2.3	2.7	2.5
2	3.9	3.9	3.9	4.8	3.5	4.0	4.0	3.9	3.1	2.7	4.5	3.2	3.7
3	12.3	11.1	13.0	13.1	14.2	8.8	13.8	12.1	11.8	10.3	13.4	13.8	11.4
4	0.9	1.5	1.7	1.1	1.3	1.5	1.3	1.6	1.0	1.2	1.2	1.9	1.1
5	7.9	7.9	9.7	9.6	8.6	8.1	9.3	9.1	7.8	6.4	9.8	7.7	8.4
6	4.8	4.9	4.6	5.7	4.8	4.7	5.4	6.9	3.9	3.5	5.8	5.8	5.3
7	8.9	7.3	6.2	6.8	9.1	5.9	9.3	9.1	10.1	6.9	8.3	9.3	8.6
8	9.0	8.3	9.5	7.9	9.4	7.0	9.1	9.0	9.3	8.5	8.6	8.5	8.2
9	1.3	1.0	0.9	1.0	1.3	1.4	1.6	1.5	1.6	1.0	1.2	1.4	1.4
Specific surface (α — mm^{-1})													
1	38	47	36	53	42	42	50	44	42	62	40	40	42
2	45	39	40	47	42	37	42	43	44	58	43	44	44
3	42	40	39	47	36	38	47	39	40	56	33	39	42
4	14	18	16	45	12	18	23	15	11	21	18	22	14
5	29	34	30	38	28	26	37	30	31	50	31	33	30
6	28	34	38	41	27	27	39	25	33	45	31	33	27
7	16	18	18	24	16	21	18	15	12	30	22	22	18
8	21	23	19	29	20	25	25	22	19	28	27	27	22
9	11	20	16	54	11	22	22	12	6	23	17	18	12

A = automated; P = manual point count; R = manual traverse (Rosiwal).

Table 3
Z-scores for air volume content (*A*)

	C1	C4	C5	C11	C12	C13	C3	C9	C8	C2	C6	C7	C10
Sample	Type A						Type P			Type R			
1	− 0.65	1.76	− 0.45	− 0.85	− 0.05	− 0.45	0.76	− 0.25	1.36	− 0.25	0.56	0.56	− 2.05
2	0.22	1.83	− 0.49	1.29	− 1.03	− 0.14	0.22	− 1.21	0.22	0.22	0.40	0.40	− 1.92
3	0.04	0.55	1.26	0.74	1.00	− 0.54	0.49	− 0.28	− 0.09	− 0.73	− 2.20	1.00	− 1.24
4	− 1.47	− 0.79	− 0.11	− 0.45	1.95	− 0.79	1.26	− 1.13	0.92	0.58	0.58	− 0.11	− 0.45
5	− 0.59	1.08	0.12	1.34	− 0.79	− 0.08	1.24	− 0.69	0.63	− 0.59	− 0.39	0.83	− 2.11
6	− 0.32	0.70	− 0.32	0.81	0.81	0.24	− 0.55	− 1.34	2.06	− 0.21	− 0.44	0.36	− 1.80
7	0.56	− 0.99	0.71	0.12	0.86	0.34	− 1.43	1.45	0.71	− 0.62	− 1.65	0.86	− 0.91
8	0.52	− 1.06	1.09	− 0.06	− 0.20	− 0.63	1.24	0.95	0.52	− 0.49	− 2.35	0.66	− 0.20
9	0.10	− 1.16	0.10	− 0.32	0.52	0.52	− 1.58	1.35	0.93	− 1.16	0.52	1.35	− 1.16

if $p/A > 4.342 \quad \bar{L} = \frac{3}{\alpha}\left[1.4\left(\frac{p}{A}+1\right)^{1/3} - 1\right]$

where $\bar{L}$, spacing factor (mm); p, paste content (%); A, the air volume content (%); α, the specific surface (mm^{-1}).

$\bar{L}$, A and α are not independent parameters. Therefore, the spacing factor will not be treated further here in this article as this spacing factor results from a calculation with the paste content, the air content and the specific surface as input.

2.4.1. ASTM C457-90

Total air content and the spacing factor or the specific surface of the air bubbles are traditionally determined worldwide following ASTM C457 wherein a manual method is described using either a point count or a linear-traverse method (Rosiwal method). These measurements are made on finely ground sections of the hardened concrete mounted under a microscope. The air void structure is examined by scanning along a series of traverse lines.

2.4.2. EN480-11

Recently, the new European standard EN480-11 *Admixtures for concrete, mortar and grout; Test methods: Determination of air void characteristics in hardened concrete* has been adopted.

The major differences between these two standards are summarised in Table 1.

3. Round robin test

A round robin test has been held on nine concrete samples. Nine concrete mixes were prepared by one of the participants of the intercomparison test taking care to cover the whole range of air void content and specific surface currently found in practice. Specimen with dimensions $10 \times 10 \times 2$ cm were prepared out of these nine concrete bodies. These nine samples were polished and measured by the seven laboratories using a manual air void analysis method. The samples were thereafter in a second step prepared for the automated air void analysis measurements. The samples have been contrast-enhanced so that the air voids can easily be selected from the cement paste and the aggregates. After being prepared in this way, the samples have been measured by the six laboratories using automated air void analysis measurement systems. The paste content for the nine samples involved was as follows:

Sample	1	2	3	4	5	6	7	8	9
Paste content (%)	26.0	26.0	26.5	26.5	26.5	26.5	24.1	24.1	27.3

4. Results

The summary of the results of the round robin measurements is presented in Table 2. Thirteen participants (C1, . . .,

Table 4
Z-scores for specific surface (α)

	C1	C4	C5	C11	C12	C13	C3	C9	C8	C2	C6	C7	C10
Sample	Type A						Type P			Type R			
1	− 0.92	1.21	− 0.35	− 0.63	− 0.63	− 0.35	− 1.20	− 0.35	− 0.07	0.36	− 0.35	0.79	2.49
2	0.26	0.66	− 0.34	− 0.14	0.06	0.06	− 0.73	0.06	− 0.14	− 0.93	− 1.33	− 0.34	2.84
3	0.11	0.96	− 0.92	− 1.44	− 0.41	0.11	− 0.41	− 0.24	− 0.41	− 0.24	− 0.58	0.96	2.50
4	− 0.58	3.01	− 0.81	− 0.12	0.35	− 0.58	− 0.35	− 0.93	− 0.46	− 0.12	− 0.12	0.46	0.23
5	− 0.62	0.84	− 0.79	− 0.30	0.02	− 0.46	− 0.46	− 0.30	− 0.46	0.19	− 1.11	0.67	2.78
6	− 0.79	1.23	− 0.95	− 0.30	0.02	− 0.95	0.82	0.02	− 1.27	0.18	− 0.95	0.98	1.95
7	− 0.70	1.04	− 0.70	0.60	0.60	− 0.27	− 0.27	− 1.57	− 0.92	− 0.27	0.38	− 0.27	2.34
8	− 0.76	1.56	− 1.05	0.98	0.98	− 0.47	− 1.34	− 1.34	− 0.47	− 0.18	0.40	0.40	1.27
9	− 0.66	2.99	− 0.66	− 0.15	− 0.07	− 0.57	− 0.23	− 1.08	− 0.57	0.10	0.27	0.27	0.36

Table 5
Across-samples means of *Z*-scores

	C1	C4	C5	C11	C12	C13	C3	C9	C8	C2	C6	C7	C10
Sample	Type A						Type P			Type R			
A	− 0.18	0.21	0.21	0.29	0.34	− 0.17	0.18	− 0.13	0.81	− 0.36	− 0.55	0.66	− 1.32
α	− 0.52	1.50	− 0.73	− 0.17	0.10	− 0.39	− 0.46	− 0.64	− 0.53	− 0.10	− 0.37	0.44	1.86

C13) have measured the same nine samples for air void content, for specific surface and for the spacing factor.

5. Statistical evaluation

5.1. Z-score

The results were converted to *Z*-scores to be able to study the interrelationships in the data by neutralizing the influence of the specifics of the nine samples used in the round robin experiment. The differences, perceived in these converted data, should then be due to the round robin participants and not a result of some specific property of the samples being analyzed. This transformation has the following form:

$$Z_{ij} = \frac{\text{row}_{ij} - \text{mean(row)}}{\text{stdev(row)}}$$

The original matrix of nine samples has different row average values and standard deviations. The *Z*-score transformation changes it into a matrix that has rows with the mean value of 0 and a standard deviation of 1.0. The *Z*-scores are presented in a tabular fashion in Tables 3 and 4. Note that the columns of the matrix have been reordered to bring together participants of the same type of equipment: A stands for automatic, P for point-count measurement instruments and R for Rosiwal-type (i.e., linear-traverse) instruments.

To allow uncluttered assessment of the quality of results, the *Z*-scores have been averaged across the nine samples, giving one single *Z*-score for every participant in the experiment (Table 5). A scattergram of the mean *Z*-scores of the specific surface (α) vs. the air content (*A*) (Fig. 1) indicates that the measurements are not a homogenous sample.

Two cases at the top of Fig. 1 exhibit behavior, which is significantly different from the rest of the group. Note that they belong to different measurement methods. One is using the automated and one the Rosiwal-traverse measurement method. The data set (Table 2) has been evaluated for the presence of outliers following the Dixon *Q*-test (ISO 5725 Precision of test methods — Determination of repeatability and reproducibility for a standard test method by interlaboratory tests — 13 Dixon's test). No outlier values were found for the air content values (95% confidence interval). If we perform this *Q*-test for the specific surface results, two of the nine results of C10 and two of the nine results of C04 are evaluated as being outliers.

5.2. Sampling variability

In search of possible sources for the variance between the different cases in the round robin experiment, the issue of the influence of sampling on the measurement has to be addressed. By calculating the values for the expected variability using 2400 mm for total traverse and the group averages for air volume content and specific surface, than on average the sampling variability contributes 86% to the air

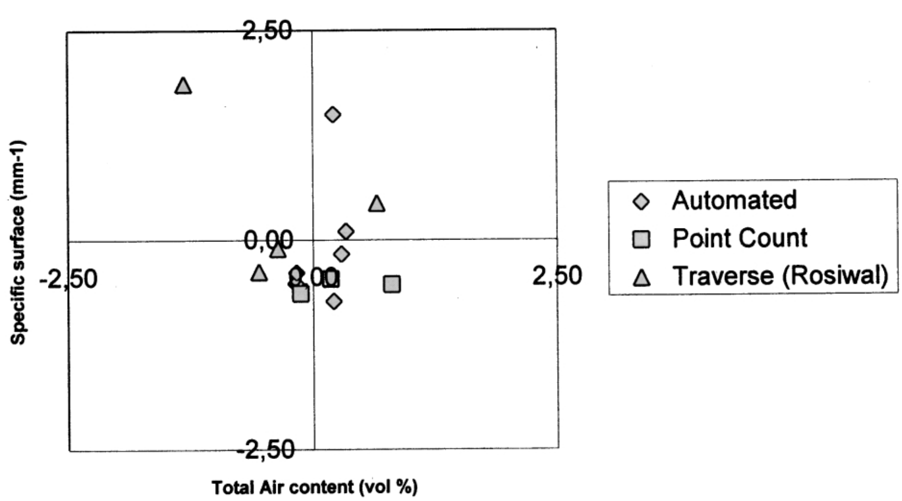

Fig. 1. Plot of the mean *Z*-score for the specific surface (α) against the mean *Z*-score for the total air content (*A*). The 13 participating laboratories used an automated or point-count or Rosiwal-traverse method.

volume percent and 60% to the specific surface variability in our measurements.

6. Conclusions

A round robin test has been held on nine concrete samples covering the whole range of air void content and specific surface currently found in practice. Thirteen laboratories in Europe participated in the intercomparison test of which six used an automated method and seven a manual method for air void analysis. Three out of these last seven laboratories use a manual point-count method and the other four laboratories use a manual linear-traverse (Rosiwal) method.

The results indicate that the method used did not seem to have a significant influence on the results and that, excluding two outliers, they all lie within the sampling error to be expected on the basis of standard requirements. The results obtained by automated measuring methods all lie statistically in the group of all measurement results, a statistical analysis points out that sampling is the major reason of variation for air void analysis.

The automated methods are very fast but they can be problematic when a high amount of porous sand grains is present in the concrete. A second disadvantage of these automated methods is that it is not possible with the current methods being used to measure the paste content of the sample in an automated way. Furthermore, for these automated methods, it became clear that sample preparation is of crucial importance for obtaining reliable and comparable results. Therefore, detailed guidelines describing sample preparation have been produced before the intercomparison testing program. The repeatability of the Rosiwal-traverse method using automated IA techniques has been evaluated in one laboratory by repeated measurements (10) performed on 15 samples. A mean coefficient of variation of 3.01% has been found for total air content with a standard deviation of 1.54, and of 3.48% with 1.89 as standard deviation for the specific surface of the air voids.

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